Output power control of nuclear reactor using ant lion optimization-based controller

Tarek A. Boghdady, Mostafa Mahmoud Ibrahim, Essam Aboul Zahab, Mahmoud Sayed
Department of Electrical Power Engineering, Faculty of Engineering, Cairo University, Giza, Egypt

Article Info	ABSTRACT
	Power level control is a critical issue in nuclear power stations due to its nonlinear dynamics. One of the most commonly used controllers is fractional order proportional–integral–derivative (FOPID). The FOPID is an enhanced and modern controlling system that has two additional added parameters. In this paper, comparison between particle swarm, gray wolf and ant lion optimization techniques is performed to determine the FOPID controller parameters. The nuclear reactor is a pressurized water reactor which is a fifth order nonlinear reactor model and is simulated using MATLAB software based on the point kinetic model. The integral square error (ISE) performance index is used to evaluate the performance of the three optimization techniques. The simulation results show that ant lion optimization for tuning the FOPID controller parameters gives the best performance and integral square error index better than the two other optimization techniques. *This is an open access article under the CC BY-SA license.*
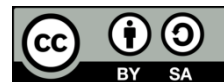
Corresponding Author:

Mostafa Mahmoud Ibrahim
Department of Electrical Power Engineering, Faculty of Engineering, Cairo University
Giza City, Giza, Egypt
Email: mostafa.mahmoud@eng.cu.edu.eg

1. INTRODUCTION

Due to the severe environment problems resulted from using fossil fuels, it is very important to propose clean energy techniques in order to keep human sustainability. Previous fact gives the modern focus on nuclear energy generation [1], [2]. It was consedered that fission energy is a pivotal clean energy that does not emit greenhouse gases and could replace fossil fuels in an efficient way with huge amount and economic competitiveness [3], [4]. Because the pressurized water reactor (PWR) is the most commonly applied nuclear reactor, safe and stable operation of the PWRs is considered very important issue for the nuclear industry [5], [6]. Power-level regulation is important in order to maintain a satisfactory operation of PWRs. The main rule of power level control is to determine the injection and withdrawal speed for the reactor controlling rods to maintain the generated power at a required rate [7], [8].

The most widespread and simple control element in different fields of industry is the proportional-integral-derivative (PID) controller because of its singularity in its plain structure and easy implementation in modern applications and complex industries [9], [10]. Although the PID controller is very simple in construction and implementation, it needs uninterrupted refinement in order to enhance its performance [11]–[13]. The PID performance can be further enhanced through the process of making use of fractional order derivative and integral. The two added parameters in the FOPID controllers give more opportunities for flexibility, control and stability [14].

In general, the tuning methods for FOPID controller can be classified into analytical, numerical and rule-based ones [15], [16]. The controller parameters can be analytically determined by solving nonlinear

equations in order to achieve the required specifications in the gain and phase margin and crossover frequency. But this method is applicable only when the equations are small in number and plain. So, it is difficult to get FOPID parameters for the the PWR. For the rule-based method, it can determine the required parameters depending on empirical tuning rules. However, the consedered system usually must be a system that having an S-shaped step response [17].

On the other hand, the numerical method - which is usually an optimization-based method - is a relative suitable solution for tuning FOPID for the PWR [18], [19]. Three optimization techniques is used in this study which are particle swarm optimization (PSO) [20], [21], gray wolf optimization (GWO) [22], [23] and ant lion optimization (ALO) [24], [25] and the evaluation will be based on the integral square error (ISE).

2. PROBLEM FORMULATION

The nominal PWR model used in FOPID controller designing is from order five. It is point kinetics having only one delayed neutron group. It also has a temperature feed-back from agglomerated fuel and coolant temperature computation that can be listed as follows [6], [8], [26], [27]:

$$\frac{dn_r}{dt} = \frac{\delta\rho-\beta}{\Lambda}n_r + \frac{\beta}{\Lambda}c_r \tag{1}$$

$$\frac{dc_r}{dt} = \lambda n_r - \lambda c_r \tag{2}$$

$$\frac{dT_f}{dt} = \frac{f_f P_{0a}}{\mu_f}n_r - \frac{\Omega}{\mu_f}T_f + \frac{\Omega}{2\mu_f}T_l + \frac{\Omega}{2\mu_f}T_e \tag{3}$$

