

# Enhancing frequency regulation in Nuclear-Renewable hybrid energy systems through optimally configured FOPID controllers and adaptive pelican optimization algorithm

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This study has explored the application of Fractional Order Proportional-Integrator-Derivative (FOPID) controllers within Nuclear-Renewable Hybrid Energy Systems (N-RHES). N-R HES has played a pivotal role in the transition to decarbonized energy systems, holding substantial promise for establishing sustainable, carbon-free energy infrastructure in the near future. The investigation has focused on an N-R HES that incorporates diverse energy sources such as solar, wind, nuclear, fuel cell systems, Battery Energy Storage Systems (BESS), and Flywheel Energy Storage Systems (FESS). To achieve performance objectives, the study has employed various meta-heuristic algorithms, including the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Pelican Optimization Algorithm (POA), and Adaptive POA (APOA), to optimize the parameters of the FOPID controllers. Additionally, the research has introduced an enhanced version of the conventional POA, incorporating a velocity computation strategy to enhance the tuning capabilities of FOPID controllers. The results have indicated that optimally configured FOPID controllers effectively manage system frequency and ensure stability within the examined N-R HES. The incorporation of the velocity computation strategy in the POA has contributed to improved tuning performance for FOPID controllers. This study has highlighted the potential of advanced optimization techniques for achieving superior control strategies for N-R HES.

**Keywords:** Nuclear-Renewable Hybrid Energy Systems, Fractional-order proportional-integral-derivative (FOPID) controllers, Adaptive Pelican Optimization Algorithm, System frequency, Stability, Microgrid

## 1 Introduction

The modern electrical grid is increasingly integrating renewable energy sources like wind and solar power<sup>1</sup>. However, the intermittent and uncertain nature of these sources presents significant challenges in maintaining the stability and reliability of energy systems<sup>2</sup>. Given this, nuclear energy offers a reliable and consistent power source that can complement renewables in HES<sup>3</sup>. N-R HES are envisioned as the future's infrastructure for sustainable and carbon-free energy<sup>4</sup>. To ensure the stability and reliability of N-R HES, advanced control techniques, such as FOPID controllers, play a crucial role<sup>5</sup>. Precise frequency control, which is essential for power system operating, is provided by FOPID controllers<sup>6</sup>.

By maximizing the efficiency of the FOPID controller-based N-R HES, this study aims to reduce frequency variations in a microgrid that consists of

nuclear reactors, energy storage devices, and renewable energy sources<sup>7</sup>.

In order to solve the difficulty of guaranteeing stable and dependable functioning in these systems<sup>9</sup>, this research looks into the tuning of FOPID controllers in N-R HES for frequency regulation<sup>8</sup>.

Frequency control in N-R HES is a critical aspect of ensuring stable and reliable operation<sup>10</sup>. Fluctuations in renewable energy sources can lead to frequency deviations, which in turn may result in system instability and power outages<sup>11</sup>. Thus, the research gap lies in developing effective control strategies to mitigate frequency variations in N-R HES. This study evaluates the compatibility and effectiveness of FOPID controllers, compared to classical controllers, to ensure stability in N-R HES. The FOPID controllers are optimized utilizing the Pelican Optimization Algorithm (POA), a sophisticated meta-heuristic method<sup>12</sup>. The designed controllers' performance is assessed utilizing a simulation model of a micro grid system that includes

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nuclear reactors, energy storage, and renewable energy sources<sup>13</sup>.

The findings of this study provide valuable insight into the effectiveness of the POA optimization technique for tuning FOPID controllers in N-R HES for frequency regulation<sup>14</sup>. As the integration of decarbonized energy infrastructure and renewables with nuclear power plants is crucial for reliable and resilient energy supply<sup>15</sup>, this research contributes to addressing the challenges associated with their integration. By improving the performance, efficiency, reliability, and resiliency of integrated energy systems<sup>16</sup>, the optimal FOPID controllers developed in this study can effectively handle system frequency and maintain stability in N-R HES.

The following literature review provides a concise summary of relevant studies, including their objectives, methodologies, and key findings, contributing to the scientific research on frequency control of N-RHES utilizing optimal FOPID controllers.

Hasan *et al.*<sup>17</sup> “investigated the applications of FOPID and proportional-integrator-derived (PID) controllers in N-R HES to evaluate their compatibility in ensuring system stability. The study utilized the Artificial-Bee-Colony optimization algorithm to adjust the controller parameters. The findings demonstrated that, in the examined N-R HES, the most effective FOPID and PID controllers maintained system stability while controlling system frequency”.

Abdussami *et al.*<sup>18</sup> “discussed resources for the generation of carbon-free energy, such as renewable energy and micro-nuclear reactors (MNRs), and emphasized the benefits of an integrated nuclear-renewable microgrid (NRM) in terms of low greenhouse gas emissions and high dependability. They suggested for NRMs a strategy called probabilistic energy modeling that makes use of the Slime Mould Algorithm (SMA) to maximize the mixing of energy resources in order to effectively meet energy demand”.

Three optimization techniques PSO, GA, and Firefly Algorithm were compared by Kumar *et al.*<sup>19</sup> in order to optimize PID controller parameters in the load frequency regulation of a two-area hybrid power system. The investigation revealed that the PSO approach outperformed the others in terms of settling time, objective function, and convergence qualities.

Redfoot *et al.*<sup>20</sup> proposed the concept of N-R HES, considering a combination of nuclear power plant,

renewable power generation sources, industrial processes, and energy storage components. They utilized fuzzy Analytical Hierarchy Process (AHP) as a risk assessment and management technique for evaluating N-R HES. The study identified desalination as a strong candidate based on profitability, flexible operation, and safety criteria, highlighting the usefulness of fuzzy AHP for NRHES design.

Barakat *et al.*<sup>21</sup> utilized the chaos game optimization (CGO) approach to formulate a cascade controller for load-frequency management in connected power systems. In contrast to prior studies, they proposed and showcased the superior performance of a fractional-order (FO) proportional-integral-derivative-FO proportional-integral (FOPID-FOPI) controller using CGO, resulting in decreased frequency, tie-line power deviations, and settling time.

Trojovský *et al.*<sup>22</sup> introduced the POA, a stochastic, nature-inspired optimization algorithm based on a simulation of pelicans' hunting behavior. The algorithm was assessed across various objective functions and real-world applications, demonstrating its superior exploitation and exploration abilities compared to other well-known meta-heuristic algorithms.

These relevant studies provide valuable insights into the application of FOPID controllers, optimization approaches, and risk assessment approaches for frequency control and system stability in nuclear-renewable hybrid energy systems. They contribute to the scientific understanding and development of optimal control strategies for N-R HES.

## 2 Materials and Methods

The intermittent and unpredictable character of renewable energy sources makes it difficult to maintain system stability and dependability when integrating them with nuclear reactors in N-R HES. Five settings on the FOPID controller enable more flexibility and a more tunable frequency response. However, the FOPID tuning is far more complicated because of the increased number of parameters. In order to guarantee steady and dependable operation, the objective of this study is to maximize the performance of FOPID controllers in N-R HES for frequency regulation. To achieve this objective, the study will investigate the compatibility and effectiveness of FOPID controllers in comparison

to classical controllers for ensuring stability in N-R HES. The selected optimization techniques for tuning the FOPID controllers include GA, PSO, POA, and APOA. APOA incorporates a velocity computation strategy into the traditional POA to enhance the tuning capabilities of FOPID controllers.

The methodology involves the following steps:

Step-1: creation of a simulation model that reflects a micro grid system with an energy storage component, renewable energy sources, and a nuclear reactor. The dynamic behaviour of the system and its reaction to different frequency variations will be captured by the model.

Step-2: Integration of the FOPID controllers into the simulation model, considering their parameters and initial settings.

Step-3: Application of the optimization algorithms (APOA, GA, PSO, and POA) to modify the FOPID controllers' parameters. The algorithms will iteratively search for the optimal values that minimize frequency variations and ensure stable system operation.

Step-4: Comparative evaluation of the performance of FOPID controllers optimized using different algorithms, considering key metrics such as settling time, overshoot, and frequency deviation reduction.

Step-5: Analysis of the simulation outcomes to assess the effectiveness of the optimized FOPID controllers in mitigating frequency variations and maintaining system stability in N-R HES.

Step-6: Discussion of the insights gained from integrating advanced optimization techniques and their potential for achieving enhanced control strategies in N-R HES.

Step-7: Consideration of the reliable and resilient integration of decarbonized energy infrastructure with renewables and nuclear power plants, and the contribution of the proposed control strategies in addressing these challenges.

## 2.1 System Modeling

The study focuses on simulating a micro grid system made up of connected distributed power production components, such as transformers, storage devices, power converters, and energy sources. Energy storage systems like BESS and FESS, as well as solar, wind, nuclear, and fuel cell technologies, are all included in the micro grid. An electric load and renewable energy generation fluctuation template is used to produce time series data with small stochastic deviations from the mean. In order to simulate real-

world events, the models also take abrupt shifts in the mean value into consideration. After the integration of renewable energy systems, other energy systems including nuclear, fuel cell, and FESS are integrated. By obtaining input from the micro grid and making decisions regarding energy storage or supply to the network, the fuel cell system plays a critical role. The micro grid uses the BESS to supply power as needed.

For solar, wind, and electric demand, the big deterministic drift and minor stochastic power fluctuation can be computed utilizing the approach described below<sup>23</sup>.

$$P = \left( \psi \cdot \eta \cdot \sqrt{\beta \frac{(1 - G(s) + \beta)}{\beta}} \right) \Gamma = \chi \cdot \Gamma \quad \dots (1)$$

Where  $P$  stands for wind, solar, and load powers;  $\beta$  is the power's mean value;  $\eta$  is a constant that normalizes generated power or demand powers;  $\chi$  is a constant that corresponds to the power per unit (p.u.); and  $\Gamma$  is a time-dependent switching signal with a gain that causes the value of stochastic powers to fluctuate. The sudden variation in the stochastic power output mean value is controlled by a gain-dependent switching signal that varies over time.  $G(s)$  is a low pass filter. Figure 1 displays N-R HES modeling with a FOPID controller.

### 2.1.1 Solar energy

Renewable energy sources are gaining momentum as viable alternatives for clean energy generation. Among these sources, photovoltaic (PV) systems have emerged as a prominent technology for converting solar radiation into electrical energy. The main non-polluting energy source is solar energy, which has long been acknowledged. However, the inherent unpredictability of solar energy poses a significant challenge. Standalone PV arrays often fail to generate usable electricity for a considerable portion of the year. Furthermore, there is a mismatch between the demand profile and the solar and wind energy's temporal distribution.

We consider and describe the parameters of Equation 1 in relation to the generation of solar power below. Furthermore, the equivalent values for solar energy generated from Equation 1 are represented by Equations 2 and 3.

$$\Phi \sim U(-1, 1), \eta = 0.9, \beta = 10$$

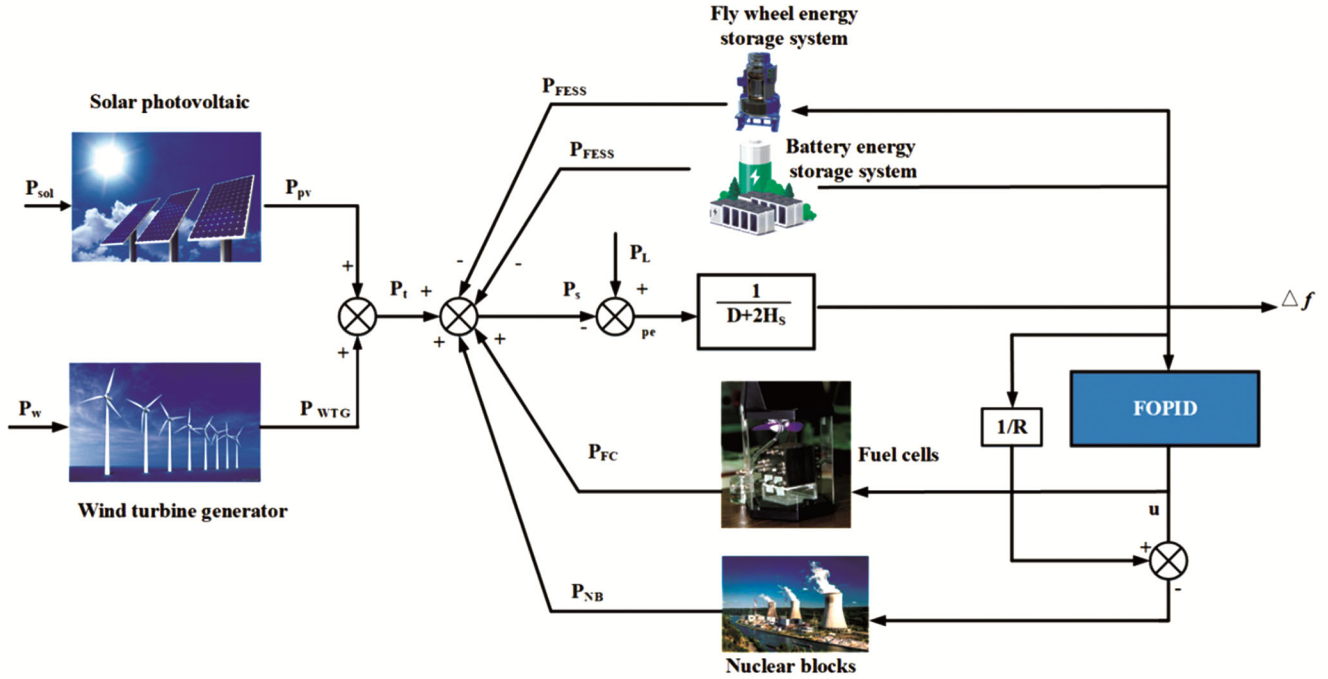


Fig. 1 — Nuclear-Renewable Hybrid Energy System modeling with FOPID controller.

$$G(s) = \frac{1}{10^4 \cdot s + 1} \quad \dots (2)$$

$$\Gamma = 0.05h(tm) - 0.02h(tm - 180) \quad \dots (3)$$

2.1.2 Wind energy

Nowadays, wind energy systems are recognized by many as reliable and secure renewable energy sources. These systems have been widely adopted in response to national development and environmental concerns because they provide infinite energy sources, favourable environmental features, and quick technological developments<sup>24</sup>.

In wind energy systems, the power output of wind turbines (WTs) is subject to variations and disruptions caused by changes in wind speed and power supply failures. Due to the inertia of WTs, there is a small time delay between wind speed variations and the corresponding changes in WT power output. Conventional modelling techniques, such component-based equivalent modelling, treat the WT system as an input/output model devoid of a clear physical interpretation. In contrast, the transfer function modeling technique relies on transfer functions to describe the system's behavior. However, because the component-based equivalent modelling technique requires precise knowledge of WT parameters, its accuracy is higher than that of the transfer function-based equivalent modeling approach<sup>25</sup>.

Equations 4 and 5 represent the corresponding values for wind energy that come from Equation 1.

$$\Phi \sim U(-1, 1), \eta = 0.8, \beta = 10$$

$$G(s) = \frac{1}{10^4 \cdot s + 1} \quad \dots (4)$$

$$\Gamma = 0.24h(tm) - 0.02h(tm - 140) \quad \dots (5)$$

$h(tm)$  is the Heaviside function in this case. Equations 6 and 7 indicate the pertinent demand load numbers from Equation 1.

$$\Phi \sim U(-1, 1), \eta = 0.9, \beta = 10$$

$$G(s) = \frac{300}{300s + 1} + \frac{1}{1800s + 1} \quad \dots (6)$$

$$\Gamma = \frac{1}{z} \left[ \begin{array}{l} 0.09h(tm) + 0.03h(tm - 110) \\ + 0.03h(tm - 130) + 0.03h(tm - 150) \\ - 0.15h(tm - 170) + 0.1h(tm - 190) \end{array} \right] + 0.02h(tm) \quad \dots (7)$$

2.1.3 Nuclear energy

The formulation of the transfer function for a nuclear reactor is a critical aspect of this research. It gives insight into how variations in neutron flux at a particular place and time affect the system as a whole. Analyzing the system's reaction to known disturbances is made feasible by identifying the usual reactor features<sup>26</sup>.

The governor's transfer function for a nuclear power plant ( $Pm$ ) is given by Equation 8.

$$\frac{Pm}{Pv} = \frac{1}{0.08s + 1} \quad \dots (8)$$

$$\frac{Fn}{Pv} = \frac{2}{0.5s + 1} \quad \dots (9)$$

$$T_{LP1}(s) = \frac{0.3}{0.05s + 1} \quad \dots (10)$$

$$T_{LP2}(s) = \frac{5s + 1}{10s + 1} \quad \dots (11)$$

$$T_{RH1}(s) = \frac{1}{7s + 1} \quad \dots (12)$$

$$T_{RH2}(s) = \frac{1}{9s + 1} \quad \dots (13)$$

According to Equations 9, 10, 11, 12, and 13, respectively, the Transfer Function ( $Fn$ ) of the High-Pressure Turbine, Low-Pressure Turbine\_1 ( $T_{LP1}$ ), Low-Pressure Turbine\_2 ( $T_{LP2}$ ), Reheater\_1 ( $T_{RH1}$ ), and Reheater\_2 ( $T_{RH2}$ ) can be expressed as follows<sup>27</sup>.

#### 2.1.4 Flywheel energy storage system (FESS)

Electromagnetic, electrochemical, kinetic, and potential energy are some of the ways that electrical energy in an AC system might be stored in a microgrid. It cannot be stored electronically. The storage capacity of the component and the rate at which energy enters and exits the storage device are the two main characteristics of energy storage technology applications.

A FESS contains of a reversible motor/generator unit, vacuum chamber, power electronics system, and set of bearings. The FESS's motor/generator unit utilizes electrical power for both acceleration and deceleration, assisting in the transfer of energy to and from the flywheel system. The flywheel's moment of inertia and rotational velocity determine the system's capability for energy storage. The device is housed in a vacuum atmosphere to reduce power losses and wind resistance.

#### 2.1.5 Battery energy storage system

Practical solutions, such as Electrical Energy Storage (EES) systems, particularly battery banks, have been developed to secure system stability and reliability while addressing the issues posed by the fluctuation of renewable energy sources. EES provides a way to meet load requirements and

maintain energy generation by enabling load shifting through grid connectivity and demand control.

Electrochemical cells are linked in BESS in either a series or parallel configuration to produce power at a specified voltage. The bidirectional conversion of electrical and chemical energy is made possible by these cells. Batteries are utilized in many different transportation and energy management systems. However, it is important to note that batteries have limitations in terms of Depth of Discharge cycles, which restrict the extent to which they can be fully discharged<sup>28</sup>.

#### 2.1.6 Fuel cell (FC)

A promising technology that offers noiseless operation and environmental friendliness is FCs, which transforms chemical energy directly into electrical energy. With distinct electrodes (anode and cathode) for hydrogen and oxygen, FCs generates electricity and water as byproducts. Numerous advantages of this technology include lower emissions of carbon dioxide and sulphur dioxide, a high power density, and a reasonable efficiency when compared to traditional thermal machines. FCs is available in multiple configurations, with distinctions between fuel type, operating temperature, and electrolyte composition. Proton exchange membrane FCs, alkaline FCs, phosphoric acid FCs, solid oxide FCs, and molten carbonate FCs are the six main categories of FCs according to their properties. These variations allow for flexibility and adaptation to different applications and operational conditions.

#### 2.1.7 Micro grid system with FOPID controller

Edet *et al.*<sup>29</sup> introduced the FOPID controller, a fractional-order calculus-based alternative to the traditional PID controller. The FOPID controller demonstrates superior performance in terms of system stability compared to the conventional PID controller. The effectiveness is further enhanced with the inclusion of fractional order terms  $\lambda$  and  $\mu$ . Despite the increased tuning complexity due to the additional terms, the FOPID controller provides several advantages over the conventional PID controller.

Fractional-order controllers can offer the control system more flexible time and frequency responses. It only occurs if the fractional-order controller has more degrees of freedom (DOF) than its integer-order counterpart. For instance, utilizing a conventional integer-order PID controller, which only has three parameters that can be tuned, will only allow

satisfying up to three criteria of choice. The performance of the overall control system may improve with the application of FOPID. This is because, in contrast to the typical classical PID controller, having three parameters to be tuned for three robustness criteria, employing a FOPID might meet up to five robustness requirements. FOPID is preferable because it can adjust five parameters:  $K_p$ ,  $K_i$ ,  $K_d$ ,  $\mu$ , and  $\lambda$  if four or five robustness criterion is required. A FOPID controller can satisfy up to five robustness criteria: phase margin specification, gain cross-over frequency specification, damping-robustness to gain variations, complementary sensitivity specification, sensitivity specification, and elimination of steady-state error”.

The FOPID controller's mathematical expression is shown in Equation 14 below

$$G_f(s) = \frac{U(s)}{E(s)} = K_p + K_i s^{-\lambda} + K_d s^{\mu} \quad \dots (14)$$

Whenever  $(\lambda, \mu) > 0$ , typically, a FOPID controller needs a significant amount of computer power and makes utilize of more intricate approximations.

**2.2 Inspiration of Pelican Optimization Algorithm (POA)**

Motivated by the hunting strategies of pelicans, the POA represents a novel class of meta-heuristic optimization algorithms. Pelicans are aquatic birds that reside in warm waters such as lakes, rivers, coasts, and swamps<sup>30</sup>. They exhibit remarkable flying and swimming abilities and possess keen eyesight and observation skills. Pelicans primarily feed on fish and employ a unique hunting strategy. When locating their prey, pelicans swoop down from heights of 10-20 meters and dive straight into the water to capture the fish. In instances where pelicans encounter schools of fish, they form a line or U-shape, descend from the sky, and utilize their wings to create water disturbances, compelling the fish to move upwards. Subsequently, the pelicans collect the fish in their expandable throat pouch. The POA algorithm's mathematical model was developed by taking notes on these actions. The POA algorithm exhibits several advantages, including minimal parameter adjustments, rapid convergence speed, and straightforward calculations. It leverages the collective intelligence of pelican behavior to create an effective optimization approach.

**2.3 Adaptive Pelican Optimization Algorithm (APOA) for tuning FOPID controller**

In order to regulate system frequency and preserve the stability of the N-R HES under investigation, the FOPID controller is adjusted utilizing the APOA. APOA is an enhanced version of the traditional POA that incorporates a velocity computation strategy. The APOA optimization process involves iteratively adjusting the parameters of the FOPID controller utilizing the velocity computation strategy. This strategy allows the algorithm to consider the speed and direction of the search in the solution space. APOA improves the optimization algorithm's exploration and exploitation capabilities by adding velocity information. During the optimization process, APOA explores different parameter combinations of the FOPID controller to find the optimal configuration that minimizes frequency variations within the N-R HES. The algorithm iteratively updates the parameters based on the performance evaluation using specific criteria, such as frequency deviation reduction and stability assessment. This iterative optimization process continues until a satisfactory solution is obtained. Figure 2 displays the APOA flow chart for fine-tuning the FOPID controller.

**2.3.1 Initialization**

An M-dimensional space contains N pelicans; the i-th pelican's location can be expressed as  $Tp_i = [Tp_{i1}, Tp_{i2}, \dots, Tp_{iM}]$  in this space. Thus, the overall position of the N pelicans, denoted as  $Tp$ , can be expressed as follows Equation 15:

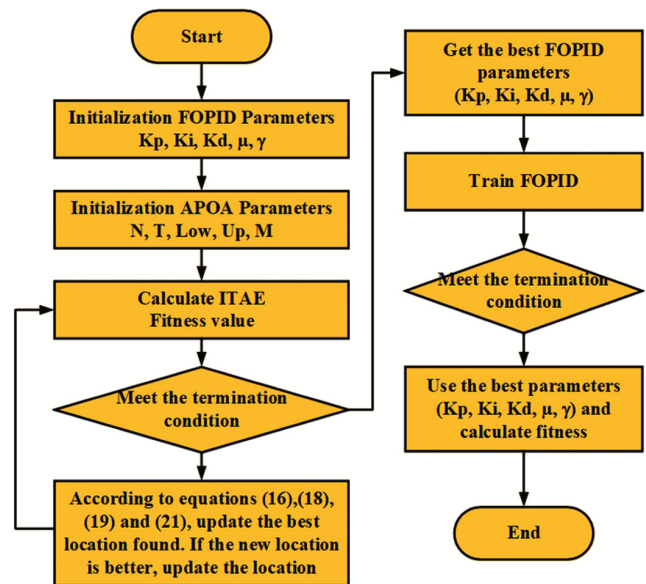


Fig. 2 — Flow chart of proposed Adaptive Pelican Optimization Algorithm for tuning FOPID controller.

$$Tp = \begin{bmatrix} Tp_1 \\ Tp_2 \\ \vdots \\ Tp_i \\ \vdots \\ Tp_N \end{bmatrix} = \begin{bmatrix} Tp_{11} & Tp_{12} & \dots & Tp_{1m} & \dots & Tp_{1M} \\ Tp_{21} & Tp_{22} & \dots & Tp_{2m} & \dots & Tp_{2M} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Tp_{i1} & Tp_{i2} & \dots & Tp_{im} & \dots & Tp_{iM} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Tp_{N1} & Tp_{N2} & \dots & Tp_{Nm} & \dots & Tp_{NM} \end{bmatrix}, i=1,2,\dots,N \quad \dots (15)$$

In this context,  $Tp_{iM}$  denotes the location of the  $i$ -th pelican in the  $M$ -th dimension. Initially, pelicans are scattered randomly within a predefined range, and the update of a pelican's position is determined by the Equation 16.

$$Tp_{im} = low_m + rand \cdot (up_m - low_m), i=1,2,\dots,N; m=1,2,\dots,M; \quad \dots (16)$$

Where  $rand$  is a random integer between 0 and 1, and  $low_m, up_m$  represent the pelican's search range.

**2.3.2 Fitness computation**

The ITAE value is utilized to evaluate the system frequency, and controllers are designed to minimize this value. Closer to system stability is indicated by a lower ITAE rating. It is possible to successfully manage the system frequency if the ITAE is within an acceptable range. The APOA algorithm will be utilized to minimize the fitness function objective function in order to determine the ideal parameters for the FOPID controller. The fitness functions utilized during the design of the load frequency control are the ITAE as stated in Equation 17.

$$ITAE = \int (|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie\ line}|) t_s dt \quad \dots (17)$$

Where,  $t_s$  are the time of simulation,  $\Delta F1$  Frequency deviation in area 1,  $\Delta F2$  Frequency deviation in area 2,  $\Delta P_{tie\ line}$  Tie-line power deviation. The following constraints are placed on the objective function:

$$K_{p2, \min} \leq K_{p2} \leq K_{p2, \max} \quad K_{i2, \min} \leq K_{i2} \leq K_{i2, \max} ,$$

$$K_{d2, \min} \leq K_{d2} \leq K_{d2, \max} ,$$

$$\lambda_{\min} \leq \lambda \leq \lambda_{\max} \quad \mu_{\min} \leq \mu \leq \mu_{\max}$$

Where,  $K_{d2}$  Derivative gain of FOPID controller,  $K_{i2}$  Integral gain of FOPID controller,  $K_{p2}$  Proportional gain of FOPID controller,  $\lambda$  is integral order and  $\mu$  is the derivate order. [0, 0, 0, 0, 0] is considered the lower limit, and [100, 100, 100, 1, 1] is the upper limit.

**2.3.3 Moving towards prey**

In this phase, the pelican finds its target and makes a very high dive to get to it. The random distribution of the prey in the search space increases the pelican's exploratory ability; the location update for each repetition is described by Equation 18.

$$Tp_{im}^{tm+1} = \begin{cases} Tp_{im}^{tm} + rand \cdot (S_m^{tm} - \lambda \cdot Tp_{im}^{tm}), & F(Tp_s) < F(Tp_i) \\ Tp_{im}^{tm} + rand \cdot (Tp_{im}^{tm} - S_m^{tm}), & F(Tp_s) \geq F(Tp_i) \end{cases} \quad \dots (18)$$

where  $tm$  is a current iteration number;  $F(Tp_s)$  is the objective function value;  $F(Tp_i)$  is the value of the fitness function of the  $i$ -th pelican in the  $m$ -th dimension;  $P_{im}^t$  is the location of the  $i$ -th pelican in the  $m$ -th dimension;  $S_m^{tm}$  is the position of the prey in the  $m$ -th dimension;  $\lambda$  is randomly equal to 1 or 2.

**2.3.4 Winging on the water surface**

When the fish reaches the surface of the water, the pelicans use their wings to lift it up and scoop it up into their neck pouch. A mathematical modeling of this pelican hunting action is provided by Equation 19.

$$Tp_{im}^{tm+1} = Tp_{im}^{tm} + \gamma \cdot \left( \frac{M_T - tm}{M_T} \right) \cdot (2 \cdot random - 1) \cdot Tp_{im}^{tm} \quad \dots (19)$$

Where, the maximum iteration number is represented by  $MT$ ;  $\gamma (M_T - tm / M_T)$  is the neighborhood radius of  $Tp_{im}^{tm}$ , and it denotes the radius of the neighborhood of the population members to search locally near each member to converge to a better solution;  $random$  is a random number between (0, 1).

**2.3.5 Adaptive computation**

By integrating the adaptive computation strategy, in association with the traditional updating strategy of the POA, the research effectively tune FOPID controllers to ensure stability in N-R HES. The mathematical function of adaptive computation strategy is as follows,

$$A_i(tm+1) = \omega A_i(tm) + cn_1 r_{11} (pbest(i, tm) - Tp_i(tm)) + cn_2 r_{22} (gbest(tm) - Tp_i(tm)) \quad \dots (20)$$

$$Tp_i(tm+1) = Tp_i(tm) + A_i(tm+1) \quad \dots (21)$$

Equations 20 and 21 The variables  $A$  and  $\omega$  represent velocity, global exploration and local exploitation are balanced by the inertia weight  $\omega$ ,  $r_{11}$  and  $r_{22}$  are uniformly distributed random variables within limit [0,1], and  $cn_1$  and  $cn_2$  are positive

constant parameters known as acceleration coefficients.

### 3 Results and Discussion

The investigation focused on improving the stability and efficiency of frequency regulation within the integrated energy system. The results demonstrated that the APOA effectively optimized the parameters of the FOPID controllers, leading to improved frequency regulation in the N-R HES. The algorithm dynamically adjusted the controller parameters, leveraging the benefits of both Pelican Optimization and adaptive computation techniques. Consequently, the system exhibited enhanced stability and maintained the desired frequency set-point more accurately. The proposed approach offers improved control precision, stability, and adaptability, paving the way for more efficient and reliable operation of integrated energy systems.

The frequency at which the integrated energy system operates is 50 Hz, a widely utilised frequency in many parts of the world. Despite the hybrid system's built-in controlling capability, it has been noted that the N-R integrated energy system has restricted ability to maintain a constant frequency when it is not running with a controller. As Fig. 3 (a & b) illustrate, the frequency of the N-R integrated system fluctuates significantly over time before stabilising at about 58 Hz (without a controller). This frequency is considerably higher than the desired 50 Hz. In electric power systems, the acceptable range of frequency fluctuation varies across regions. However, typically, a permissible range of  $\pm 1.5$  Hz is considered acceptable for frequency fluctuation. In this particular case, the observed frequency fluctuation exceeds the acceptable range of  $\pm 1.5$  Hz.

The suggested FOPID controller's error correcting capabilities are illustrated in Fig. 3(b), which also highlight how well it can minimize deviations from the target value. Unlike traditional PID controllers, FOPID incorporates five parameters, offering greater flexibility and adjustability to achieve and maintain a set value of 50 Hz. However, tuning FOPID is more complex due to the increased number of parameters. This complexity can be resolved by integrating optimization techniques. The FOPID tuning process improves responsiveness compared to traditional controllers. Control robustness is improved in FOPID by the integral and derivative terms' fractional order.

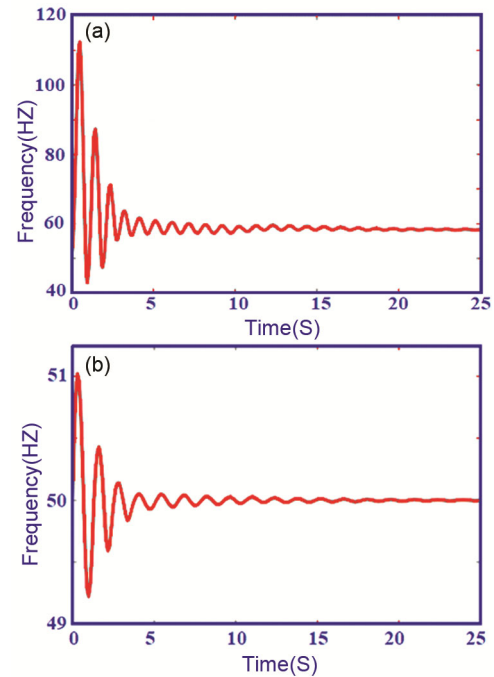


Fig. 3(a) — Grid frequency in the absence of a controller, & (b) System frequency from APOA tuned FOPID controller.

Furthermore, process performance is greatly improved by adding two more parameters,  $\lambda$  and  $\mu$ , in addition to the standard PID tuning arguments. To lower the error, the control procedure progressively raises the proportional component; however doing so may cause overshoot. The differential controller is triggered by a sudden shift in frequency, which minimizes overshoot. As time goes on, the integrated controller assists in keeping the frequency at the predetermined value. For the majority of energy systems, a maximum variation from the fixed value of less than 1 Hz is considered acceptable. FOPID controllers are frequently utilized in industrial control systems due to their superior parameter tweaking capabilities and simple architecture.

The ITAE criterion plays a crucial role in tuning the FOPID controller. ITAE is a performance metric used in optimization techniques to evaluate and adjust controller parameters. In the context of FOPID tuning, ITAE helps determine the optimal values for the five controller parameters (proportional, integral, and derivative orders, along with  $\lambda$  and  $\mu$ ). By minimizing the ITAE value, the FOPID controller can be fine-tuned to achieve better system performance and response. The ITAE criterion, which takes into account the integral of the absolute error multiplied by time, emphasizes the need to minimize transient and steady-

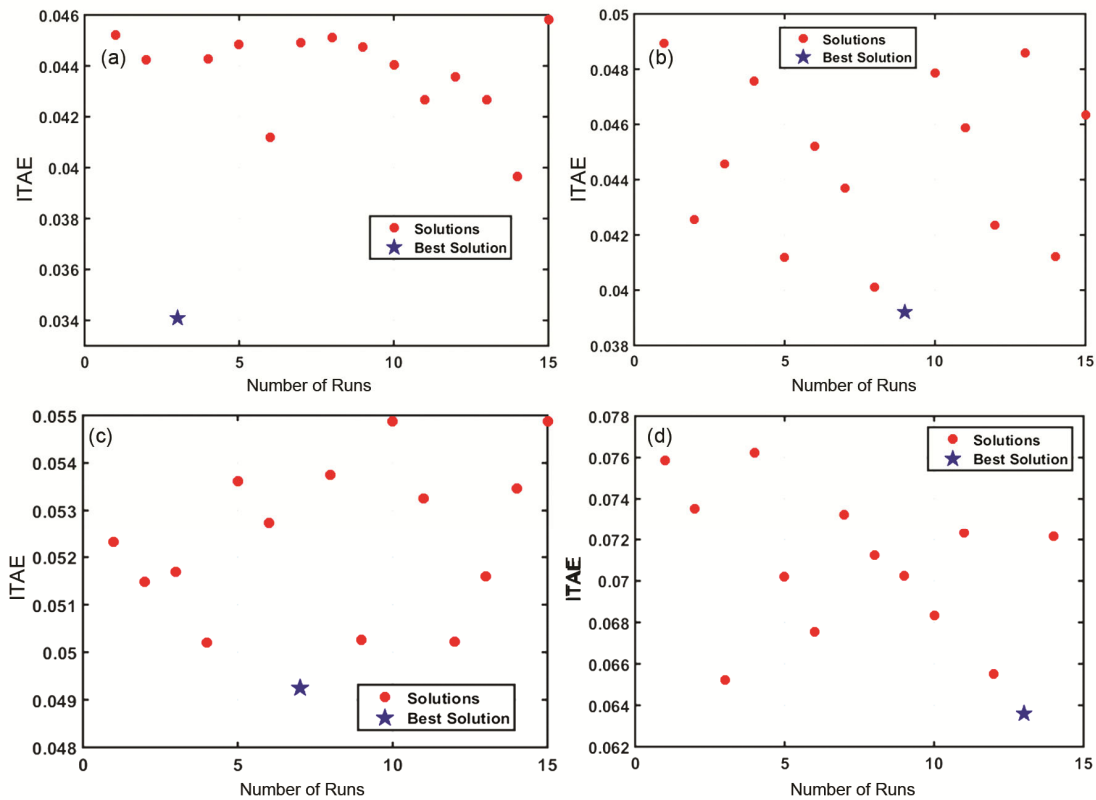


Fig. 4 — Comparison of ITAE Solutions for FOPID controller tuned by different optimization techniques.

Table 1 — Key performance indicator in time-domain analysis

Characteristics	Without controller	Controller					
		PID	FOPID	FOPID-GA	FOPID-PSO	FOPID-POA	FOPID-APOA
Rise Time (ms)	80.10	0.50	0.20	0.19	0.18	0.16	0.14
Settling Time (s)	24.82	13.04	7.65	7.30	7.24	7.18	7.12
Overshoot (%)	88.24	2.04	2.19	2.16	2.14	2.11	2.06

state mistakes over a certain period of time. The results observe from the Fig. 4 (a) shows that FOPID-APOA achieved the lowest ITAE value of 0.03409, indicating the best overall system performance among the techniques compared in Fig. 4 (b), Fig. 4 (c) and Fig. 4 (d) for FOPID-POA, FOPID-PSO and FOPID-GA respectively. FOPID-POA follows closely with an ITAE value of 0.03978. FOPID-PSO and FOPID-GA show comparatively higher ITAE values of 0.04916 and 0.06391, respectively.

The optimization techniques applied to the FOPID controllers shown in Table 1 exhibits progressive improvements in performance compared to the system without a controller. The FOPID controllers, especially when optimized using the APOA, exhibit faster rise times, shorter settling times, and significantly reduced overshoot. These results indicate improved frequency

regulation and stability in Nuclear-Renewable Hybrid Energy Systems. Notably, the FOPID controller optimized with the APOA demonstrates the best performance across all three characteristics, highlighting its effectiveness in achieving stable frequency regulation with rapid response and minimal overshoot.

### 3.1 Convergence Graph

The convergence graph depicts in the Fig. 5 (a), (b), (c) and (d) shows the performance of different optimization techniques namely APOA to tune FOPID, POA to tune FOPID, PSO to tune FOPID and GA to tune FOPID in tuning the FOPID controller to effectively manage system frequency and ensure stability in the examined N-R HES. The ITAE performance indicator is illustrated on the y-axis, while the x-axis displays the total number of

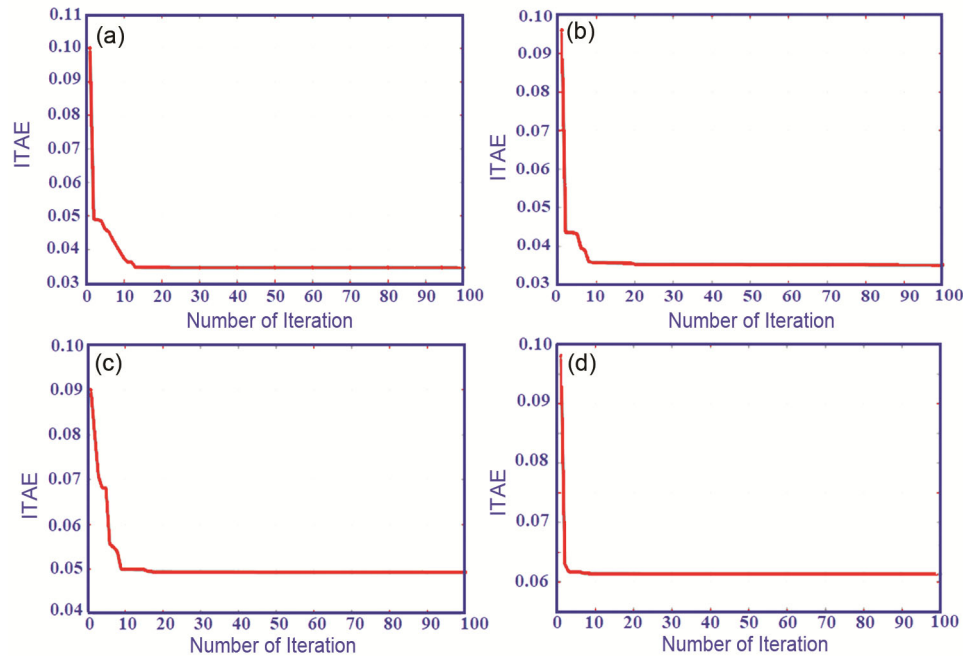


Fig. 5 — Convergence curve for FOPID controller tuned by different optimization techniques.

iterations. It illustrates how each technique converges over a number of iterations. As the iterations progress, the graph reveals how each optimization technique converges towards an optimal solution. A steeper decline in the ITAE indicates faster convergence and better optimization outcomes. The convergence graph provides clear evidence that the APOA-tuned FOPID controller exhibits a more rapid and substantial reduction in the ITAE metric, indicating superior convergence and optimization results. Compared to other techniques in the graph, like POA, PSO, and GA, the APOA-tuned FOPID controller shows a sharper drop in the ITAE as the iterations go on. This suggests that the APOA optimization method is better for fine-tuning the FOPID controller to manage system frequency and keep the examined N-R HES stable.

#### 4 Conclusion

The study illustrates how well the APOA algorithm performs when it comes to fine-tuning FOPID controller parameters for better frequency regulation in integrated energy systems. The results of this study clearly indicated that the FOPID controllers, when combined with the APOA, significantly outperformed the traditional FOPID and other optimization techniques associated with FOPID controllers in terms of frequency regulation. The APOA-tuned FOPID controller achieved better control accuracy, with a smaller minimum undershoot and peak overshoot,

faster response to disturbances, and improved robustness in maintaining the desired frequency. The APOA-tuned FOPID controller achieved the lowest ITAE value of 0.03409, indicating the best overall system performance among the techniques compared. The APOA-tuned FOPID controller also exhibited faster rise times, shorter settling times, and significantly reduced overshoot. Further research could focus on real-world implementation and validation of the proposed APOA-tuned FOPID controller. Additionally, exploring potential enhancements to the optimization techniques or alternative approaches could contribute to even better performance and wider applications in similar energy systems.

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