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LOAD FREQUENCY STABILIZATION WITH HKM-MSO FOR PI CONTROLLER DESIGN IN PV-THERMAL POWER SYSTEMS

Pramod Kumar Gouda¹, Jammu Lepakshi², V V Appalanaidu Menda³

¹Professor, Department of Electrical and Electronics Engineering, Aditya Institute of Technology and Management, Tekkali, Srikakulam District, Andhra Pradesh, India.

²PG Scholar, Aditya Institute of Technology and Management, Tekkali, Srikakulam District, Andhra Pradesh, India.

³Assistant Professor, Aditya Institute of Technology and Management, Tekkali, Srikakulam District, Andhra Pradesh, India.

¹<http://orcid.org/0000-0001-7165-3496>, ²<https://orcid.org/0009-0000-2071-1617>, ³<http://orcid.org/0000-0002-1585-6923>

Email: pkgouda18@gmail.com, sriasirithalliaselfarms525@gmail.com, naidueee54@gmail.com

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ABSTRACT

In power systems, attaining a stable equilibrium between consumed and generated power is difficult, exclusively with the incorporation of Renewable Energy Sources (RES) such Photovoltaic (PV) system. This research implements the Hybrid Komodo-Mlipir-Mantis Shrimp Optimization (HKM-MSO) based Proportional-Integral (PI) controller in a two-area PV-thermal system for Load Frequency Control (LFC). This design has the two area power system which comprises thermal reheat power plant and PV system. The HKM-MSO attains a better balance by incorporating the hierarchical cooperative search of Komodo dragons with vision based strategy of mantis shrimps. It has resilience beside parameter variations and nonlinearities with better convergence speed and averts premature convergence. The overall research is simulated in MATLAB/SIMULINK tool, demonstrates the HKM-MSO-PI controller has better performance interms of settling time with 10.5s, overshoot of 0.0156 and regulation of frequency. Moreover, this research attains a decrement in undershoot, indicating better dynamic response and robustness than existing techniques.



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I. INTRODUCTION

1.1 BACKGROUND

In order to stabilize the system frequency under various disturbance kinds, LFC is a vital issue [1]. Researchers have created a number of novel LFC control mechanisms in recent years, especially for power systems that integrate Renewable Energy Sources (RES), which provide a sustainable, clean and eco-friendly substitute for traditional fossil fuel-based generation [2-4]. With the aim of reducing possible risks and guaranteeing the reliable function of power systems, the application of LFC is emerged as a crucial component of control approaches and power system operation [5], [6]. The use of PV panels [7], [8] in linked power systems is continuously growing because of its benefits, which include reduced pollution, silence and simplicity of installation [9], [10]. The varied power output that is obtained from these sources, however, it necessitates more cautious management of the tie-line power variations and system frequency fluctuations [11], [12]. Because of its simplicity, stability margins, reduced costs and ease of deployment, the PI controllers are frequently employed [13]. The Area Control Error (ACE) is the sum of frequency fluctuations and tie-line power exchanges between control areas, presented in a linear fashion [14]. The idea behind LFC is to reduce or eradicate ACE from the system by balancing current system demand with minute by minute generation. This requires careful adjustment of controllers that monitor generating units in the power system to keep frequency deviances within a range of ± 0.1 Hz. To improve performance, metaheuristic optimization methods are exploited to fine-tune the controller gains [15].

1.2 LITERATURE REVIEW

This section comprises the examination of numerous metaheuristic optimization methods along with its benefits and demerits, as seen in Table 1.

Table 1: Analysis of optimization methods.

APPROACHES	BENEFITS	DEMERITS
Gorilla Troops Optimization [16]	❖ It is unpretentious by parameter variations and has better reliability. ❖ Also it offers better performance than others.	Its performance is mainly based on its parameters and poor tuning lead to degradation of system stability.
Hybrid Educational Competition Optimizer With Pattern Search [17]	❖ In dynamic operating conditions, it improves system reliability and stability. ❖ Also. It is robust beside parameter suspicions and real world environments.	This hybrid behaviour improves the computational load. Also, it is difficult for real-time applications with fast response.
Black Widow Optimization [18]	❖ It is unresponsive to variations in parameters and removes the need of controller parameter's resetting. ❖ Also, it has robustness and potency by considering huge difference in load demand.	It has poor tuning that lead to slow convergence and unstable control and its performance is based on the parameters.
Modified SSO Algorithm [19]	❖ It manage the frequency via reduction of Integral Time Absolute Error (ITAE) of frequency deviation. ❖ Also, it has better steady state and transient indices.	It introduces extra mechanisms to enhance convergence that improves computational load.
Flood Algorithm [20]	❖ It efficiently predicts the optimum parameters with better performance. ❖ Also, its convergence behavior has near-optimal solutions.	It is getting trapped in local optima especially in complex multi-area systems with nonlinear constraints.
Hybrid Particle Swarm Optimization–Artificial Hummingbird Algorithm (PSO-AHA) Optimizer [21]	❖ It assures optimized and robust control in LFC. ❖ Also, it offer a reliable and robust solution for improving the stability.	Incorporation of 2 algorithms improves the number of iterations and operations and computation complexity.
Hybrid Grasshopper Optimization Algorithm-Particle Swarm Optimization (GOA-PSO) [22]	It improves stability of system, response time and optimize frequency regulation.	It needs extra computational resources that influence real-time applications. Also, its performance is based on choosing proper parameters that need tuning for diverse systems.

Source: Authors, (2026).

Taking into consideration the above mentioned elements as well as the changing landscape of power system control, the current study uses an advanced LFC approach for a two-area power system that consists of a reheat thermal and a PV system. This setup exemplifies a feasible hybrid power generating situation, which is becoming more prevalent in contemporary networks as they shift to a higher percentage of renewable energy.

1.3 MOTIVATION

It is clear from the discussions and research evaluations that have come before that researchers have mostly concentrated on traditional LFC techniques. However, the importance of incorporating RES into the conventional system keeps growing in order to fulfil the growing demand of energy in a more ecologically responsible way as lifestyles change and conventional energy sources run out, along with shifting supply and demand dynamics. However, because RES are intermittent, integrating like PV panel presents substantial problems to system frequency, requiring the development of sophisticated control systems to meet LFC needs. By decreasing avoidable tie-line power fluctuations and frequency, the developed approach introduces HKM-MSO based PI controller that stabilizes system operation more quickly and effectively.

1.4 CONTRIBUTION

The proposed approach is developed to highlight the below contributions,

- The HKM-MSO based PI controller is incorporated for LFC in a two-area PV–thermal system in order to overcome the dynamic instabilities.
- Here, the PV system is incorporated to each control area of the system to demonstrate its effect on the overall response of the system.

II. PROPOSED METHOD DESCRIPTION

The system integrates PV system in one area with thermal system in another area to attain enhanced stability and performance, as presented in Figure1. In the area-1, the PV system offers clean energy and reacts to a fluctuation in a load via the controller. The HKM-MSO based PI controller in this area monitors deviances in system and regulates the output of PV system, assures the improved regulation of frequency. In the area-2, the thermal system is presented with the governor, the turbine and the reheater.

The governor managing the turbine's output of mechanical power by modifying the steam flow or fuel supply in reaction to frequency variations. The HKM-MSO based PI controller offers better control signals to the governor assuring better operation of optimal coordination between the mechanical and electrical power outputs.

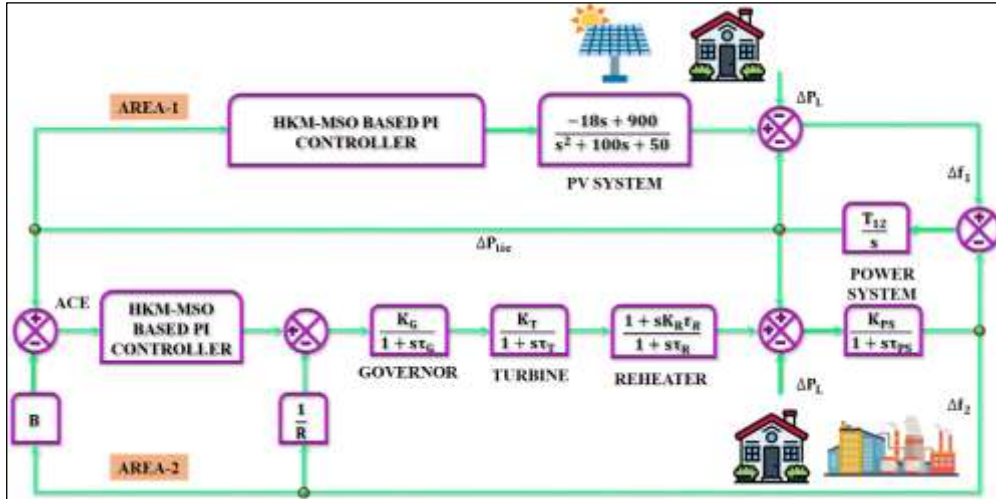


Figure 1: Block diagram of load frequency control in PV-thermal system.

Source: Authors, (2026).

The turbine transforms the mechanical energy to electrical power that is passed to the grid. Then, the turbine and reheater replicate the precise response of mechanical system to manage inputs and enhance the damping of oscillations. The load replicates differences in consumption of electrical power that impact the power system's stability and efficiency. Both areas are connected via a tie-line, enabling mutual power exchange that aids equalize the frequency deviation between regions. Thus, the system presents an adaptive and energy efficient solution for frequency control in power systems.

III. MODELLING OF PROPOSED SYSTEM

III.1 PV-THERMAL POWER SYSTEM

The power system is designated for the realization of LFC process in this research is comprised of 2 areas, known as PV system and a reheat thermal power system, as seen in Figure 2. The reheat thermal power system is comprised of 4 elements as, the governor, the turbine, the reheater and the power system. The first-order transfer functions are, The governor,

$$G_g(s) = \frac{k_g}{1 + s\tau_g} \quad (1)$$

The turbine,

$$G_t(s) = \frac{k_t}{1 + s\tau_t} \quad (2)$$

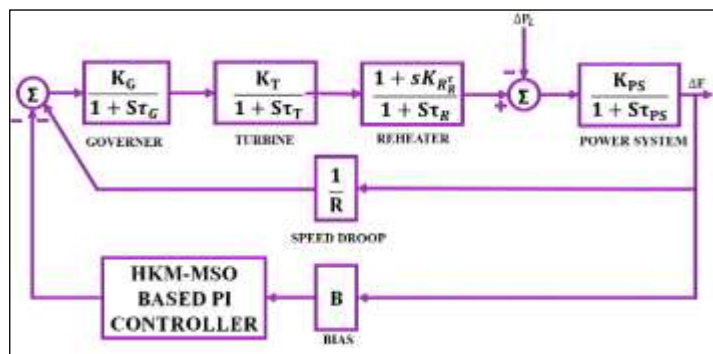


Figure 2: Block diagram of single thermal reheat area.

Source: Authors, (2026).

The reheater,

$$G_r(s) = \frac{1 + s k_r \tau_r}{1 + s \tau_r} \quad (3)$$

The power system,

$$G_{ps}(s) = \frac{k_{ps}}{1 + s\tau_{ps}} \quad (4)$$

Where, the time constant are denoted by $\tau_r, \tau_{ps}, \tau_t$ and τ_g , gain values of power system, reheater, turbine and governor are k_{ps}, k_r, k_t and k_g , tie-line power variation is ΔP_{tie} , frequency bias coefficient is B and regulator parameter is R . The PV system is known as area-1, that produce energy based on amount of temperature and radiation. The environmental conditions provide fluctuations in frequency of the system since the load demand is can't be fulfilled and is resolved by MPPT approach. The produced DC power is transformed into AC power that is utilized by the loads with the aid of inverters. The transfer function (PV system) is,

$$G_{pv}(s) = \frac{-18s+900}{s^2+100s+50} \quad (5)$$

The ACE is estimated as,

$$ACE_1 = \Delta P_{tie} \quad (6)$$

$$ACE_2 = B\Delta f_2 + \Delta P_{tie} \quad (7)$$

Then, the HKM-MSO-PI controller is utilized for resilience against parameter fluctuations and nonlinearities with improved convergence speed.

III.2 HKM-MSO-PI CONTROLLER

The HKM-MSO algorithm is employed to tune k_p and k_i values by incorporating hierarchical cooperative search of Komodo dragons with vision based strategy of mantis shrimps. In the Komodo-Mlipir optimization algorithm, each komodo indicates k_p and k_i values. Here, the population is divided into middle-quality female, high-quality big males and low-quality small males. The small males and female update their positions in the direction of this best individual with exploration and exploitation. The simple optimization problem is,

$$f(x_1, x_2) = x_1^2 + x_2^2 \quad (8)$$

Where, the horizontal and vertical axes are denoted by x_1 and x_2 . A population of komodo individuals $k_1, \dots, k_6$ is randomly initialized each related to distinct k_p and k_i values. This grouping mechanism aids to establish a balance among exploitation and exploration. The number of small males and big males are indicated as,

$$s = n - q \quad (9)$$

$$q = [(p - 1)n] \quad (10)$$

Where, the portion is indicted by p . The big males denote the better k_p and k_i values that provide the lower frequency deviation and quickest settling response. This hierarchical structure imitates the dragons' cooperative behaviour in hunting allows it to efficiently tune k_p and k_i and converge in the direction of effective and stable frequency regulation. The movement of big males has a vital role in refining the search for k_p and k_i values. The flowchart of HKM-MSO-PI controller is illustrated in Figure 3.



Figure 3: Flowchart of HKM-MSO-PI controller.

Source: Authors, (2026).

The big males interact via distraction or attraction governed by high-exploitation low-exploration. A big male with low quality is concerned in the direction of high quality one to enhance its position in the solution space. The big male's new position is,

$$w_{ij} = \begin{cases} r_1(k_j - k_i), & \text{if } f(k_j) < f(k_i) \text{ or } r_2 < 0.5 \\ r_1(k_j - k_i), & \text{otherwise} \end{cases} \quad (11)$$

$$k'_i = k_i + \sum_{j=1}^q w_{ij}, \text{ where } j \neq i, \quad (12)$$

Where, the fitness values are denoted by $f(k_j)$ and (k_i) and random numbers are r_1 and r_2 . When big males are exist, the lower quality males are perform exploitation while higher quality males are alternates among exploration and exploitation. This dynamic interaction provides the better tuning of k_p and k_i values to attain enhanced load frequency stability. The female komodo is responsible for maintaining balance among exploration and exploitation. The female strengthens the search over the global optimum by mating with the winner big male to produce 2 novel positions as,

$$k'_{il} = r_1 k_{il} + (1 - r_1) \cdot k_{jl} \quad (13)$$

$$k'_{jl} = r_1 k_{jl} + (1 - r_1) \cdot k_{il} \quad (14)$$

Where, the winner big female and male are indicated by k_{jl} and k_{il} and random number is r_1 . In the exploration phase, the female undergoes parthenogenesis to explore unexplored areas by changing its dimensions as,

$$k'_{ij} = k_{ij} + (2r - 1)\alpha|ub_j - lb_j| \quad (15)$$

$$(k_{i1}, k_{i2}, \dots, k_{im}) \rightarrow (k'_{i1}, k'_{i2}, \dots, k'_{im}) \quad (16)$$