$$\frac{dT_l}{dt} = \frac{(1-f_f)P_{0a}}{\mu_c}n_r + \frac{\Omega}{\mu_c}T_f - \frac{2M+\Omega}{2\mu_c}T_l + \frac{2M-\Omega}{2\mu_c}T_e \tag{4}$$

$$\frac{d\,\delta\rho_r}{dt} = G_r z_r \tag{5}$$

$$\delta\rho = \delta\rho_r + \alpha_f\left(T_f - T_{f0}\right) + \frac{\alpha_c(T_l-T_{l0})}{2} + \frac{\alpha_c(T_e-T_{e0})}{2} \tag{6}$$

where:
P_{0a} =Rated power level (MW)
n_r = Neutron density relative to density at rated condition
f_f = Portion of reactor power deposied in fuel
μ_f = Fuel heat capacity
μ_c = Coolant heat capacity
Ω = Fuel and coolant heat transfer coefficient
M = Mass flow rate times coolant heat capacity
T_f = Average temperature of reactor fuel
T_l = Temperture of the coolant leaving the reactor
T_e = Temperture of the coolant entering the reactor
α_f = Fuel temperature reactivity coefficient
α_c = Coolant temperature reactivity coefficient
T_{f0} = Equlibrium average reactor fuel temperature
T_{l0} = Equlibrium temperature of the coolant leaving the reactor
T_{e0} = Equlibrium temperature of the coolant entering the reactor
$\delta\rho$ = Reactivity
$\delta\rho_r$ = Reactivity because of the control rod
z_r = Control input, control rod speed (fraction of core) length per second
G_r = Total reactivity worth of controlling rod

The PWR used in this study can be modeled as 5th order nonlinear model having only delayed neutron group and pair of thermal feedback system. Table 1 shows the parameters of the PWR.

Table 1. The parameters of the PWR [28]

Parameter	Value	Unit
P_{0a}	2500	MW
f_f	0.92	
μ_f	26.3	MW. s/°C
μ_c	71.8	MW. s/°C
Ω	6.6	MW/°C
M	102	MW/°C

3. METHOD

In this section, the three optimization techniques are used to tune the five parameters of the FOPID controller applied to the process (PWR model) and the selected objective function to be minimized is the integral square error (ISE) for a unit step response. The simulation is performed using MATLAB software. Figure 1 shows the generalized block diagram for the FOPID controller with the process. The transfer function of the FOPID controller has the following form:

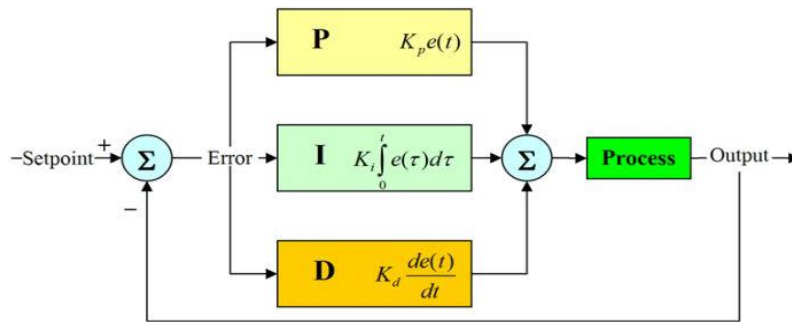$$G(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \tag{7}$$

Figure1. Block diagram for the FOPID controller with the process (PWR model)

The PSO technique relys on the intelligent motion rule of a swarm that proceeds within a search area, searching for the best solution to it [29]. So, every particle within vacant region is treated as an N-dimensional point that tries to optimize its posture with the use of the current location and the speed [21]. The GWO is a modern inspired algorithm that simulates the directing pyramid and hunting method of grey wolves in real life.

This hunting process of grey wolves consists of three steps: looking for victim, encircling the victim, and attacking the victim. Grey wolves normally move in groups and are divided into four groups. The first group wolves are the commander, the second group wolves support the first group in obligations and can replace them if they die, the third group are the hunters, keepers and explorers of the group, the forth group refers to the young group members [22]. The ALO algorithm simulates the hunting mechanism of antlions in real life. In ALO, a selected random walk is usedin order to stochastically represent the ant's motion toward the nourishment place. During optimization procedure, ants modify their locations in each iteration within walk sat stochastically determined. every random walk step is calculated using the min-max normalization technique to confirm the rate of random walks within the trait space [25], [30].

Table 2 shows the values of the parameters of the FOPID controller and the integral square error when the three optimization techniques are used to minimize the ISE due to unit step variation in the reference power. It is clear that the ant lion optimization technique gives the best ISE.

Table 2. The parameters of FOPID controller and the ISE due to unit step response

Variable	K_p	K_i	K_d	λ	μ	ISE
PSO	70	25	17.565	0.679	0.4995	0.002331
GWO	68.23	6.3748	7.2609	0.7048	0.0138	0.11017
ALO	69.9876	24.9931	17.9227	0.6345	0.5	0.002328

4.   TESTS AND SIMULATION RESULTS

Several tests are implemented using MATLAB to evaluate the efficiency of the three optimization techniques as shown in Figure 2. Figure 3 shows the normalized output power responses due to step variation of reference power from 85% to 90% at time equals 25 seconds. Figure 4 shows the normalized output power responses due to step variation of reference power from 100% to 90% at time equals 50 seconds. Figure 5 shows the normalized output power responses due to step variation of reference power from 80% to 85% at time equals 20 seconds and then back from 85% to 80% at time equals 40 seconds. In order to qualitatively judge the performance of the three optimization techniques on tuning FOPID controller parameters, Table 3 shows the ISE results and comparison.
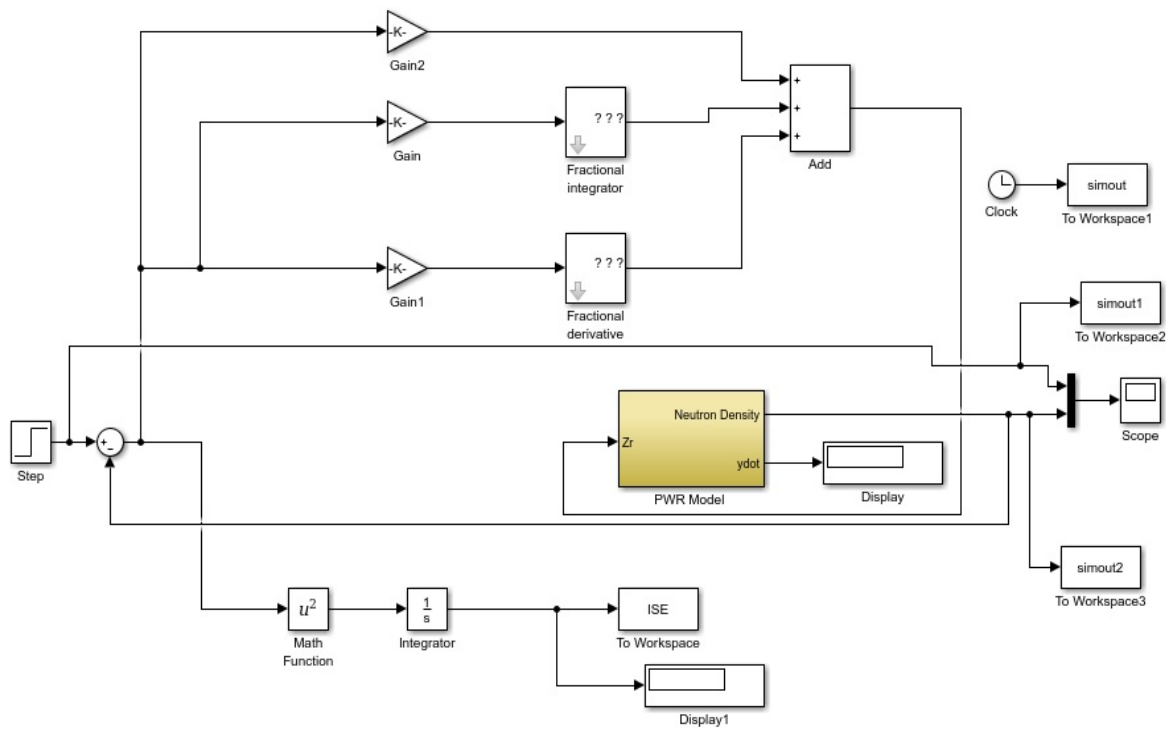
Figure 2. MATLAB simulink implementation of the FOPID controller for the PWR model
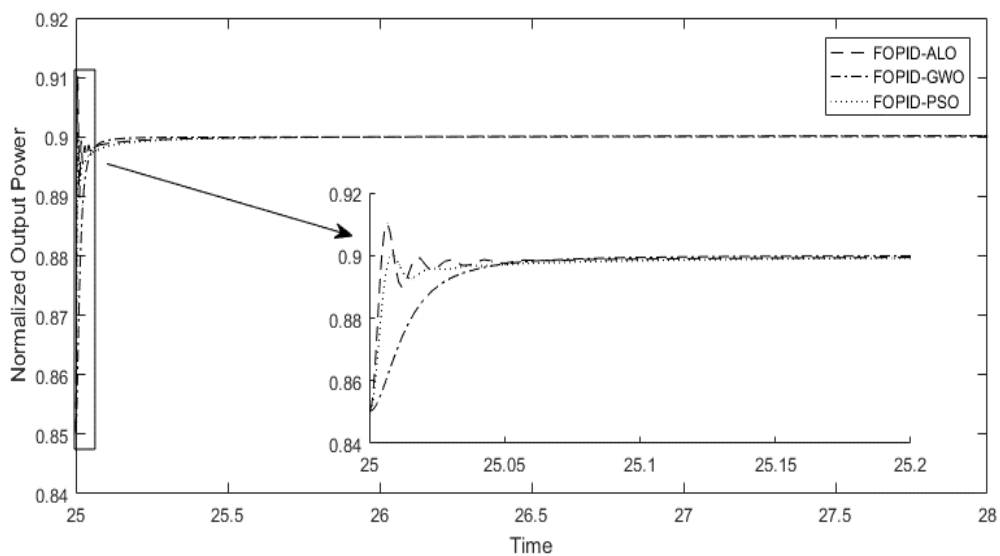
Figure 3. Perunit output power responses due to step variation of reference power from 85% to 90%
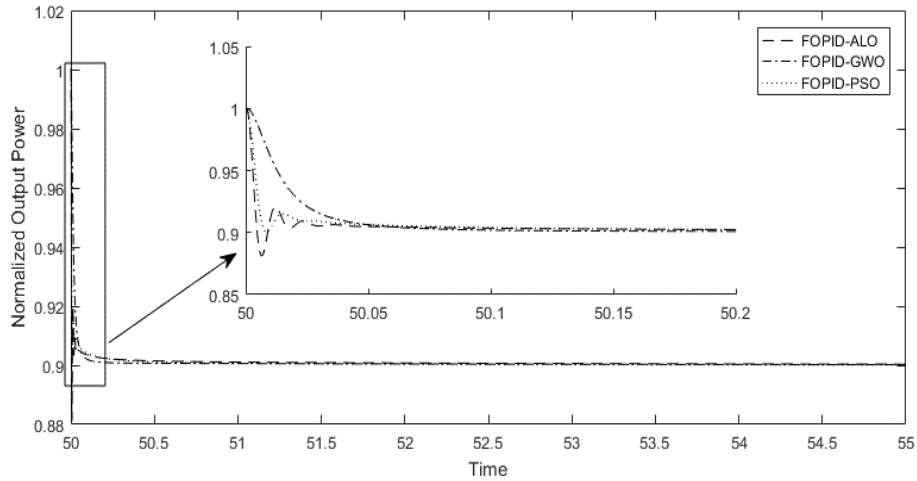
Figure 4. Perunit output power responses due to step variation of reference power from 100% to 90%
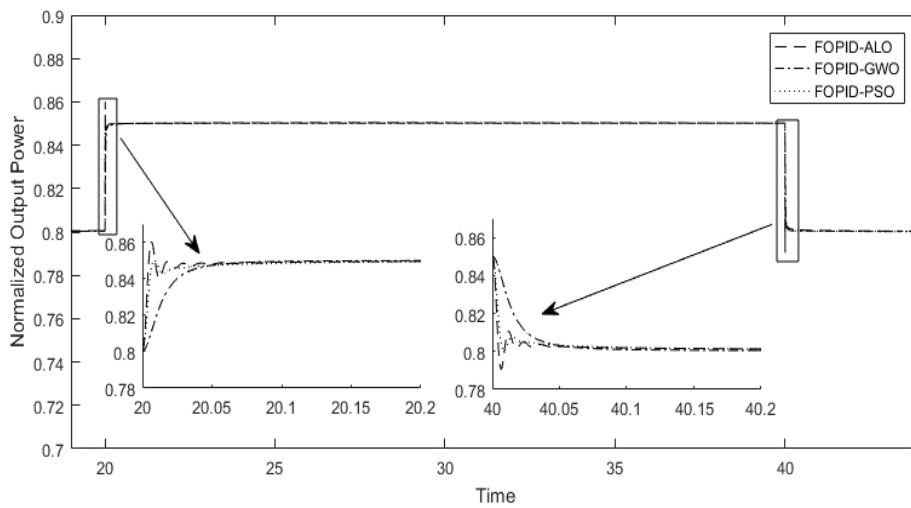

Figure 5. Perunit output power responses due to step variation of reference power from 80% to 85% and then back from 85% to 80%

Table 3. The integral square error for the responses in Figure 3-5

Technique	ISE (Figure 3)	ISE (Figure 4)	ISE (Figure 5)
FOPID-PSO	0.0020514175	0.002391215	0.001911005
FOPID-GWO	0.007242511	0.008494478	0.006430943
FOPID-ALO	0.002045736	0.002213185	0.001816844

It is noted that the PSO based FOPID controller has performance close to the ALO based FOPID controller. However, the ALO based controller has lower integral square error. Also, the GWO based FOPID controller has the least overshoot but has relatively long settling time and the worst ISE.

5.   CONCLUSION

Three optimization techniques are used to design a fractional order PID controller to control the output generated power of a pressurized water reactor. The simulation results show that the ant ALO technique gives the best performance in tracking the reference power based on the integral square error index. Also, ALO based FOPID controller gives the minimum settling time with zero steady state error. On the other hand, the GWO based FOPID controller has the higher settling time and the worst ISE.

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BIOGRAPHIES OF AUTHORS

Tarek A. Boghdady ⓘ 🇬 SC Ⓟ he was born in Egypt in March 1982. He received the M.Sc and Ph.D degrees in electrical power and machines engineering from Cairo University, Egypt, in 2011 and 2016, respectively. From 2005 to 2016, he was a Teaching Assistant with Cairo University. In 2016, he became an Assistant Professor with Cairo University. His research interests include optimization, neural networks, FACTS, HVDC as well as utilization and generation of electric power, distributed generation and renewable energy sources. He can be contacted at email: engtarek82@gmail.com.

Mostafa Mahmoud Ibrahim ⓘ 🇬 SC Ⓟ he was born in Egypt in May 1987. He received the B.S. in 2009, M.S. in 2015 in Electrical power engineering from Cairo University, Egypt. His research interests include optimization, neural networks, modern control techniques and sustainable energy generation, distribution, protection and integration. He can be contacted at email: mostafa.mahmoud@eng.cu.edu.eg.

Essam El-Din Aboul Zahab ⓘ 🇬 SC Ⓟ he received the B.Sc. and M.Sc. degrees in electrical power and machines from Cairo University, Giza, Egypt, in 1970 and 1974, respectively, and the Ph.D degree in electrical power from the University of Paul Sabatier, Toulouse, France, in 1979. He is currently a Professor with the Department of Electrical Power Engineering, Cairo University. His research interests include sustainable energy generation and distribution. He can be contacted at email: zahab0@yahoo.com.
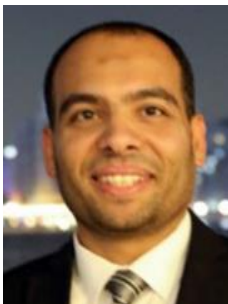
Mahmoud Sayed ⓘ 🇬 SC Ⓟ he was born in Cairo, Egypt, in 1982. He received the B.S. in 2005, M.S. in 2008 and Ph.D in 2013 in Electrical engineering from Cairo University, Egypt. He is currently an Assistant professor at faculty of engineering, Cairo University. His research interests include optimization and nuclear energy. He can be contacted at email: fecu.msayed@gmail.com.