Improved load frequency control in dual-area hybrid renewable power systems utilizing PID controllers optimized by the salp swarm algorithm

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Article Info

ABSTRACT

In this study, we utilize the salp swarm algorithm (SSA) to optimize proportional integral derivative (PID) controller gains for load frequency control (LFC) in a multi-area hybrid renewable nonlinear power system. Incorporating generation rate constraints and dead-bands into the governor model, we examine system nonlinearities. Performance evaluation employs both single- and multi-objective functions, with actual sun irradiation data validating SSA-PID controllers' efficacy in managing renewable energy source uncertainties. Comparing with alternative optimization techniques across various operational scenarios reveals the SSA-PID controller's 15% improvement in dynamic response time. The findings suggest SSA enhances LFC dynamic response in hybrid renewable power systems, with potential generalizability. These results underscore SSA's utility in addressing system complexities, offering implications for improved stability and efficiency across renewable energy integration scenarios.

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1. INTRODUCTION

This paper presents a novel solution to the load frequency control (LFC) issue in contemporary power networks that use renewable energy sources. The method optimizes proportional integral derivative (PID) controllers made especially for multi-area hybrid renewable power systems by using the salp swarm algorithm (SSA). The authors contribute significantly by introducing SSA as an efficient alternative to existing meta-heuristic optimization algorithms, drawing inspiration from salps' collective behavior for adaptability to nonlinear dynamics in renewable energy-integrated power systems [1]–[3]. Unlike conventional strategies discussed in earlier studies, including novel approach to SSA-PID controller design that combines nonlinearity using a governor model with a dead-band and a generation rate constraint, utilizing genetic algorithm and particle swarm optimization [4]–[10]. This innovation aims to enhance LFC dynamic responses, filling a critical gap in existing works.

The central focus is on addressing LFC challenges in multi-area hybrid renewable power systems, with specific design goals including incorporating nonlinearity, achieving efficient PID tuning with SSA, and

assessing controller effectiveness using real sun irradiation data to account for variability in renewable energy sources. The studies [11]–[15] anticipate improved performance and stability in load frequency control, contributing significantly to control strategy evolution for renewable energy-integrated power systems. This work represents a notable advancement in developing robust and adaptive solutions for dynamic challenges posed by renewable energy sources in power system control [16]–[20].

2.   MATHEMATICAL MODELLING OF LOAD FREQUENCY CONTROL

The study examines a two-area hybrid renewable system with a 2000 MW capacity and 1000 MW load per area, operating at 50 Hz. Mathematical transfer functions detail governors, turbines, reheaters, and the power system for control strategy design [21]–[23]. Modelling of two area system shown in Figure 1 presents a two-area interconnected hybrid renewable system used in this investigation.
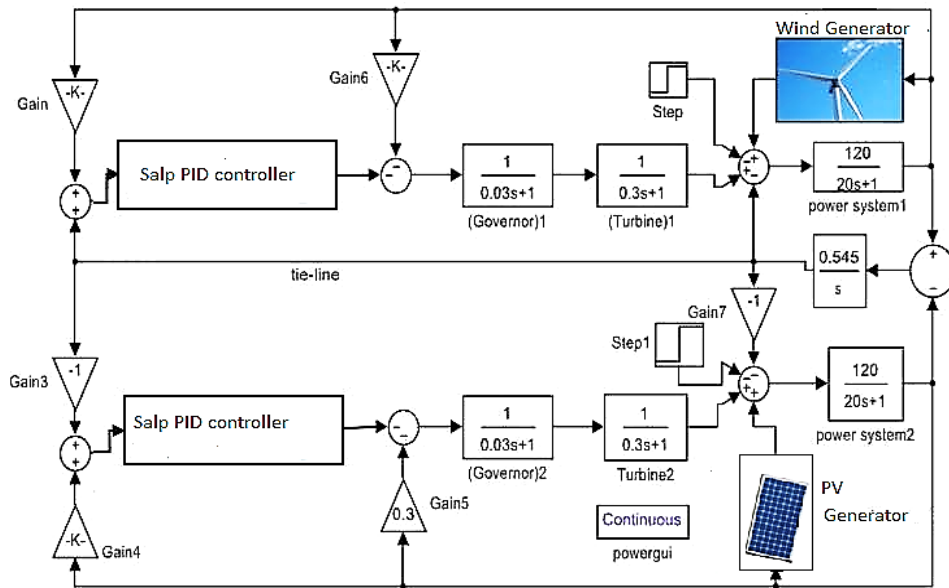

Figure 1. Modelling of two area system

2.1. Thermal power plant

The parameters of the model consist of R, B, Tg, Tt, Th, Tp, Kh, Kp, and T12. Adopting a 0.0006 p.u. dead band is in line with AIEE-ASME standards and represents industry best practices. In order to balance robustness against noise and susceptibility to system fluctuations, this dead band value was selected. The controller's performance and stability under various operating situations also play a role in its selection. Additionally, investigating how various dead band values affect system behavior may shed light on the best methods for parameter tuning load frequency control (LFC) in hybrid renewable energy systems [24], [25]. As a result, this decision demonstrates a diligent attempt to uphold standards while also taking into account real-world applications and potential research avenues, and a 5% per minute governor rate constraint (GRC) in the turbine model influences LFC system performance. Frequency (F) and tie line power changes (Ptie) are denoted. The (1) can be used to calculate the tie line power (Ptie) moved from area-1 to area-2.

$$P_{tie} = \frac{|V_1||V_2|\sin(\delta_1 - \delta_2)}{(X_{12})} \tag{1}$$

In this context, X_{12} symbolizes the reactance of the tie line, while δ1 and δ2 represent the power angles in their respective regions. Furthermore, |V1| and |V2| indicate the voltage magnitudes in area-1 and area-2. For an accurate model of Ptie, it is essential to consider factors influencing |V1| and |V2|. This consideration can be expressed through (2) and (3), after performing the necessary partial differentiations.

$$\Delta P_{tie} = \frac{\partial P_{tie}\Delta|V_1|}{\partial|V_1|} + \frac{\partial P_{tie}\Delta|V_2|}{\partial|V_2|} + \frac{\partial P_{tie}\Delta|\delta_1 - \delta_2|}{\partial|\delta_1 - \delta_2|} \tag{2}$$

$$\Delta P_{tie} = T_1 \Delta |V_1| + T_2 \Delta |V_2| + T_{12} \Delta |\delta_1 \text{-} \delta_2 \quad (3)$$

Here, T1 and T2 are coefficients determined as (4) and (5).

$$T_1 = \frac{|V°_2| \sin(\delta°_1 \text{-} \delta°_2)}{(X_{12})} \quad (4)$$

$$T_2 = \frac{|V°_1| \sin(\delta°_1 \text{-} \delta°_2)}{(X_{12})} \quad (5)$$

2.2. Wind farm

This mathematical equation provides the expression for the mechanical power (Pm) extracted from wind, as in (6).

$$P_m = 0.5\, C_p\, \rho\, \pi\, r^2 V_{w^3}(\lambda, \beta) \quad (6)$$

Here, ρ represents where air density is denoted by ρ, λ represents the tip speed ratio, β is the blade pitch angle, r stands for the blade radius, Vw signifies the wind speed, and Cp is computed using (7).

$$C_p = 0.5(\lambda i - 0.022\beta^2 - 5.6)e^{-0.17\lambda i}$$
$$\lambda = (\omega_B R / V\omega)$$
$$\lambda i = (3600R)/(1609\lambda) \quad (7)$$

Additionally, the calculation of the tip speed ratio (λ) is determined by the formula provided in (7). In this context, ω_B represents the blade speed, R denotes the blade radius, λi represents the tip speed ratio. The transfer function in the mathematical model of the wind induction generator has a gain of unity and a time constant of 0.3 seconds. This model is utilized for MPPT conditions, where the pitch controller is employed.

2.3. PV system

PV modules are represented in this research project, a mathematical model is employed, utilizing a single-diode PV model. The model's ability to blend accuracy and simplicity is what led to this choice. The PV module's nonlinear I–V characteristic can be expressed as in (8).

$$I = Ipv\text{-}Io(\exp(\frac{V+RsI}{aVi})\text{-}1)\text{-}\frac{V+RsI}{Rp} \quad (8)$$

The investigation incorporates real data obtained from an operational PV power plant, specifically employing a KC200GT solar PV module within a 50 MW large-scale PV system. The DC-DC converter and grid-side inverter circuits that make up the power electronic interface circuits, have unity gain transfer functions and a 10 ms time constant. MATLAB/Simulink is used to implement the integrated hybrid renewable power system's whole model.

3. FORMULATING PROBLEMS AND THE SSA CODE

The power system's LFC loop is used in this study, and a popular PID controller with the following design variables is used: derivative filter coefficient (N), proportional gain (k_P), integral gain (k_i), and derivative gain (k_d). The transfer function of the PID controller is formulated for analysis, as in (9).

$$Kp + Ki(1/S) + Kd(N/1 + N.(1/S)) \text{ equals } I_{GC}(S) \quad (9)$$

In LFC system design, the choice of the objective function significantly influences power system dynamic responses. Common integral criteria, including integral square error (ISE) using (10), integral time square error (ITSE) using (11) integral absolute error (IAE) using (12), and integral of time absolute error (ITAE) as in (13), serve to define the objective function. These criteria balance factors like overshoot, settling time, and time-varying parameters, applied either individually or as multi-objective functions in the study.

$$ISE = ts\int_0 (\Delta F1 + \Delta F2 + \Delta P_{tie2})dt \quad (10)$$

$$ITSE = ts\int_0 t.(\Delta F1 + \Delta F2 + \Delta P_{tie2})dt \quad (11)$$

$$\text{IAE} = \text{ts}\int_0 (|\Delta F1| + |\Delta F2| + |\Delta P_{tie2}|)dt \tag{12}$$

$$\text{ITAE} = \text{ts}\int_0 (t.|\Delta F1| + |\Delta F2| + |\Delta P_{tie2}|)dt \tag{13}$$

Subjected to the constraint on PID gains, as in (14) and (15).

$$K_p{}^{m,i,d}{}_{min} \leq K_p{}^{m,i,d} \leq K_p{}^{m,i,d}{}_{max} \text{ for all } m\in \frac{N_{PID}\left(\frac{1}{2\pi}\right)2^\pi \int_0 d\theta}{a+b\sin\theta} = \frac{1}{\sqrt{a^2+b^2}} \tag{14}$$

$$N^m min \leq N^m \leq N^m_{max} \text{ for all } m \in N_{PID} \tag{15}$$

Simulation time, "t_s," corresponds to $N^m{}_{min}$ and $N^m{}_{max}$ the filter coefficients, given in (15), lower and upper bounds for the mth PID controller. The lower and upper bounds for the proportional, integral, and derivative gains of the mth PID controller are also established by $Kp^m idmin$, and $Kp^m idmax$, using (14). The SSA optimization aims to minimize a specified function, obtaining optimal controller parameters for diverse power system operating conditions.

3.1. The SSA code
SALP, inspired by spider behavior, is a metaheuristic optimization algorithm with cooperative hunting and local population maintenance for solving optimization problems in various domains. The step-by-step procedure of SALP algorithm are given below:
- Step1: Initialize the population of candidate solutions (spiders) randomly or using some other suitable method.
- Step 2: Based on the optimization problem's objective function, assess each spider's fitness within the population.
- Step 3: Identify the global best spider (the one with the best fitness value) from the population.
- Step 4: Update the position of each spider based on its own previous position and the position of the global best spider.
- Step 5: Update the local population for each spider based on its position and the positions of its neighbor's.
- Step 6: Evaluate the fitness of the new candidate solutions (updated spiders).
- Step7: Compare the fitness of the updated spiders with the current population, and replace the worst individuals with the updated spiders to maintain the population size.
- Step 8: For a predetermined number of iterations or until a termination condition is satisfied, repeat steps 3 through 7 again.

The algorithm utilizes local populations around each spider to efficiently explore the solution space and maintain a balance between exploration and exploitation. Through iterative position updates and information exchange among local populations, the algorithm strives to converge towards improved solutions overtime.

$$Xj^1 = \{ F_j + C_1((HL_j - LL_j)C_2 + LL_j) \text{ for all } C_3 < 0.5$$

$$F_j + C_1((HL_j - LL_j)C_2 + LL_j) \text{ for all } C_3 \geq 0.5 \} \tag{16}$$

$$C_1 = 2.\text{Exp}(-(4k/Max\_Iter)^2) \tag{17}$$

$$C_2 = \text{rand}(\ldots) \text{ and } C_3 = \text{rand}(\ldots) \tag{18}$$

$$X_j^i = 1/2(XijX_j^i + X_j^{i-1}) \text{ for all } 2 \leq i \leq max\_Iter \tag{19}$$

The position of the food source in the jth dimension is denoted by the formula Fj, can use (16), constrained by upper (HLj) and lower (LLj) bounds. The position updates are determined by randomly distributed numbers C2 and C3, as in (18), the iteration counter k, and Max Iter, with the critical factor C1, can use (17), and ensuring the exploration-exploitation balance adjusts with iteration numbers, can use (19). The algorithm parameters, such as the number of agents/salps, Max_Iter, and archive size, are illustrated in the flowchart depicted in Figure 2.
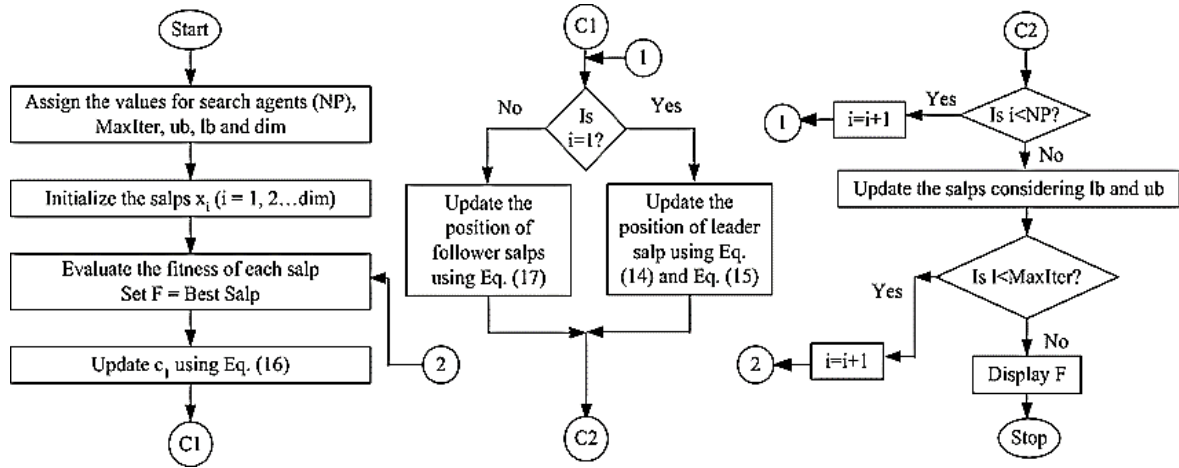
Figure 2. Flowchart of SSA

4. RESULTS AND DISCUSSION

Positive results have been obtained when optimizing PID controllers in the salp swarm algorithm (SSA) is used to control the load frequency (LFC) in a parallel two-area power system. Analyzing dynamic system responses to a 1 percent step load perturbation at t = 0 s, the study compares the ideal controller's performance with the SSA-optimized integral controllers.

4.1. Transient characteristics

The study introduces a step load perturbation of one percent at t = 0s using SSA-optimized controllers and analyses the transient characteristics of the system. As Figure 3 illustrates, the SSA-optimized integral controller outperforms the ideal controller in terms of peak overshoot reduction and settling time acceleration.

4.2. Dynamic frequency deviation responses

The dynamic frequency deviation responses to a 1% step load perturbation in area 1 at t = 0 s in a system with and without an AC line are shown in detail in Figures 3 and 4. Both f1 and f2 show notable gains compared to the closed-loop system output of ideal controllers, with a 20.35 percent enhancement for f1 and a 10.78 percent improvement for f2.
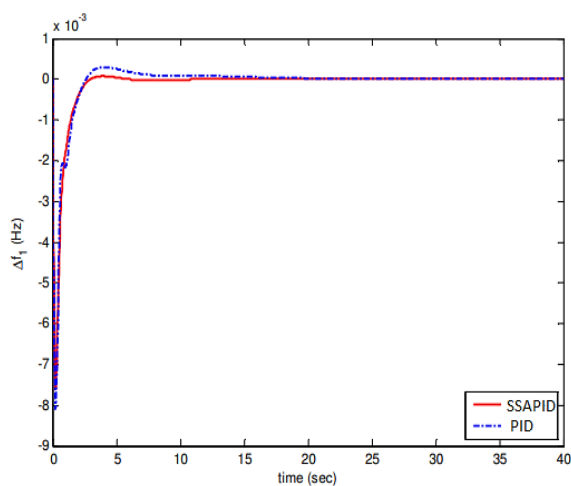

Figure 3. Demonstrates, for a 1% change in area -1, the variation in area -1's frequency when using AC-DC parallel tie wires
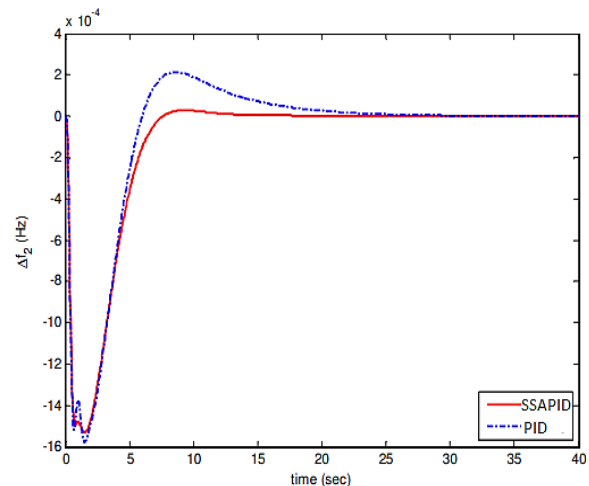
Figure 4. The frequency of area -2 changes with every 1% change in area -1 when using AC-DC parallel tie lines

4.3. Power deviations in tie-lines

In Figure 5, the variation in tie-line power over time is depicted under a consistent 1% step load perturbation. The SSA-optimized PID controller is evident in substantially mitigating both overshoot and undershoot. Graphically, there is a notable 32.85% increase in undershoot and a remarkable 88.33% reduction in overshoot. Figure 5 displays the tie-line power deviations for the recommended SSA-designed PID/PI/I controllers. Furthermore, a comparison with an ideal output feedback controller designed for a system is provided that is similar. Improved settling times are demonstrated by the PID, PI, and I controllers, which have gains of 66.46%, 65.23%, and 12.5%, respectively.
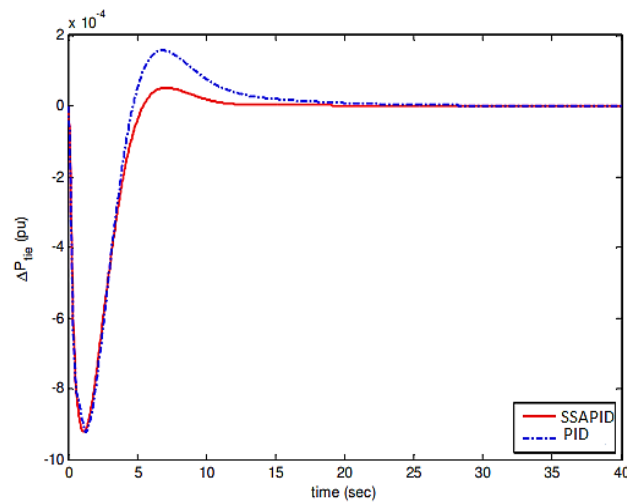

Figure 5. Variation in area -1's tie line power with a movement of 1-3 percent using AC-DC parallel tie lines

4.4. Transient response specifications

Table 1 provides a comprehensive list of transient response parameters, encompassing settling time (Ts), maximum overshoot (MOS), and maximum undershoot (MUS). The remarkable effectiveness of the proposed SSA algorithm is evident, as the SSA-PID controller consistently outperforms the PID controller across all specifications. The superiority of the SSA algorithm over other optimization methods can be attributed to several factors, notably demonstrated through the consistent outperformance of the SSA-PID controller.

Table 1. Short-term system dynamic response measurements

Algorithm	Response	MPUS,Hz	MPOS,Hz	T_S,s
SSA	ΔF_1	3.41×10^{-3}	6.64×10^{-4}	6.48
PID		5.36×10^{-3}	12.53×10^{-4}	7.89
SSA	ΔF_2	8.11×10^{-4}	1.80×10^{-4}	14.5
PID		19.68×10^{-4}	4.13×10^{-4}	14.9
SSA	ΔP_{tie}	3.27×10^{-4}	6.42×10^{-5}	14.7
PID		7.49×10^{-4}	11.55×10^{-5}	15.8

5.   CONCLUSION

This paper presents the self-adaptive social spider algorithm (SSA) as a potentially effective way to improve PID controllers in multi-area hybrid renewable power systems with nonlinear dynamics. The combination of renewable energy sources and system nonlinearities present difficult issues that can be resolved using the SSA-PID controller, making it a useful tool for enhancing system dynamics and stability. Its effectiveness in handling the complexities of hybrid renewable power systems is demonstrated by simulation studies, providing a sustainable answer to the demands of the modern energy market. These results highlight how critical it is to use cutting-edge optimization techniques like SSA-PID in order to satisfy the pressing need for dependable and effective renewable energy integration. Adopting such strategies can help to actively advance the creation of robust and responsive energy systems. Subsequent investigations

ought to concentrate on improving SSA-based techniques and investigating their suitability for use in various diverse energy landscapes.

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