Where, the position vector of female is denoted by k_{ij} , upper and lower bounds are ub_j and lb_j . This process produces novel k_p and k_i values near the present area allows the wider exploration and averting premature convergence. The natural trait algorithm is indicated as a movement of small males that enables this males to widely search while performing exploitation. Each small male adjust its position based on big males by,

$$w_{ij} = \begin{cases} \sum_{l=1}^m r_1(k_{jl} - k_{il}), & \text{if } r_2 < d \\ 0, & \text{Otherwise} \end{cases} \quad (17)$$

$$k'_i = k_i + \sum_{j=1}^q w_{ij} \quad (18)$$

Here, r_1 governs velocity of the movement while r_2 predicts dimension. This Mlipir mechanism aids to explore a broader range of k_p and k_i values averting local minima while enabling refinement near better regions. The population adaptation scheme dynamically balances the exploration and exploitation. The new population size is,

$$n' = \begin{cases} n - a, & \text{if } \delta f_1 > 0 \text{ and } \delta f_2 > 0 \\ n + a, & \text{if } \delta f_1 = 0 \text{ and } \delta f_2 = 0 \end{cases} \quad (19)$$

$$\delta f_1 = \frac{|f_1 - f_2|}{f_1} \quad (20)$$

$$\delta f_2 = \frac{|f_2 - f_3|}{f_2} \quad (21)$$

Where, the number of individual is a , the fitness differences are δf_1 and δf_2 . This scheme allows the KMA to reduce redundancy during convergence and widening diversity. It efficiently tunes k_p and k_i values assures the reduced steady state error, quicker frequency response and load frequency regulation in PV-thermal systems. In the Mantis Shrimp Optimization algorithm, each Mantis Shrimp denotes the particular set of k_p and k_i values with in the search space. The initialization phase represented by,

$$X_{i,j} = lb_{1,j} + rand_{i,j} \cdot (ub_{1,j} - lb_{1,j}) \text{ for } j = 1, 2, \dots, dim, i = 1, 2, \dots, N \quad (22)$$

Where, the upper and lower limits are denoted by $ub_{1,j}$ and $lb_{1,j}$. It assures the distinct set of k_p and k_i values for exploration. Then, the polarization type indicator (PTI) vector is produced for each Mantis Shrimp, mimicking the ability of Shrimp to predict and interpret polarized light in distinct stages. By dynamically adjusting the PTI values throughout the iterations, this algorithm alternates among exploration and exploitation enables the population to efficiently traverse and refine the gain space. Through repeated updates directed by polarization based behavioural switching, this algorithm converges in the direction of optimal k_p and k_i values that yield reduced overshoot and improved stability in PV- thermal power system. The foraging strategy is stimulated by behaviour of Shrimp for searching food that is implied with the generalized Langevin equation as,

$$x_{best} - v + D.R(t) = x_i(t + 1) \quad (23)$$

$$v = x_i(t) - x_{best} \quad (24)$$

$$R(t) = x_r(t) - x_i(t) \quad (25)$$

Where, the present optimal solution is x_{best} , updated position is $x_i(t + 1)$, velocity is v , diffusion constant is D and random force is $R(t)$. With the aid of this phase, the mantis shrimp explore numerous regions of k_p and k_i values that averts premature convergence in local optima. The attack phase is simulated by shrimp's striking behaviour that exploits the area around the present best solution. Each individual updates its position along a circular motion trajectory toward the optimal solution.

$$x_i(t + 1) = x_{best} * \cos\theta \quad (26)$$

Where, the randomly generated attack angle is θ . The defense or Shelter phase aiding individuals to avert poor regions while local exploration. The update of position is,

$$x_i(t + 1) = x_{best} + k * (x_{best}), k \in [0,0.3] \quad (27)$$

$$x_i(t + 1) = x_{best} - k * (x_{best}), k \in [0,0.3] \quad (28)$$

Where, the randomly generated scaling factor is k . In the Komodo-Mlipir optimization algorithm, big males exploit high quality regions with a exploration strategy to refine better k_p and k_i values. Females either perform sexual reproduction with the best big male to strengthen search near optimal solutions. Small males execute their Mlipir movement to broadly explore while exploiting nearby better solutions. Meanwhile, in the mantis shrimp optimization algorithm, the foraging allows global exploration, attack phase focuses search near the best solutions and defense or shelter offers local diversification. Overall, the HKM-MSO algorithm predicts the optimal k_p and k_i values that reduce frequency deviation and assure stable load frequency control in PV-thermal power system.

IV. RESULT AND DISCUSSIONS

The performance of HKM-MSO PI controller is assessed via simulation outcomes in distinct scenarios in MATLAB/SIMULINK tool. Also, it comprises the analysis with existing approaches to show the proficiency of developed system.

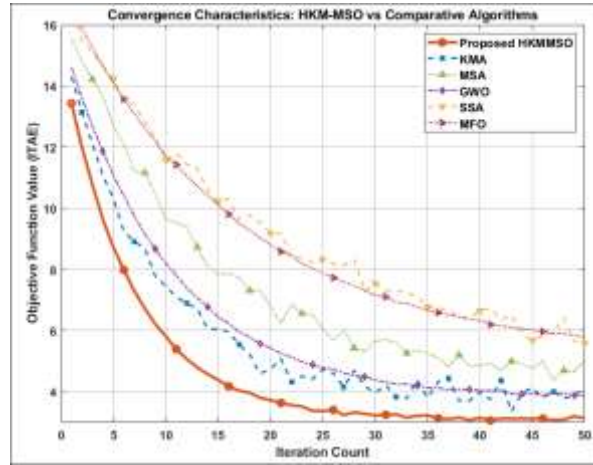


Figure 4: Convergence characteristics.

Source: Authors, (2026).

The HKM-MSO algorithm's convergence characteristics are displayed in figure 4 in comparison to other optimization techniques as Komodo Mlipir Algorithm (KMA), Grey Wolf Optimization (GWO), Moth-Flame Optimization (MFO), Salp Swarm Algorithm (SSA) and Mantis Shrimp Algorithm (MSA). Within the first few iterations, the HKM-MSO shows a steeper and faster drop in ITAE values, indicating higher optimization efficiency and quick convergence. In contrast to the other algorithms, HKM-MSO exhibits improved exploration and exploitation balance by rapidly reaching a minimal and stable objective function value with little oscillations. The outcomes demonstrate that HKM-MSO outperforms in convergence speed and control parameter tuning performance, guaranteeing efficient load frequency stability.

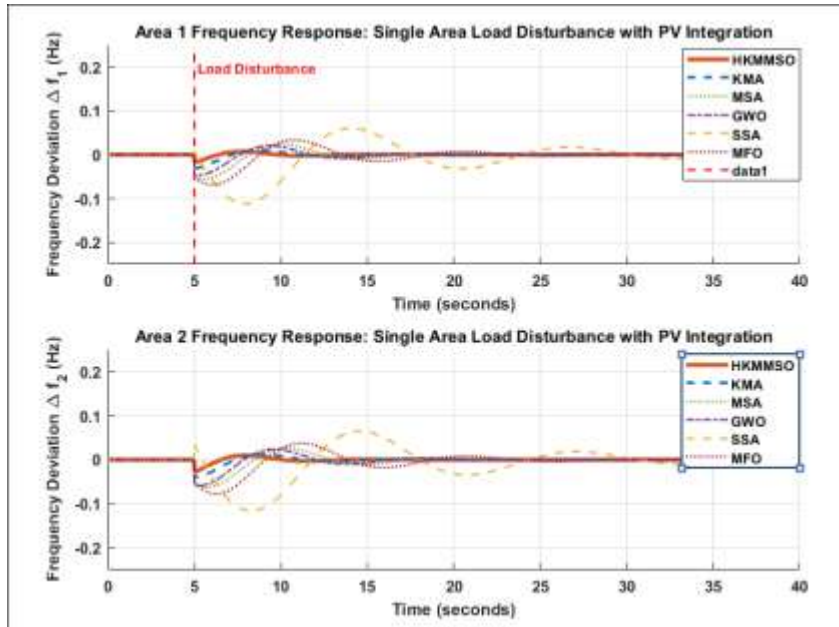


Figure 5: Frequency response of area 1 and 2.
Source: Authors, (2026).

The frequency deviation responses of both interconnected areas in a PV-integrated system under a single-area load disturbance are depicted in the Figure 5. A sudden load disruption is applied at 5 seconds, resulting in observable frequency variations. Compared to KMA, MSA, GWO, SSA and MFO, the HKM-MSO-based PI controller stabilizes the system more quickly and shows the quickest recovery and least amount of overshoot/undershoot. Weaker disturbance rejection is shown by slower damping and stronger oscillations in other techniques. The HKM-MSO's superior dynamic stability, resilience and coordination in managing frequency deviations under PV generating variability are confirmed by its capacity to efficiently limit transient fluctuations and guarantee smooth frequency deviations in both areas.

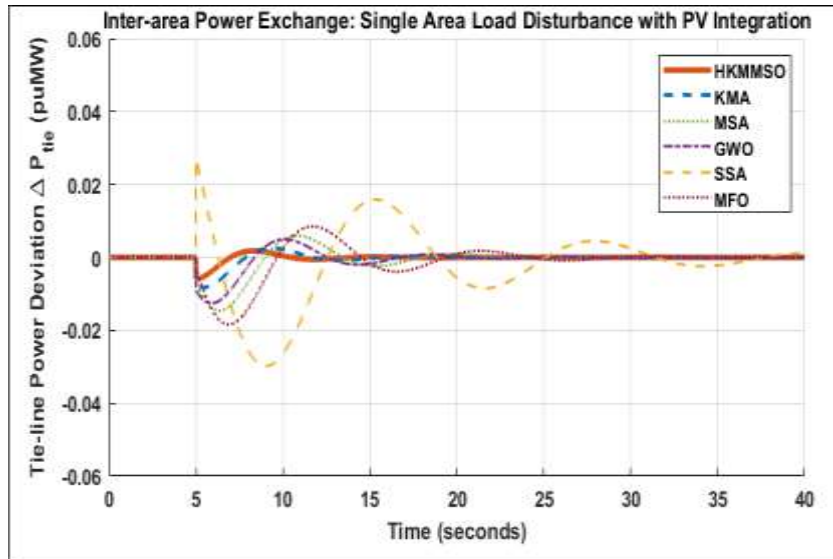


Figure 6: Inter area power exchange.
Source: Authors, (2026).

The response of inter-area power exchange in a PV-integrated system to a single-area load disturbance is shown in the figure 6. There are discernible variations in the tie-line power flow when the disturbance appears at 5 seconds. Strong synchronization between the two regions is demonstrated by the HKM-MSO-based controller that attains quicker damping and reduced amplitude variations. Other algorithms, including SSA and MFO has delayed settling and more oscillations. Fast restoration of steady-state tie-line power with less overshoot is guaranteed by the HKM-MSO, denoting improved coordination and fewer inter-area oscillations. In comparison to current techniques, the developed controller offers better stability, more seamless power exchange and strong dynamic performance under load disturbances.

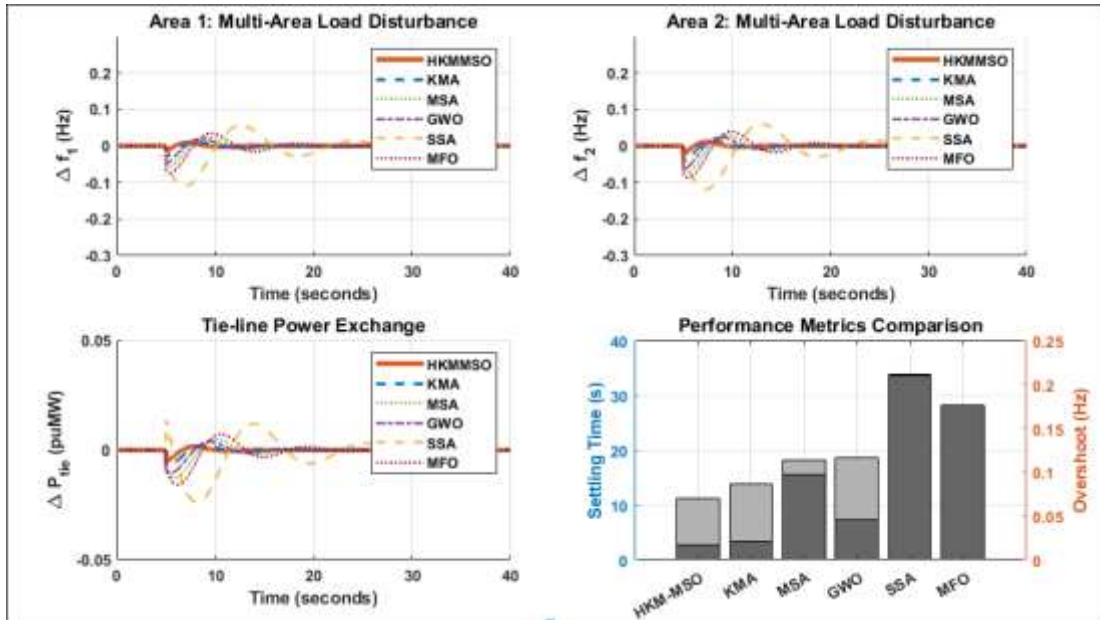


Figure 7: Performance of algorithms.
Source: Authors, (2026).

The dynamic performance of various metaheuristic optimization techniques for load frequency management is compared in the figure 7. The frequency variations f_1 and f_2 over time in two distinct places after a load disturbance are displayed in the top-left and right graphs. The tie-line power exchange among the locations is depicted in the bottom-left graph. With less overshoot and faster settling, the HKM-MSO algorithm shows the fastest and most steady response. It highlights that HKM-MSO attains the lowest overshoot and settling time values.

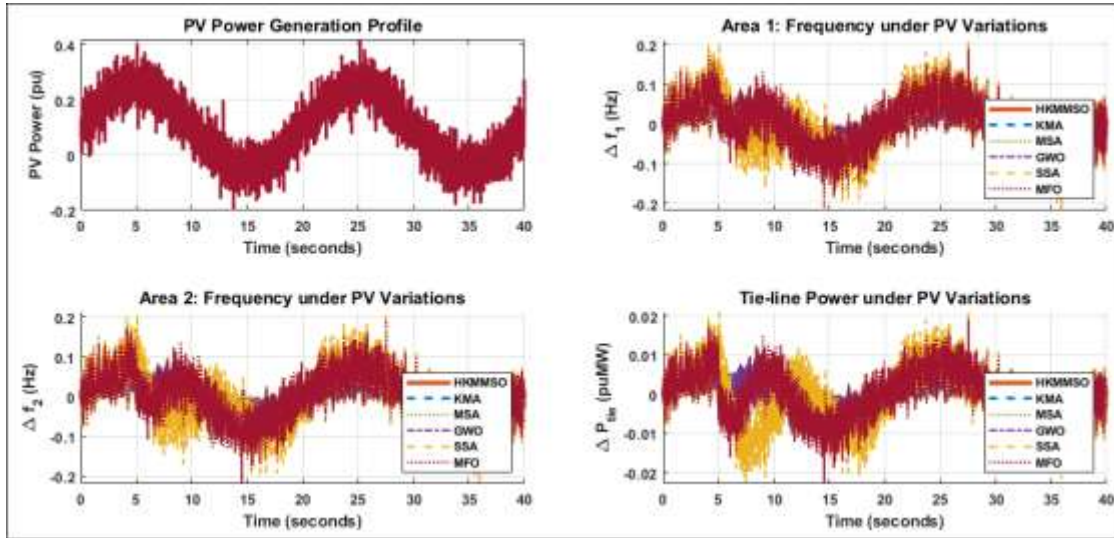


Figure 8: Performance of PV system.
Source: Authors, (2026).

The main disruption to the system is the extremely fluctuating power production from PV source is presented in Figure 8. The tie-line power flow deviation is displayed in the bottom-right graph, while the frequency deviations in Area 2 and 1 are presented in the top-right and bottom-left graphs. Performance of the HKM-MSO optimized controller is the most efficient in all three graphs. In comparison to the other approaches, it shows better dynamic response and stability under PV power fluctuations with fewer frequency deviations and quicker settling time.

Table 2: Performance Metrics in Single Area Load Disturbance.

Approaches	Settling time (t_s) in s			Maximum Overshoot (MO) in Hz			ITAE	ISE
	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}		
KMA	12.70	18.00	16.40	0.0216	0.0497	0.0432	0.06810	0.01820
MSA	16.25	21.55	19.95	0.0800	0.1840	0.1600	0.12560	0.04560
GWO	15.03	20.32	18.73	0.0471	0.1083	0.0942	0.09870	0.03210
SSA	33.11	38.41	36.81	0.2390	0.5497	0.4780	0.23450	0.08970
MFO	25.52	30.82	29.22	0.1640	0.3772	0.3280	0.18720	0.06730
HKM-MSO	10.50	15.80	14.20	0.0156	0.0359	0.0312	0.01250	0.04520

Source: Authors, (2026).

The HKM-MSO approach performs better than KMA, MSA, GWO, SSA and MFO in regulating load frequency, as seen in Table 2. With the quickest settling time of 10.50 seconds, the HKM-MSO outperforms the KMA, which takes 12.70seconds. The HKM-MSO method also minimizes maximum overshoot with values of 0.0216 and 0.0497 for frequency deviations in the two areas, indicating a steadier and less oscillatory system response. Additionally, HKM-MSO produces the lowest ITAE and Integral Square Error (ISE) values of 0.01250 and 0.04520, proving its superiority. It is very efficient, providing the power system with the quickest stabilization with the least amount of oscillations.

Table 3: Performance Metrics in Multi-Area Load Disturbance.

Approaches	$t_s(s)$			MO(Hz)			ITAE	ISE
	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}		
KMA	13.88	18.98	19.18	0.0207	0.0497	0.0269	0.07150	0.01950
MSA	18.20	23.30	23.50	0.0976	0.2342	0.1269	0.13420	0.05120
GWO	18.52	23.62	23.82	0.0456	0.1094	0.0593	0.10560	0.03680
SSA	33.73	38.83	39.03	0.2100	0.5040	0.2730	0.24890	0.09560
MFO	25.84	30.94	31.14	0.1760	0.4224	0.2288	0.19870	0.07210
HKM-MSO	11.20	16.30	16.50	0.0168	0.0403	0.0218	0.04870	0.01380

Source: Authors, (2026).

Table 3 represents the performance metrics in multi-area load disturbance condition. The HKM-MSO has the lowest setting time of 11.20s than KMA, MSA, GWO, SSA and MFO. Moreover, the HKM-MSO minimizes system oscillations with reduced MO for both frequency deviations. It has the lowest ITAE and ISE values of 0.04870 and 0.01380, denoting that it reduces errors assuring stable load frequency control.

Table 4: Performance Metrics in PV Variation Scenario.

Approaches	$t_s(s)$		MO(Hz)		ITAE	ISE
	Δf_1	Δf_2	Δf_1	Δf_2		
KMA	14.80	19.60	0.0230	0.0506	0.07890	0.02180
MSA	19.10	23.90	0.1050	0.2310	0.14560	0.05890
GWO	19.80	24.60	0.0520	0.1144	0.11560	0.04120
SSA	35.20	40.00	0.2280	0.5016	0.26780	0.10230
MFO	27.30	32.10	0.1880	0.4136	0.21340	0.07890
HKM-MSO	12.50	17.30	0.0180	0.0396	0.05430	0.01560

Source: Authors, (2026).

The performance Metrics in PV variation Scenario is displayed in table 4. The settling time of 12.50s and MO of 17.30s is attained by the HKM-MSO algorithm. Moreover, the HKM-MSO approach has low value of 0.05430 for ITAE and 0.01560 for ISE, representing it properly regulates the system among KMA, MSA, GWO, SSA and MFO approaches.

Table 5: Performance Metrics in Nonlinearity Scenario.

Approaches	$t_s(s)$		MO(Hz)		ITAE	ISE
	Δf_1	Δf_2	Δf_1	Δf_2		
KMA	15.50	21.00	0.0250	0.0625	0.08340	0.02350
MSA	20.10	25.60	0.1120	0.2800	0.15230	0.06230
GWO	20.80	26.30	0.0580	0.1450	0.12340	0.04560
SSA	36.50	42.00	0.2450	0.6125	0.27890	0.10890
MFO	28.70	34.20	0.2010	0.5025	0.22560	0.08560
HKM-MSO	13.20	18.70	0.0190	0.0475	0.05890	0.01680

Source: Authors, (2026).

Table 5 reveals the performance metrics in nonlinearity scenario. The HKM-MSO algorithm attains the better setting time of 13.20s than KMA, MSA, GWO, SSA and MFO approaches. The SSA has the setting time of 36.5s, denotes its ability to stabilize the system quickly. It also reduce the oscillations with MO of 18.70s. The lowest ITAE and ISE of 0.05890 and 0.01680, highlighting its efficacy in reducing steady state error.

Table 6: Parameters of PI controller.

Algorithm	k_p	k_i
KMA	-0.5235	-0.0973
MSA	-0.4563	-0.2254
GWO	-0.6671	-0.5477
SSA	-0.5156	-0.9012
MFO	-0.5663	-0.4024
HKM-MSO	-0.6235	-0.0873

Source: Authors, (2026).

The gain values of KMA, MSA, GWO, SSA, MFO and HKM-MSO approaches are shown in Table 6. The HKM-MSO has better k_p and k_i values of -0.6235 and -0.0873. It contributes to the reduced oscillations and quickest system response outperformed than KMA, MSA, GWO, SSA and MFO approaches.

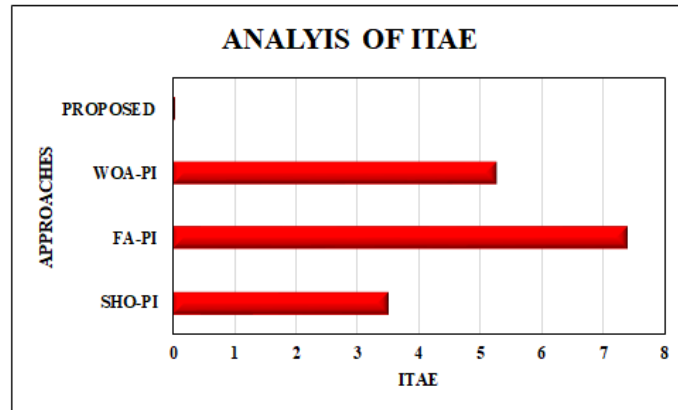


Figure 9: Analysis of ITAE.
Source: Authors, (2026).

An analysis of ITAE for PI controller approaches like Sea Horse Optimization (SHO) [23], Firefly Algorithm (FA) [24], Whale Optimization Algorithm (WOA) [25] and proposed approach is depicted in Figure 9. The HKM-MSO has better ITAE value of 0.04520 than SHO, FA and WOA (3.505, 7.3783 and 5.2619), indicating fast transient response and minimal long-term steady-state error.

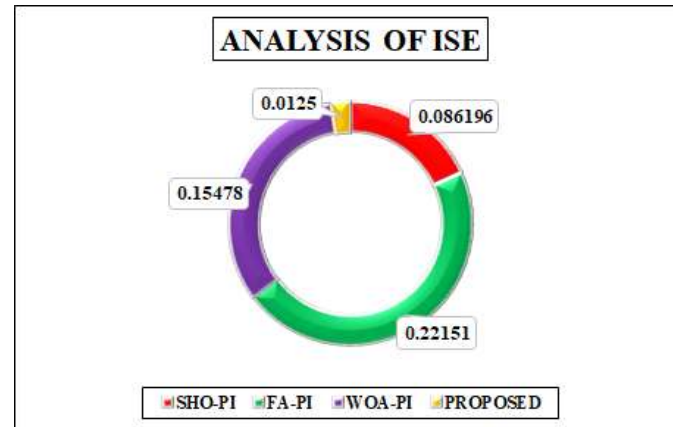


Figure 10: Analysis of ISE.
Source: Authors, (2026).

Figure 10 represents an analysis of ISE for SHO [23], FA [24], WOA [25] and proposed approach. The lowest ISE of 0.01250 is attained by HKM-MSO approach, denoting the performance is improved for better of load frequency control.

V. CONCLUSION

This research presents the technique of LFC in PV–thermal system to overcome the dynamic instabilities. The incorporation of HKM-MSO based PI controller allows quicker stabilization, reduced overshoot and settling time for tie-line power and frequency deviations. It also has robustness and maintain stability in distinct operating conditions while facing difficulties in PV-thermal power system. The HKM-MSO–PI controller outperforms traditional PI controllers, based on extensive simulation in MATLAB/SIMULINK tool that comprise abrupt load perturbations, parametric uncertainties and nonlinear system conditions. The outcomes reveals the significant improvement in time-domain performance like better dynamic response with quick abolition of oscillations with settling time with 10.5s and overshoot of 0.0156. The proposed approach may be assessed in more difficult applications like wind turbines and electric vehicles in the future work.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Pramod Kumar Gouda, Jammu Lepakshi and V V Appalanaidu Menda.

Methodology Pramod Kumar Gouda and Jammu Lepakshi.

Investigation: Pramod Kumar Gouda and Jammu Lepakshi.

Discussion of results: Pramod Kumar Gouda, Jammu Lepakshi and V V Appalanaidu Menda.

Writing – Original Draft: Pramod Kumar Gouda.

Writing – Review and Editing: Pramod Kumar Gouda and Jammu Lepakshi.

Resources: Jammu Lepakshi.

Supervision: Jammu Lepakshi and V V Appalanaidu Menda.

Approval of the final text: Pramod Kumar Gouda, Jammu Lepakshi and V V Appalanaidu Menda.

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