Optimization of load frequency control systems using PSO technique

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ABSTRACT

This paper investigates the improvement of low-frequency load control (LFC) by optimizing integral part (PID) control using particle swarm optimization (PSO). Load frequency control is important to ensure energy stability by maintaining the balance between production and consumption. Conventional proportional integral derivative controllers are widely used for this purpose; however, their performance can be further improved through optimization. This work uses particle swarm optimization, a nature-inspired algorithm, to set the parameters of the proportional integral derivative controller. PSO was chosen because it can search for good solution space and find a good agreement between control parameters, thus improving the dynamic and stable response of the system. This article provides a comprehensive evaluation of the proposed approach, including simulation results and comparisons with standard PID controllers. The effectiveness of the optimized PID controllers in reducing the frequency difference and improving the overall efficiency of the power plant under different conditions is demonstrated. This study provides insight into the use of artificial intelligence to improve control parameters in the power grid, providing a promising way to improve the efficiency and reliability of frequency controllers.

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1. INTRODUCTION

Power systems play a crucial role in our everyday lives as they are responsible for supplying electricity to the entire world. Without a stable and reliable electric network power supply, our socio-economic development would be severely impacted. To ensure the smooth operation of power systems, it is necessary to implement various protection and control techniques [1]. These techniques aim to maintain the stability of power systems by effectively controlling three important quantities: frequency, rotor angle, and voltage. An important aspect of energy management is energy management [2]. Control of voltage and reactive power ensures that they remain within the required limits. Additionally, power management control plays a crucial role in improving the performance of the power transmission system by increasing energy efficiency [3]. Among the different control methods, frequency control is the most time-consuming method. The main reason for this is the mechanical components included in the control algorithms [4]. Load frequency control (LFC) systems face problems when dealing with complex data analysis processes due to the safety control system operating for more than a second. These systems therefore become more susceptible to compromises and cyber-attacks [5].

The load frequency control system operates using continuous digital open communication methods, minimizing the need for human intervention [6]. While this design provides convenience, it also makes the system vulnerable to network threats. Moreover, a frequent change due to a change in a region or a cyber-attack will affect all parts of the power networks, threatening its overall security [7]. Incorporating renewable energy sources (RES) into electricity generation is a promising solution to solve environmental problems. However, the interactions of RES output power pose a problem in terms of electrical power system stability and frequency operation. However, RES technology and the use of smart inverters and smart controllers have been accepted in many countries [8]. Smart inverters play an important role in the distributed electric power (DER) grid by acting as the interface between DERs and the grid, controlling power flow, and detecting faults [9]. However, these technologies also expose power systems to cyber-attacks due to poor communication and vulnerabilities [10]. It is important to monitor and control operating frequencies to ensure good performance, safety, and reliability of generators. Changing the nominal frequency value directly affects the performance of the system. LFC schemes are used to control the balance between load and frequency in the power system and minimize frequency variations [11].

2. RESEARCH METHOD

2.1. LFC system configuration

Control loops play an important role in the control of electronic systems, including LFC devices. LFC systems provide control centers, field electronics, and communications to provide reliable and efficient transmission and distribution [12]. Sensors collect measurements from field equipment, such as terminal voltage, power flow, and rotor speed, enabling control centers to make informed decisions for efficient power management [13]. It is important to control the stable operation of the generator. One approach to achieving this is through the implementation of a single-area LFC system [14]. Unlike interconnected systems that require complex adjustments, the single-area scheme focuses solely on stabilizing the frequency to its nominal value. This ensures that the system operates smoothly and efficiently [15]. Figure 1 represents a Governor Control Loop within a power system, where a control center monitors and adjusts the system based on data from sensors that measure parameters like power flow and frequency. The local controller sets values for the speed changer motor, which adjusts the governor. The governor then regulates the flow of steam or water to the turbine through control valves, influencing the generator's power output. The generator converts mechanical power into electrical energy, and sensors provide real-time feedback to the control center to maintain system stability and meet load demands.

