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Hybrid intelligent optimization algorithms-based power management for microgrid system

R. Indumathi[1], S. A. Lakshmanan[2]
[1]Department of Electrical and Electronics Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Chennai, India
[2]Department of Electronics and Communication Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Chennai, India

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ABSTRACT

The integration of the photovoltaic (PV) and wind sources of power in microgrids is a beneficial method toward decentralized, efficient, and sustainable energy management. This research endeavors to develop and implement a novel hybrid control strategy that efficiently combines grey wolf optimization (GWO) and particle swarm optimization (PSO) algorithms for the optimization of renewable energy-based microgrids. The proposed method addresses three critical tasks under one integrated control mechanism: i) maximum power point tracking (MPPT) for PV and wind systems under fluctuating environmental conditions, ii) smart management of energy storage systems for batteries, and iii) adaptive load scheduling based on real-time availability of energy. By leveraging the complementary strengths of GWO and PSO, the system enjoys improved convergence rate, global search, and decision-making robustness. The hybrid controller is tested and validated through thorough testing in MATLAB/Simulink under dynamic simulation scenarios that mimic sudden weather and load variations. Comparative performance with conventional methods and benchmarking based on IEEE 516 standards demonstrates the improved reliability, responsiveness, and energy efficiency of the proposed system. This research contributes to the state-of-the-art of intelligent microgrid control through an integrated, bio-inspired solution toward resilient and optimized energy management.

Corresponding Author:

Dr. S. A. Lakshmanan
Department of Electronics and Communication Engineering, Amrita School of Engineering
Amrita Vishwa Vidyapeetham
Chennai, India
Email: sa_lakshman@ch.amrita.edu

1. INTRODUCTION

Renewable power generation currently fulfils 30% of the world's electricity demand [1], and renewable energy systems (RES) have emerged as vital solutions to counter environmental issues and increase global energy demand. These systems face challenges such as intermittency, voltage stability, power quality, and the economic viability of new technologies on a large scale. Innovations such as hybrid energy storage systems (HESS), fuzzy logic controllers, and economic optimization of RES counter these issues and contribute to the growth and efficiency of their use. HESS integrates batteries and supercapacitors [2]. Full-bridge bidirectional DC-DC converters provide a constant DC bus voltage by using voltage and current control loops [3]. Physical embedding of hydrogen storage technologies offers a feasible solution to satisfy fluctuating grid demand and supply needs [4]. These innovations have overcome intermittency problems associated with stalled renewable power sources [5]. Enhancing the power quality is another key factor. Adaptive power control (APC) solutions using fuzzy logic controllers (FLC) counter adaptive power distribution problems [6], improve power quality, and minimize operational losses. Dynamic power management systems balance the generation and load [7] to enhance viability and lower costs. Perturb and observe (P&O) algorithms improve power delivery and control, and stabilize systems tracking maximum power point tracking (MPPT) [8]. Hybrid PV-wind systems using MPPT and better energy storage technology effectively control renewable energy instability [9], [10] to provide constant power flow and stabilize grid power strength [11].

Renewable energy systems have retained their economic viability and system conversion efficiency as success parameters. Microgrid systems incorporate extensive energy management operations [12], [13] increase power dispatch to locals, lower costs, and enhance efficiency [14]. Three-dimensional metal-organic framework hydrogen storage systems offer efficient energy storage solutions [15], while electrolyzers and fuel cells enhance energy sheets and reduce CO2 emissions [16]. Battery-supercapacitor systems, coupled with research on new storage solutions [17], enhance energy storage and reduce operational costs [18]. These advancements ensure the efficacy and storability of renewable energy systems [19], enabling a global shift towards sustainable and resilient energy systems [20]-[23].

Renewable energy (RE) systems can potentially revolutionize global energy systems that are presently fossil-fuel-based. These systems have attained greater efficiency, reliability, and economic effectiveness by addressing key challenges, such as HESS [24], MPPT [25], and hydrogen storage [26], [27]. As research and development continue to widen existing possibilities [28]. Renewable energy systems will play a vital role in building a sustainable future [29], [30]. They will also reduce environmental degradation and address the growing demand for energy. Until now, using smart energy management, mixed intelligent solar controllers and new multilevel inverters has provided important upgrades in how efficiently the system pulls from the sun, integrates with the grid and works overall [31]-[33].

Research gap: Despite the progress in harnessing renewable energy systems, gaps remain. Controlling the mismatch between renewable energy sources to form a stable grid requires improved algorithms and control schemes. Although MPPT and HESS methods are helpful, they require refinement for scalability and real-time control. The development of future energy storage systems, such as hydrogen storage, requires further research to improve efficiency and economic viability. Pilot studies to complement these technologies and to test them under various conditions are lacking. An artificial neural cluster analysis has shown that filling these gaps is crucial for a sustainable and efficient energy system.

Scope for future research: Future research should explore an integrated energy system with advanced storage, intelligent control, and real-time algorithms. The development of new materials and storage designs can increase efficiency and sustainability. Using microgrid systems with decentralized facilities and distributed energy management will enhance neighborhood energy efficiency and reduce reliance on large power grids. Large-scale pilot studies are necessary to assess the cost, performance, and viability in various settings. These research directions can further advance renewable energy systems and enhance prospects for cleaner environments.

The remainder of this paper is organized as follows: i) Section 2 discusses the hybrid modeling of the hybrid intelligence algorithm (PSO + GWO), including its merits and mathematical evaluations; ii) