# Efficiency Improvement of NTPL Power Plant Using Fractional Order Controller

***Mathew, G. Joy***
*Department of Electrical Engineering, University of California, Riverside, U.S.A*

***Jamal, D. Najumnissa*●**
*Department of Electronics and Instrumentation Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai 600048, Tamil Nadu, INDIA*

***Beevi, S. Jennathu***
*Department of Electrical and Electronics Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai 600048, Tamil Nadu, INDIA*

***Shajahan, M.S. Murshitha**+**
*Department of Electronics and Instrumentation Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai 600048, Tamil Nadu, INDIA*

***Manokar, A. Muthu***
*Department of Mechanical Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai 600048, Tamil Nadu, INDIA*

**ABSTRACT:** *Most of our power requirements are fulfilled by coal-fired power plants. This paper aims to improve its efficiency by designing a Fractional Order Proportional Derivative Controller (FOPD). A mathematical model is developed from the real-time data from the fossil-fueled power plant in Tuticorin India. The optimal tuning parameters for the FOPD controller are chosen from a selection of widely popular Optimization Algorithms (OA) [Sine Cosine OA (SCOA), Ant Lion OA (ALOA), Moth Flame OA (MFOA), and Whale OA (WOA)]. The analysis evaluates the controller's performance with time domain specifications like settling time, undershoots, and overshoots, and the superiority is highlighted. The operational efficiency of the power plant is evaluated against The efficiency values were calculated by the proposed controller using various OAs. The plant's operational efficiency is determined to be 37.2%. An increase in efficiency of 23.5% is achieved while using the intelligent controllers. Improvement in efficiency is also highlighted.*

**KEYWORDS:** *Thermal power plant; Electric power generation control; Boiler-turbine-generator station; Efficiency calculation; Fractional order controller; Evolution and optimization techniques.*

**To whom correspondence should be addressed.*
*+ E-mail: murshitha@crescent.education*
*●Other Address: Department of Electronics and Instrumentation Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai 600048, Tamil Nadu, INDIA*
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**INTRODUCTION**

Rystad Energy, an independent research and business intelligence group estimates that, in 2023 about 10,373 TWh of electricity was generated worldwide by fossil-fuelled thermal power plants—recent developments in A.I and increasing economies are anticipated to increase energy demand in the coming years. One of the strategies that can be used to cope with the looming energy demands is to upgrade the existing facilities of coal-powered power plants.

In regards to this, designing a fractional order controller that can improve the efficiency of thermal power plants has been proposed. The fractional order controller is the latest in the control engineering community, its ability to utilize values in between derivatives makes it revolutionary. To optimize the controller gains four OA, SCOA, ALOA, MFOA, and WOA have been chosen. All the algorithms used are nature-inspired except the SCOA. Moreover, a small section of the report is allocated to compare the efficiency of the OA used. It must also be noted that all the simulations were carried out using Simulink models designed for the 500 MW thermal power plant located in Tuticorin; the real-time data was used to test the controllers which were also obtained from the same power generation site (*Shajahan et al*., 2022). The paper elaborates on the design of a controller that can potentially boost the efficiency of the thermal power plant. This study closely mimics real-time factors by simulating models using actual data obtained from the plant.

(*Zamani et al.,* 2009) An automatic voltage regulator is created to be controlled by a Fractional Order Proportional Integral Derivative (FOPID) controller, and the search technique used in this study is the particle swarm OA (PSOA). To establish the effectiveness, a detailed comparison is made of the Proportional Integral Derivative (PID) and FOPID's performance (*Aleksei Tepljakov et al*., 2018).

Among the nature-inspired algorithms, the genetic algorithm is well-studied and widely used. On the other hand, FOPID is widely recognized for better performing than traditional controllers. *Cao et al*., 2005 designed a FOPID controller optimized by a genetic algorithm. The study takes Integral Time Absolute Error (ITAE) as the objective function and proceeds to minimize it with its proposed controller setup [31]. In the medical sector, an FOPID controller was designed for blood pressure regulation; Genetic Algorithm (GA) was chosen as the OA.

The rules and guidelines for optimal tuning of PID and FOPID are discussed by (*Padula* and *Visioli,* 2011), the guidelines are found on a process model which is in the category of 'first-order-plus-dead-time'. The guidelines are carefully formulated to reduce Integral Absolute Error (IAE). The study finally concludes on the note that FOPID has superior performance to traditional PID. To design FOPID in the virtual environment this work (*Lachhab et al.,* 2013) publishes a FOPID toolbox design. Since most of the FOPID performances are proven by simulation, this FOPID toolbox plays a vital role in obtaining the required results. Further, the configuration of loop sharing has been used to design the controller. To prove the superiority of their design the authors have included the simulation results towards the end of the report. The process of designing an H∞ FOPID controller that can control the margin stability characteristics, transient and steady-state response is addressed (*Zamani et al*.,). The paper identifies a cost function to be minimized and is made with the H∞ norm.

This study by the authors (*Das et al*., 2011) is dedicated to the processes of higher order, by comparing the time and frequency domain tuning techniques in FOPID controllers a better technique is shortlisted. The efficacy of a FOPID controller in practical situations is also discussed in the paper. The authors of this paper (*Idir et al*., 2018) propose FOPID controllers that work in fractional order. The fractional order PID design proposed here is optimized by PSOA and differential evolution algorithms. According to the authors, FOPID tuned through differential integration performed better than the one tuned by PSOA. The performance criteria taken into account are error reduction, setpoint tracking, and noise depletion analysis. [34] A FOPID controller optimized by PSOA was designed and utilized to control a non-linear Twin Rotor Multi Input Multi Output (TRMIMO). As FOPID controllers are getting popular in the energy sector, a study was made to analyze optimization techniques for FOPID controller design in grid integration [35, 36, 37]. An interesting experimental setup is constructed where three cylindrical tanks are connected and are filled with fluid (*Mohamed Hussain K et al*., 2018). The objective lies in controlling the fluid. Originally, modeling was done by changing differential equations into the state space model, simultaneously it was converted into a transfer function. The control was achieved by using a PID controller; the chosen tuning methods were Simulated annealing, Genetic algorithm, and Quantitative feedback theory. By comparing the time domain specification of each algorithm, the best method is declared in the conclusion.

To control the coal flow, airflow, and the feed water flow in a coal-fuelled thermal power plant a Proportional Derivative (PD) controller operating in Quantitative Feedback Theory is proposed (*Murshitha Shajahan et al*., 2019). To prove the efficiency of the controller real-time data used in this paper is collected from the 500 MW thermal power plant. The Simulink model is also precisely modeled based on the features of the station. Any reduction of the settling time will directly have an impact on the efficiency of a power station, translating into less coal required without losing out on the required power output. It is well established that fractional order controllers derive better results than the integer order controllers. To solidify this concept the authors of this article (*Gu et al.,* 2005) have stated two examples and have compared the simulation results with both the variants. The paper also gives insight into the science behind this controller to answer some of the most frequently asked questions. OA with faster settling times is another aspect to creating a perfect controller. The algorithm set proposed in this article (*Hamamci*, 2007) is said to bring stability with faster settling times. Along with the algorithms, the range of search for λ and μ. Since the superiority of fractional order PID is well documented and established at this point, researchers (*Jun-yi Cao; Bing-gang Cao.,*2006) are bringing in experimental OA to observe the reaction of these controllers. Here, a nature-inspired particle swarm OA (PSAOA) is used. The identified objective function is control input and ITAE. Insights into the ‘design of fractional order controllers are also given.

A complete analysis of fractional order PID is done (*Ahn et al.,* 2009). The Kp, Ki, and Kd controller gains and the λ, μreal orders are found to reduce the target function, Integral Square Error. The stability in the frequency domain is checked by a numerical method. A multi-objective robust PID is designed for two multi-input multi-output processes (*Zhao et al.*, 2011) specifically, the longitudinal control system of high alpha research vehicle and distillation column plant. The ‘multi-objective particle swarm optimization (MOPSO) is applied in the design process. The objective functions identified in this report are ISE and balanced robustness. The superiority over PID controllers optimized by a non-sorted genetic algorithm (NSGA-II) is highlighted. A fuzzy PID is designed for a nonlinear system of fourth order (*Mahmood Abadi; Jahanshahi*, 2016). The Pareto front is calculated by using the ‘Multi-Objective Genetic Algorithm (MOGA). The results of MOGA are compared with MOPSO.

To achieve efficiency the ‘fractional order PID is used to design the system, with the OA being MOPSO (*Chhabra et al.*, 2016). Simultaneously a traditional PID is also developed for the same process and optimized by the same MOPSO algorithm. The article concludes by explaining how both of these systems differ in terms of performance. Among the latest set of nature-inspired algorithms, MFO (*Mirjalili*, 2015) mimics the navigation method used by moths to travel in a straight line; they do this by keeping a fixed degree with the moonlight. The MFO algorithm has already been credited for its performance in areas like medical science, energy systems, and engineering design (*Shehab et al.*, 2020). Keeping these achievements and the problem results in perspective a comparison is made with other nature-inspired algorithms like this, strengths and weaknesses are also stated. The most common problem control engineers face while working with OA is that quite often the OA ends up in the local best solution without exploring the global best. This not only affects the results but also increases the research period.

To combat this phenomenon a new improved version of MFO is scripted (*Li et al*., 2020), called the Improved Moth-Flame OA (IMFOA). This version of the algorithm uses the Levy flight algorithm to improve exploration capabilities and maintain strong population diversity. The MFO algorithm is among the newest developed metaheuristic OA. While working with these algorithms engineers have noted a reduction in speed of convergence and a lack of exploration capabilities. To balance the shortcomings, an IMFO is proposed. The novelty lies in the addition of a hybrid phase to the existing algorithm (*Pelusi et al*., 2020). Simulation results prove that this add-on has stricken a better balance between exploitation and exploration.

Two algorithms namely SA (Simulated Annealing) and MFO are interlinked to create a new algorithm that allows for better problem-solving performance (*Sayed; Hassanien*, 2018). WOA (*Mirjalili; Lewis*, 2016) is formulated by studying the hunting habits of humpback whales in the ocean. The algorithm closely mimics the bubble-net hunting behavior, where the whale circles its prey from the bottom and slowly raises its level while simultaneously shrinking its radius. [26] Based on the mathematical trigonometric function’s sine and cosine, a population-based algorithm was built called SCA (*Suid et al.*, 2018). Using the sine and cosine trigonometric functions, the technique generates a random collection of solutions and lets them evolve toward the best one.

To improve the exploration abilities numerous random and adaptive variables have been added. Test results prove that the sine cosine algorithm can be employed to solve real-time problems. ALO (*Mirjalili*, 2015a) algorithm imitates the hunting behavior of the insect ant lion which is, walking around in search of potential hunting grounds, setting up the trap, catching the ant, and rebuilding the trapping mechanism. The results show promising exploration abilities, faster convergence speed, and escaping local optima in search of a global optimal solution. The algorithm was tested by designing optimal sizes and shapes for a propeller of the given ship capacity. After analysis, it was concluded that the ALO algorithm is ready to be utilized for real-time applications. Initially, the ALO algorithm was proposed to be fit for real-time application by testing it to obtain the best propeller design for a specified ship capacity. To give a better perspective on the ant lion algorithm this paper was published where the authors took a survey of all the possible applications and their effectiveness against certain types of problems (*Abualigah et al*., 2021).

The biology-inspired optimization algorithm ALO was used to design and develop a ‘fractional order PID that can control higher order systems (*Pradhan et al*., 2020). The target functions taken into consideration were Integral Squared Error (ISE), Integral Time Squared Error (ITSE), Integral Time Absolute Error (ITAE), and ‘Integral Absolute Error (IAE). The simulations were done using MATLAB software. In the energy sector, a nonlinear cascade controller optimized by ALO was developed to regulate voltage and frequency in hybrid power systems [33]. Utilizing FOPID and self-tuning schemes a Continuous Conduction Mode (CCM) boost converter was designed, ALO was the OA used [35]. [30] Using a novel ‘OA called Elephant Herding OA (EHOA) the gains of an integer order PID controller is optimized for regulating the load frequency of the single area reheat thermal power plant setup (*Sambariya; Fagna*, 2017). Results show better performance when the EHO algorithm is used. Spotted Hyena Optimizer, a nature-inspired OA, was used to enhance the performance of a FOPD controller in a tricopter drone [32].

Efficiency improvements offer extensive advantages. As a power plant's efficiency increases, the facility's fuel and operating expenses decrease, thereby lowering electricity costs for consumers. Enhanced efficiency also reduces the quantity of coal required for generating each kilowatt-hour of electricity and diminishes the amount of cooling water needed per kWh in more efficient plants. Additionally, the combustion of fossil fuels releases various air pollutants detrimental to human health and natural environments. Significantly, the substantial enhancements in thermal power plant efficiency have markedly reduced the per kWh impact of these pollutants compared to a scenario without efficiency gains. From the above literature, it is inferred that the fractional order-based controllers for thermal power plant processes are not much addressed. Intelligent based fractional order controllers are not addressed for the fossil fuelled power plant processes. And the efficiency calculation and the analysis of efficiency improvement also not much addressed. Implementing the intelligent controller based on fractional order will enhance efficiency, leading to cost reduction. ‘The main objective of this ‘paper is to improve the efficiency of the thermal power plant by implementing the fractional order-based intelligent controller.

## THEORETICAL SECTION

### *Real-time model of the 500-MW plant*

The real-time cold start-up data was collected from NTPL (NLC Tamilnadu Power Limited) which is located in Tamil Nadu. It is a two unit of 500 MW Thermal Power Plant with a total capacity of 1000MW. The flow of coal, air, feed water, and steam in Tonnes per Hour (TPH), along with the corresponding electric power in MW, have been meticulously documented every minute over 9 hours, from 8 AM to 5 PM. By using these data, the system with three inputs and one output that exhibits nonlinearity. Interactions and couplings between the loops are not considered in this model.

Specifications of the plant:

| | |
|---|---|
| Plant Capacity | : 2 X 500 MW, Coal based firing |
| No. of Coal mill | : 8 per unit |
| No. of Oil Burners | : 4 set per unit |
| Boiler Capacity | :50.97 BHP (Boiler Horsepower) |
| Turbine | : HP, IP and LP |
| Boiler Drum Level span | : ±800mm |
| No. of FD fans | : 2 per unit |
| No. of ID fans | : 2 per unit |
| No. of Air Preheater line | : 3 per unit |
| Primary Air fan | : 2 per unit |

In this nonlinear model, the inputs include flows of coal, air, and feed water. The controlled variable is the generated power in MW. Process loops for these inputs have been tuned using OA and for these inputs, the fractional order controller is intended. The generated power will be regulated by the process loops.

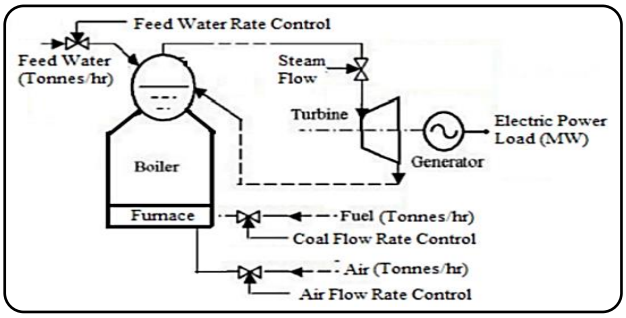


*Fig.1: Control loop of 500 MW unit.*

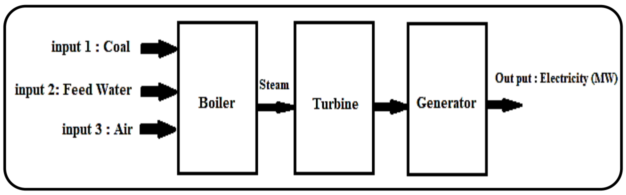


*Fig. 2: Block diagram of the process to be controlled.*

The three-input data are modeled into the transfer function model as indicated by the following equations, which are created in MATLAB by employing system identification to model the obtained data, [*Shajahan et.al*, 2018]. In this mathematical model, the interaction between the loops is not considered.

$$\frac{0.0497s^2 + 0.1426s + 0.0118}{s^3 + 0.4908s^2 + 0.2504s + 0.0105} \quad (1)$$

$$\frac{0.0074s^2 + 0.0026s - 0.00008}{s^3 + 0.4908s^2 + 0.2504s + 0.0105} \quad (2)$$

$$\frac{0.0071s^2 + 0.0241s + 0.0017}{s^3 + 0.4908s^2 + 0.2504s + 0.0105} \quad (3)$$

The flow of coal loop, the flow of air and the flow of feed water loops are given in the Eq. (1, 2, 3) respectively. Fig. 2 shows the proposed system's block diagram.

### *Fractional order controllers*

The significant use of FOPID controllers in the process ‘industry is mainly driven by the ‘two additional tuning parameters, which can be used to change the law of control in such a way that the control loop can benefit. For industrial process control, PID controllers are commonly used because of their high adaptability feature [101]. It is widely acknowledged that only a portion of the current PI/PID control loops are tuned for optimal performance. In recent years, the emergence of fractional calculus has facilitated a shift from conventional controllers to those described by non-integer differential equations. The block diagram of the FOPID controller is given in Fig. 3.

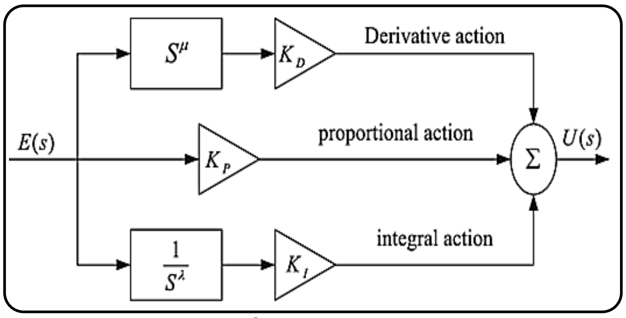


*Fig 3: Block ‘Diagram of FOPID controller.*

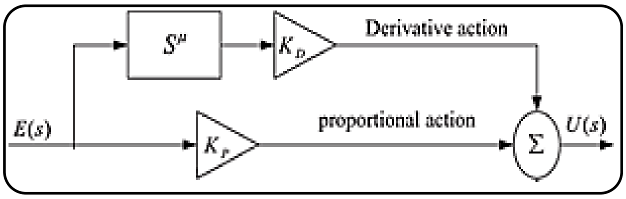


*Fig4: Block Diagram of FOPD controller.*

Fractional order controllers, also known as fractional controllers, are a type of control system that employs fractional calculus principles to improve system performance. Unlike traditional integer order controllers (e.g., PID controllers), fractional order controllers use fractional differentiation and integration to adjust the system's response. The Fractional-Order PID controller's parallel configuration, recommended by *Podlubny et al*., is provided by Eq. (4):

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \quad (4)$$

where $\lambda$ is the fractional-order integrator and $\mu$ is the fractional-order derivative operator.

### *FOPD controller*

Designing and implementing FOPD controllers is simpler compared to FOPID controllers. FOPID controllers have an additional integral action, which can introduce complexity and tuning challenges, especially for systems with variable or uncertain dynamics. FOPID controllers are prone to integral windup issues in systems with significant disturbances or actuator saturation. FOPD controllers, lacking the integral component, are less susceptible to wind-up problems and can provide stable control in such situations. FOPD controllers are better suited for applications where a faster response is required. The fractional derivative action can be tuned to provide a more aggressive control response without the integral term's potential slow-down effect. For systems with clearly identified non-integer order characteristics, FOPD controllers can provide a simpler and more effective solution.

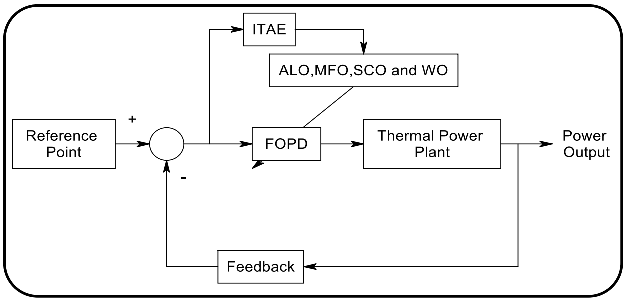


***Fig. 5: Block Diagram of the process.***

FOPID controllers, on the other hand, might introduce unnecessary complexity in such cases.

Such a system with greater tuning flexibility and an increased region of parameters will stabilize the controlled plant and increase the effectiveness of the control loop. Such a system with greater tuning flexibility and an increased region of parameters will stabilize the controlled plant and increase the ‘effectiveness of the control loop. Generally, for a valid comparison of Integer Order PID (IOPID) and FOPID controllers, global optimization methods can be explored for tuning since this is the way to obtain the best feasible controller gains and orders. Fractional controls usually configure the controller according to system requirements with the adjustment of a greater number of parameters. It provides more flexibility to accurately and precisely design the control system to suit the system requirements.

***Optimization algorithms***

Controller tuning is a critical aspect of thermal power plants as it directly affects the performance and stability of the plant. However, there are several challenges associated with controller tuning in thermal power plants. Firstly, thermal power plants are highly nonlinear and complex systems with multiple interacting loops. This complexity makes it challenging to determine the optimal tuning parameters for each controller. Secondly, the performance requirements of thermal power plants are often changing due to varying operating conditions, which can make it difficult to maintain optimal controller performance over time. Thirdly, traditional controller tuning methods, such as trial-and-error or manual tuning, can be time-consuming, costly, and inefficient. To address these challenges, OA is commonly used in controller tuning for thermal power plants. These algorithms can efficiently search for the optimal tuning parameters by iteratively adjusting them based on feedback from the system.

The OA can also take into account the nonlinear and dynamic nature of thermal power plants and can adjust the tuning parameters to different operating conditions. This makes it possible to achieve better performance and stability of the plant under varying conditions. In summary, OA is crucial in controller tuning for thermal power plants because it offers an efficient, accurate, and adaptive approach to adjusting the tuning parameters, which can improve the performance and stability of the plant.

Metaheuristic OA like ‘Moth Flame Optimization (MFO), ‘Ant Lion Optimizer (ALO), Whale Optimization ‘Algorithm (WOA), and Sine Cosine Algorithm (SCA) are utilized for tuning controller gains in thermal power plants. These algorithms are effective in solving complex optimization problems, including optimizing the controller gains of thermal power plants. By using these OA, the controller gains can be tuned to ensure that the power plant operates efficiently and safely.

MFO is an OA inspired by moths attracted to flames, utilized for finding optimal solutions. It has been applied successfully to optimize the gains of Proportional-Integral-Derivative (PID) controllers in thermal power plants. ALO, on the other hand, is an OA inspired by the hunting behavior of antlions. It has been employed to optimize the gains of PID controllers in thermal power plants by employing both global and local search strategies to determine the optimal solution. WOA is an ‘OA that simulates the behavior of whales searching for prey. It has been used to optimize the PID controller gains in thermal power plants by searching for the optimal solution using a combination of exploration and exploitation strategies. SCA is an OA that simulates the sine and cosine functions to find the optimal solution. It has been used to ‘optimize the PID controller gains in thermal power plants by searching for the optimal solution using a combination of local search and global search strategies.

***Moth Flame Optimization (MFO)***

Moth Flame Optimization (MFO) is a nature-inspired metaheuristic ‘algorithm that draws inspiration from the navigation behavior of ‘moths in the presence of artificial light. In MFO, moths are attracted to the light source, representing the global optimum, and their positions are updated iteratively. The algorithm involves the simulation of moth movements towards light, where the attraction strength and light absorption influence the optimization process.

MFO has been applied to various optimization problems and is known for its simplicity and effectiveness.

The optimization using MFO:

1) Estimate the fitness of each month using the objective function.
2) Update the position of each month based on its attraction toward light:

new_position=old_position+β*exp(−γ×distance$^2$) × (best_position−current_position)

where β controls the strength of the attraction towards light., γ represents the light absorption coefficient, distance is the Euclidean distance between moths, best_position is the current global best position and current_position is the position of the current moth.

3) Update the global best position if a better solution is found.
4) Until convergence or the maximum number of iterations is attained, repeat steps 1-3.

The algorithm terminates when the stopping criteria (maximum iterations, convergence threshold, etc.) are met.

### Ant Lion Optimization (ALO)

Ant Lion Optimizer (ALO) is motivated by the hunting strategy of antlions, where ants are lured toward the antlion's pit. In this algorithm, the optimization process involves two phases: an attractive phase and a repulsive phase. During the attractive phase, ants move towards the best solution, while in the repulsive phase, ants move away from the worst solution. This dual-phase approach enhances exploration and exploitation, making ALO a versatile OA applicable to a wide range of problems.

1) Evaluate the fitness of each ant and antlion using
2) the objective function:

ant_fitness = evaluate_fitness(ants)

antlion_fitness = evaluate_fitness(antlions)

3) Update ant positions using a random walk:

new_ant_position = old_ant_position + step_size * random_direction

4) This step encourages exploration. Update antlion positions based on the chosen strategy:

(i) Attractive phase:new_position = old_position + alpha * best_ant_position - current_position

(ii) Repulsive phase:new_position = old_position - alpha * worst_ant_position + current_position.

α (alpha) is a parameter that plays a vital role in updating the positions of ants and antlions.

The value of α determines the step size in the movement of individuals during different phases of the algorithm.

These steps enhance both exploration and exploitation.

5) Until convergence or the maximum number of iterations is achieved, repeat steps 1-3.

The algorithm terminates when the stopping criteria (maximum iterations, convergence threshold, etc.) are met.

### Sine Cosine Optimization (SCO)

The Sine cosine Algorithm (SCA) is a population-based optimization ‘algorithm that simulates the ‘sine and cosine functions to update the positions of individuals. The algorithm employs a chaos-based strategy to enhance exploration, making it suitable for problems with complex search spaces. SCA is characterized by its simplicity and ease of implementation. It has been successfully applied to various optimization tasks, and its performance can be fine-tuned by adjusting parameters like the chaos factor.

1) Initialize Constants: Initialize constants for the sine and cosine functions, a, A, rand_individual
2) ‘Evaluate the fitness of each individual using the objective function:fitness = evaluate_fitness (population)
3) Update the position of each individual using the sine and cosine functions:

new_position=old_position+$A$×sin($a$)×|rand_individual×best_position−current_position|

4) Introduce a chaos-based strategy for exploration:

new_position=new_position+β×chaos_value

This enhances exploration in the search space.

5) Until convergence or the maximum number of iterations is achieved, repeat steps 2-4.

The algorithm terminates when the stopping criteria (maximum iterations, convergence threshold, etc.) are met.

### Whale OA (WOA))

The social interactions that occur between humpback whales during bubble-net feeding serve as the model for the WOA. The WOA combines exploration and exploitation phases to balance global and local search. During exploration, whales move randomly in search space, and during exploitation, they adjust their positions based on the proximity to the global optimum. WOA introduces a spiral updating mechanism to encourage exploration. This algorithm is particularly effective in solving optimization problems with diverse landscapes and has been applied to engineering and scientific optimization challenges.

1. Apply the objective function to each whale's fitness evaluation.:

Fitness=evaluate_fitness(whales)

Fitness=evaluate_fitness(whales)

2. Identify the global best position among the whales:global_best_position=whales [argmin(fitness)]
3. Update the positions of whales using various strategies:

Exploration Phase:

D=|C×global_best_position−whales|

new_positions=global_best_position−A×D

Exploitation Phase:

D=|global_best_position−whales|

new_positions=D×exp(b×p)×cos(2×π×p)+global_best _position

b is a random value between 0 and 1, and

p is a random value between 0 and 1.

4. ‘Until convergence or the maximum number of iterations is achieved, repeat steps 1- 3.

The algorithm terminates when the stopping criteria (maximum iterations, convergence threshold, etc.) are met.

***Efficiency calculation***

The efficiency of a power plant is estimated by calculating the ratio of output obtained from the system to the input supplied to the system. As per the Bureau of Energy Efficiency, Efficiency is determined by the ratio of useful heat output to the heat input. Efficiency stands as a crucial engineering, economic, and environmental attribute of thermal power plants. In essence, efficiency measures the ratio of electricity generated to the energy input into the plant. Technically, efficiency is quantified as the heat content per kilowatt-hour (kWh) of electricity divided by the ‘heat rate of the ‘plant, represented as a percentage, defining how effectively energy is converted into electricity.

The heat input of thermal power plants is based on the supply of air, coal, and feed water. The power generation is based on the heat output. Since the heat generation–combustion process is the prime and important process, better control schemes of the combustion process may lead to achieving better efficiency. If the combustion process is complete and efficient, the subsequent process of steam generation and power generation will be perfect and efficient. Most TPP's widespread range of efficiency is between 30% to 50%. This suggests that the plant generates electricity using only half or less of the heat, with the remaining heat being squandered.

Therefore, efficient controllers to be addressed to enhance the heat generation and hence efficiency.

The coal flow and steam entered into the turbine serves as the main factors affecting the efficiency of the TPP. As per the statement of US Energy information, the TPP in India has an efficiency range between 28% to 38%. Thermal efficiency is ‘defined as the percentage ratio of total energy produced to the heat energy generated by coal.

As per Bureau of Energy Efficiency, Efficiency is determined using two different methods:

Direct Method: This method is also acknowledged as an input-output method. The ratio of usable output to heat input Eq. (5).

$$Efficiency = \frac{\text{Heat Output}}{\text{Heat Input}} X\ 10( \qquad (5)$$

Indirect Method: ‘‘The efficiency is determined by comparing the energy input with the energy losses.

$Efficiency = \{100 - (L1 + L2 + L3 + L4 + L5 + L6 + L7 + L8)$

L1 – Losses by dry flue gas (sensible heat)

L2 – Losses by hydrogen in fuel (H2)

L3 – Losses by moisture in fuel (H2O)

L4 – Losses by moisture in air (H2O)

L5 – Losses by carbon monoxide (CO)

L6 – Losses by surface radiation, convection

L7 – Losses by unburnt in fly ash (Carbon)

L8 – Losses by unburnt in bottom ash (Carbon)

The operational efficiency of the NTPL plant stands at 37.2%. The amount of steam that enters the turbine is used to compute this efficiency. This steam mainly depends on the amount of coal, air, and feedwater supplied to the steam generator. An effective controller has been proposed and developed to enhance the efficiency. In this study, combustion may be managed or controlled based on the fuel and airflow rates. If the combustion process is regulated or controlled, the amount of heat generated will be more. This enhances the generation of steam; Increasing the flow of steam to the prime mover inlet can improve the plant's efficiency. The developed controller for the flows of coal, air, and feedwater increases the flow of steam to the prime mover inlet, thereby improving efficiency.

## RESULTS AND DISCUSSION

The PID controller is the conventional controller used in control engineering. In this study, a PD controller is suggested because a small integral gain with a slightly longer integral time helps avoid integral wind-up.

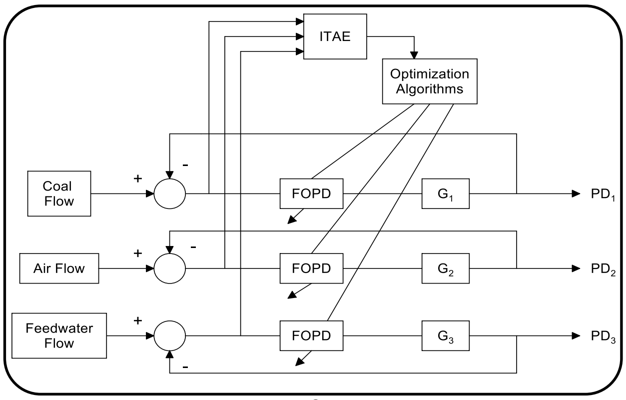


***Fig. 6: Control loop diagram of the proposed system.***

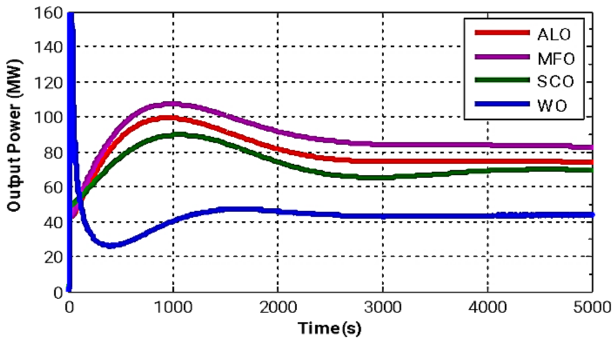


***Fig. 7: Electric power output (Set Value is 70MW) response from the FOPID-based system obtained using ALO, MFO, SCO, and WO.***

Although a PID controller offers less overshoot than a PD controller, it typically has a longer settling time, whereas a PD controller settles more quickly. The proposed research deals with the design of a performance-based controller, if the set value reaches quickly, hence the efficiency can be improved. These demonstrate why, in most cases, a PD controller is better for thermal power plant operations. The fractional order proportional derivative (FOPD) controller is designed and it is used to control or maintain the generated electric power (which is the controlled variable) by controlling the ‘flow of coal, air and feed water ‘. Unlike normal PD controllers, fractional order PD controllers have four variables namely *Kp, Kd, λ*, and *μ*. The extra variables *λ* and *μ* are understood to be any real variables depending on the situation. Below given in Eq. (3, 4) is the general equation that suits all the controllers designed with fractional order. In this ‘proposed approach, the controller gains are determined through optimization ‘methods, utilizing the Integral of Time-weighted Absolute Error (ITAE) as the criterion for optimization. Controller parameters are computed to minimize the ITAE value. Fig. 6 ‘shows the block diagram of the multiloop controller designed using PSO and GA. This controller is applied to the previously discussed boiler-turbine-generator system with three inputs and one output, incorporating the proposed fractional-order PID controllers. Unlike normal PID controllers, FOPID controllers have five variables namely *Kp, Ki, Kd, λ*, and *μ*. The extra variables *λ* and *μ* are understood to be any real variables depending on the situation. The common structure of FOPID is shown in Fig. 8. Below, Eqs (6, 7) are the general equation that suits all the controllers designed with fractional order.

$$G_c(s) = \frac{U(s)}{E(s)} = k_P + k_I \frac{1}{s^{\lambda}} + k_D s^{\mu}, (\lambda, \mu > 0) \quad (6)$$

The *$G_c(s)$* character in the above equation represents the transfer function of the controller. Where, *$1/s^{\lambda}$*, *E(s)* and *U(s)* are integrator terms, error, and output respectively.

In the time domain, the control signal *u(t)* is denoted as the expression given below Eq. (7).

$$u(t) = K_p e(t) + K_I D^{\lambda} u(t) = K_p e(t) + K_I D^{\lambda} e(t) + K_D D^{\mu} e(t) K_D D^{\mu} e(t) \quad (7)$$

Under the study, fractional order PD has shown better results in maintaining stability when the parameters are disturbed and controlling systems that display dynamic properties. These properties are owed to the two variables λ and μ which bring in more degrees of freedom.

What makes this controller more special is the ability of the user to make it into a PI or PD controller depending on the requirements of the scenario, it's done by giving the value 1 for λ and 0 for μ to make a PI controller and, 0 for λ and 1 for μ to make a PD controller. The user can also bring out the classical PID controller by assigning the value 1 to both λ and μ. The block diagram featured in Fig. 7 gives a clear understanding of the explained concept. In this study, the PD controller was identified to be the perfect controller for our problem. With the knowledge of fractional order, the FOPD controller was designed in MATLAB by using the FOMCON toolbox.

The time domain specification for the set value of 280 MW is given in the above table. From the above table, it is inferred that the SCO-based controller settles quickly when compared to other controllers. Also, SCO based controllers give less undershoot of 10 MW and more overshoot of 315 MW when compared with the set value. ALO-based controllers, WO-based controllers, and MFO-based controllers produce similar undershoot values and closely the same value of overshoot value.

***Table 1: Time domain specifications.***

| | SCO | ALO | MFO | WO |
|---|---|---|---|---|
| Undershoot (MW) | 10 | 168 | 165 | 166 |
| Overshoot (MW) | 315 | 288 | 290 | 286 |
| Settling Time (sec) | 28 | 26 | 25 | 15 |

***Table 2: Power generated per minute & efficiency.***

| Algorithm | Conventional | SCO | ALO | MFO | WO |
|---|---|---|---|---|---|
| Power generated per 60 sec in MW | 5 | 6.3916 | 6.176 | 6.1074 | 9.263 |
| Efficiency (%) | 37.2 | 47.55 | 45.95 | 45.43 | 68.92 |

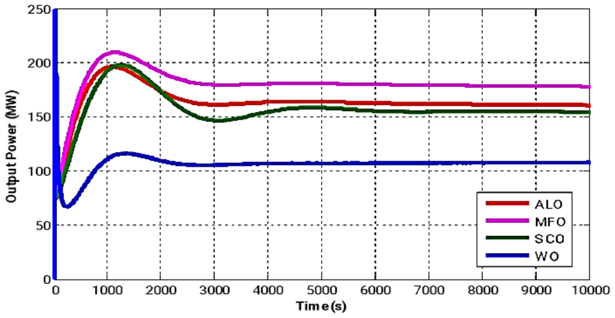


***Fig 8: Electric power output (Set Value is 150MW) response from the FOPID-based system obtained using ALO, MFO, SCO, and WO.***

Control action taken by the controller i.e., quick settling time is the key point to measure the performance of the plant hence SCO SCO-based controller produces better control action when compared to other controllers.

Based on the settling time data obtained through simulation, the plant efficiency is calculated. The NTPL plant's operating efficiency is determined to be 37.2%. Every increase/decrease in load of the NTPL plant is achieved in steps of 5MW. According to the plant design, using a standard controller will take 60 seconds to make a 5MW shift. When the proposed controller is used, the time to achieve 5MW change is reduced considerably. Accordingly, fuel intake can be regulated and the heat and the steam flow can also be regulated simultaneously. The NTPL plant's 500 MW unit takes 1s to generate 0.0980 MW and 5 MW in a minute. With this in perspective, the efficiency value when optimized with SCO gave 47.55%, which means it generates 6.3916 MW in a minute. When tried with ALO and MFO the efficiency value of 45.949% and 45.43% is obtained respectively. Finally, tried with WOA, it generates 9.263MW and an efficiency of 68.92%.

Below, the efficiency chart comparing each algorithm’s performance with the traditional PID controller has been provided. A table comparing power generated per minute is also provided along with the power output graphs.

## CONCLUSIONS

An intelligent fractional-order proportional derivative controller has been developed to regulate the generated electric power at NTPL Thermal Power Station by adjusting the coal, air, and feed water flow rates. Based on the boiler-turbine-generator mathematical model, the results demonstrate that the controller achieves the ‘favored electric power production ‘with minimal offset and rapid settling times, even when there are significant offsets in the individual process loop outputs.

The control schemes developed using SCOA, ALOA, MFOA, and WOA achieved the desired responses, but the SCOA-based FOPD controller produces the required power output with a faster settling time and less offset.

WOA-based FOPD controller settles more quickly than SCOA-based FOPD but the offset is more. With the developed FOPD controllers, the efficiency of the plant was calculated which was compared with the operating efficiency of the plant. Efficiency improvements offer extensive advantages.

As a ‘power plant's efficiency enhances, the facility's fuel and operating expenses decrease, thereby lowering electricity costs for consumers. Enhanced efficiency also reduces the quantity of coal required for generating each kilowatt-hour of electricity. When the quick-settling SCOA-based FOPD controllers are used, an efficiency of 47.55% is obtained which is 10.35% more than the operating efficiency of the plant.

When WOA-based FOPD controllers are used, an efficiency of 68.92% is obtained which is 31.72% more than the operating efficiency of the plant with more offset of 55%. It is inferred that the SCOA-based FOPD controllers offer quick settling time with less offset. The calculations are solely based on simulation results. If implemented in real-time, the outcomes may differ.

**List of abbreviations used**

| | |
|---|---|
| FOPD | Fractional Order Proportional Derivative Controller |
| SCOA | Sine Cosine Optimization Algorithm |
| ALOA | Ant Lion Optimization Algorithm |
| MFOA | Moth Flame ‘Optimization Algorithm |
| IMFOA | Improved Moth-Flame Optimization Algorithm |
| WOA | Whale Optimization Algorithm |
| PID | Proportional Integral Derivative |
| PD | Proportional Derivative |
| GA | Genetic Algorithm |
| MOGA | Multi-Objective Genetic Algorithm |
| PSOA | Particle Swarm Optimization Algorithm |
| MOPSO | Multi-objective Particle Swarm Optimization |
| SA | Simulated Annealing |
| ISE | Integral Squared Error |
| ITSE | Integral Time Squared Error |
| ITAE | Integral Time Absolute Error |
| IAE | Integral Absolute Error |
| EHOA | Elephant Herding Optimization Algorithm |
| NTPL | NLC Tamilnadu Power Limited |
| TPH | Tonnes Per Hour |
| OA | Optimization Algorithms |

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