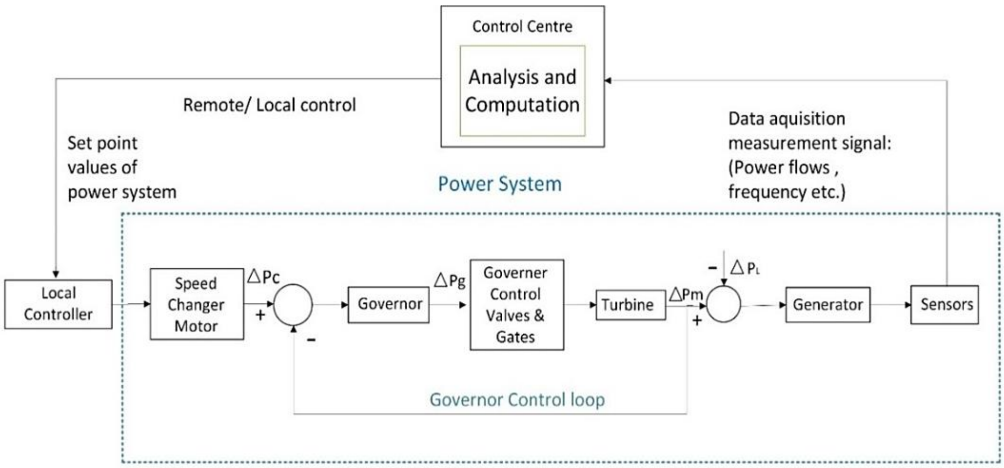

Figure 1. A classic LFC loop

2.2. Dynamic equations for the single-area LFC system

To delve deeper into the evolution of local LFC systems, let us consider differential equations. The power-load dynamic relationship between the mismatched power difference ($\Delta P_m(t) - \Delta P_L(t)$) and the frequency deviation is expressed mathematically as (1) [16].

$$\Delta f(t) = \frac{1}{M}\Delta \mathrm{Pm(t)} - \frac{1}{M}\Delta \mathrm{Pl(t)} - \frac{1}{M}\mathrm{D}\Delta \mathrm{f(t)} \quad (1)$$

Where $\Delta P_m(t)$ is mechanical power change, $\Delta P_L(t)$ is load change, and M is equivalent inertia coefficient. Additionally, turbine dynamics can be explained as (2).

$$\Delta Pm(t) = \frac{1}{Tt}\Delta Pg(t) - \frac{1}{Tt}\Delta Pm(t) \tag{2}$$

Where $\Delta P_m(t)$ is mechanical power change, $\Delta P_g(t)$ is governor output change, and T_t is turbine time constant. Similarly, the governor dynamics can be defined by (3).

$$\Delta \mathrm{Pg(t)} = \frac{1}{Tg}\Delta \mathrm{Pc(t)} - \frac{1}{RTg}\Delta \mathrm{f(t)} - \frac{1}{Tg}\Delta \mathrm{Pg(t)} \tag{3}$$

Where $\Delta P_g(t)$ is the governor output change, R is speed drop characteristic, $\Delta P_c(t)$ is control signal, and T_g is the governor time constant.

2.3. Application of PSO, sine cosine, and genetic algorithm for optimization of PID controller

To ensure system stability and minimize variability, the commonly uses proportional-integral-derivative (PID) controller. However, due to the weak and weak characteristics of the generator, it may be difficult to tune the PID parameters for good performance [17]. Particle swarm optimization (PSO) and genetic algorithms provide powerful meta-heuristic optimization algorithms. This content provides an in-depth study of the application of PSO and genetic algorithms to develop PID controllers in the case of a local LFC and compare them for the frequency response of the system [18]. The main purpose of a local LFC system is to optimally control the power system frequency by adjusting the output power of the generator. PID controller has parallel, fundamental, and time-varying elements and plays an important role in responding to changes and restoring the system to its nominal frequency [19].

2.4. PSO algorithm

Going to the in-depth working of the PSO algorithm, the best solution for the problem is found by communicating the results with every particle of the swarm and learning from the personal best solution of each particle and going towards the direction of that solution simultaneously checking for other best solutions possible on the way. Each particle is associated with two vectors, a process vector, and a position vector as we can see in Figure 2 [20]. Both are of the same length. In addition to the above vectors, each particle also has a memory to store its p best position. The group also has the world's best memory and the best work of the entire group. Where $\vec{\mathrm{V}}(\mathrm{t})$ is a clipping vector, $\vec{\mathrm{P}}(\mathrm{t})$ is one's individual best position, $\vec{\mathrm{X}}(\mathrm{t})$ is position vector and $\Delta\mathrm{G(t)}$ is the global best position of the group.

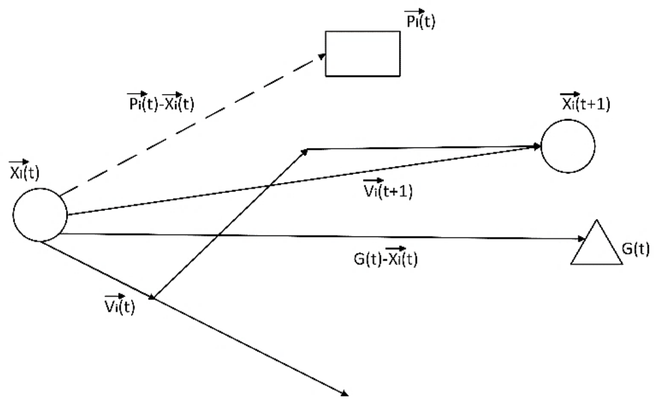

Figure 2. Vector diagram of the position of a PSO particle

2.4.1. Pseudo code for PSO algorithm

The pseudo code is in Algorithm 1, and it initializes a PSO by setting dimensions, bounds, cost function, swarm size, iterations, and coefficients. Particles' positions (Xij) and velocities (Vij) are randomly set. Each particle's cost is evaluated, and the best positions (local and global) are updated to optimize the objective function. The pseudo code in Algorithm 2 describes the PSO process across iterations. For each particle in the swarm, velocities $V_{(ij)}$ and positions $X_{(ij)}$ are updated. The cost $F(X_{ij})$ is calculated, and the best personal and global positions are updated. After reaching the maximum iteration, the global best solution is finalized [21].

Algorithm 1. Initialization of PSO
Set variable dimension; Set upper bound of dimensions; Set lower bound of dimensions; Set cost function;
Set swarm size; Set max iterations; Set inertia coefficient; Set acceleration coefficients.
Select randomly X_{ij} and V_{ij} for each particle;
Evaluate $F(X_{ij})$ for each particle;
Set F_{min} as the min value of $F(X_{ij})$ among all the particles;
update $X_{ij(particlebest)}$ and $X_{ij(global\ best)}$ best

Algorithm 2. Main loop of PSO algorithm
For i=1 to i= $Iteration_{(max)}$ do;
- For j=1 to j= Particle number do;
    - Update $V_{(ij)}$;
    - Update $X_{(ij)}$;
    - Calculate $F(X_{ij})$;
    - Update $F_{(min)}$;
    - Update $X_{ij(particlebes)}$;
- End; End;

Update $X_{ij(global\ best)}$; Check if iteration= $Iteration_{(max)}$; Final value $X_{ij(global\ best)}$

2.5. Genetic algorithm

Genetic algorithms (GA) work on populations with multiple solutions where the population size is the solution. Every solution is called personal. Every substance has a chromosome. Chromosomes are represented as characteristics that define a person [22]. Each chromosome contains a pool of genes. Everyone has a fitness level. Use intermediaries to choose the best candidates. The solution to the physical problem is the fitness value that represents the optimal solution [23]. The greater the number, the better the resolution. Selecting the best individuals based on performance is used to create a mating pool from which individuals with better results will be selected in the mating pool; Individuals with better results from this pool are selected into the mating pool. The people living in this lake are called parents [24]. Each pair chosen from the pool will produce two offspring (children). Each group formed is called a generation.

2.5.1. Pseudo code for genetic algorithm

The pseudocode in Algorithm 3 initializes the population genetic algorithm. At each iteration, it evaluates the population, selects parents, creates offspring through competition, and returns the best individual when a decision is made. The pseudocode in Algorithm 4 swaps the children, evaluates them, replaces the current individual with the new child, and returns the best individual. Offspring are produced by crossing selectedparents.

Algorithm 3. Genetic algorithm main loop
```
% Initialization
        Population = InitializePopulation()
% Main Loop:
        While termination criteria not met:
                CalculatePopulation(population)
                Selected_parents= SelectParents(population)
                Offspring = Crossover(selected_parents)
return BestIndividual(population)
```

Algorithm 4. Genetic algorithm mutation
```
% Mutation
   Mutate(offspring)
% Evaluation
   EvaluatePopulation(offspring)
   population = Replace(population, offspring)
% Return best individual found
   return BestIndividual(population)
   offspring = Crossover(selected_parents)
```

2.6. Sine cosine algorithm

Sine cosine algorithm (SCA) is an optimization based on the oscillatory behavior of sine and cosine functions. It follows the movements of celestial objects in the sky, where the sine and cosine functions are important. The SCA can be used for the optimization of PID controllers [25]. The random initial population of potential solutions. These solutions represent different sets of PID parameters (common gain, time integration, time difference). Define an objective function that evaluates the performance of the PID controller. This includes how well the control system tracks signal usage reduces noise, adjusts speed, and measures [26], [27]. This work evaluates the security of each solution. Enter each solution as a vector representing PID parameters. For example, the solution can be expressed as [Kp, Ti, Td]; where Kp is the equation, Ti is the integration time, and Td is the divergence time. Iterate solutions across generations and modify them as necessary. Evaluate the security of each solution using the target function. Updated the position of each solution using the equivalent sine-cosine algorithm, which includes oscillatory motion based on sine and cosine powers. The aim of this is to find better solutions in the search space. Use the search process and appropriate usage to achieve a balance between exploring new areas of the search space and using effective solutions [28], [29]. Re-perform the above steps until the stop is complete (i.e., maximum number of repetitions, satisfactory performance is achieved).

After the optimization process converges or reaches a stopping criterion, extract the best solution(s) found. These solutions represent the optimal PID parameters that best suit the control problem under consideration. Implement the optimized PID controller with the extracted parameters in the real system or simulation environment [30], [31]. The sine-cosine algorithm helps in efficiently exploring the solution space and finding optimal or near-optimal PID parameters. Leveraging oscillatory movements inspired by sine and cosine functions, provides a balance between exploration and exploitation, leading to effective optimization results [32]. However, as with any optimization algorithm, the performance of the sine-cosine algorithm can vary depending on the problem characteristics and parameter settings. Therefore, it's essential to validate the obtained results and fine-tune the algorithm parameters if necessary [33]. The pseudocode in Algorithm 5 initializes the random solution X_i, evaluates the target value, updates the target P, adjusts the inequality, updates the solution using the equation, and repeats this process until the maximum iteration is completed.

Algorithm 5. Sine cosine algorithm
Initialize the random set of solutions $X_i(i= 1,2,\ldots\ldots,n)$
While t less than T_{max} do
Evaluate the objective value for each X_i
Revise the destination (P= X)
Revise the random parameters
Revise the solution using the equation (6)
End while
Return the destination P

3. RESULTS AND DISCUSSION

In Figure 3, the performance of the tuned PID controller is measured by simulating its response to various load disturbances and incorporating the uncertainty of the system. The frequency response of the system after optimization without using a PID controller. Figure 4 shows the integrated response of a local LFC system with and without the optimization technique. While observing the graph it is realized that with the use of optimization techniques, the system can be stabilized within the negligible time period. Although for complex systems this time may enlarge.

To overcome this, use different optimization techniques for improved results. Below, three algorithms were executed: PSO algorithm, genetic algorithm, and sine cosine algorithm. Figure 4 is the optimization results of the PSO algorithm where it has stabilized the curve well before the natural stabilization of the signal. But in Figure 5, the optimization results of the genetic algorithm outperform the PSO algorithm with a margin of 0.0188739 sec. This can be because GAs are particularly effective in problems with many local optima. The crossover and mutation operations in GAs can help explore the search space more thoroughly and avoid premature convergence to local optima, which can be a challenge for PSO.

Figure 6 is the optimization results of the sine cosine algorithm. From the figure, one can conclude that although the SCA performed better than the PSO algorithm but it failed to give better results than the GA. The GA outperforms the SCA with a time margin of 0.0064027 sec. GAs, with their crossover and mutation operations, is well-suited for navigating complex, multimodal landscapes. They can escape local optima more effectively than SCAs, which rely on deterministic sine and cosine functions for exploration and exploitation. In Table 1, the stabilization time that each algorithm took to stabilize the signal. The table also shows the stabilized final frequency after the algorithm is executed. For the above case of optimization of PID controller in a single area load frequency control, the genetic algorithm outperforms PSO and SCA with a stabilization time difference of 0.0188739 sec and 0.0067627 sec, respectively.

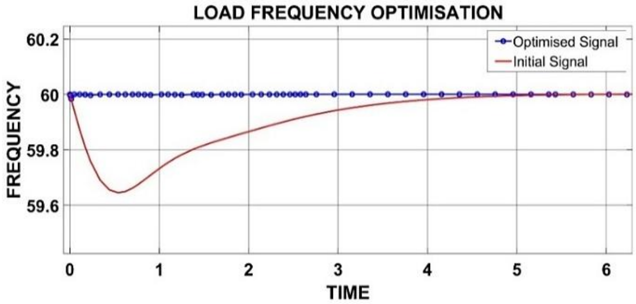

Figure 3. Frequency response of single area LFC system

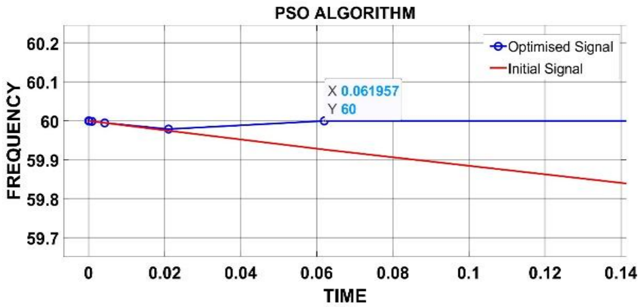

Figure 4. Frequency response using PSO algorithm

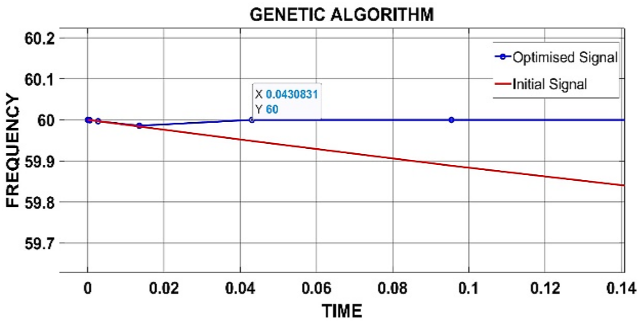

Figure 5. Frequency response using genetic algorithm

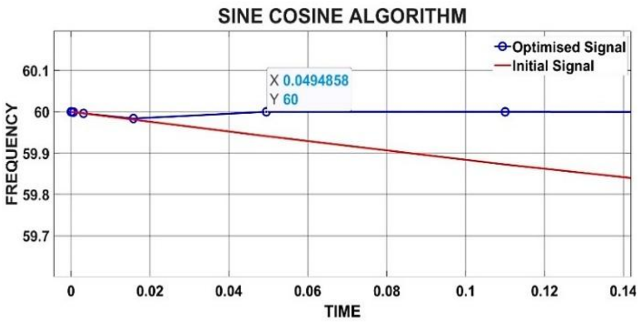

Figure 6. Frequency response using sine cosine algorithm

Table 1. Optimization results

Algorithm	Stabilization time (sec)	Stabilized frequency (Hz)
PSO algorithm	0.0619570	60
Genetic algorithm	0.0430831	60
Sine cosine algorithm	0.0498458	60

4. CONCLUSION

In the context of optimizing local LFC and optimizing PID controller parameters, the performance of the genetic algorithm (GA) may differ depending on the situation compared to particle swarm optimization (PSO). Here are some reasons why GA is preferred over PSO in this particular case GA typically excels in the exploration of the solution space due to its ability to maintain a diverse population and perform global search through operations like crossover and mutation. In single-area LFC, where the system dynamics can be complex and non-linear, effective exploration of the solution space is crucial to finding optimal or near-optimal PID controller parameters. PSO, while effective in exploitation due to its ability to quickly converge to promising regions, might struggle in exploring diverse regions of the solution space, potentially leading to suboptimal solutions. While GA may have advantages over PSO in certain aspects, it's essential to note that the performance of optimization algorithms can vary depending on the specific characteristics of the problem, the implementation details, and the tuning of algorithm parameters. Therefore, it's often beneficial to experiment with multiple optimization algorithms to find the most suitable one for a particular application, such as optimizing PID controllers in single-area LFC. The choice of SCA and GA to optimize the PID controller does not depend on factors such as the complexity of the control problem, available computational ability, and the specific requirements of the application. It is often a good idea to experiment with multiple algorithms and compare their performance on your specific optimization problem to determine which algorithm works best in practice. From the above results, one can conclude that the genetic algorithm is better than the PSO algorithm and the sine and cosine algorithms for the optimization of the PID controller in the local load frequency control system.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Lingam Yashwanth	✓		✓	✓	✓		✓			✓	✓		✓	✓
Peesodi Uday		✓	✓			✓				✓			✓	
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable requests.

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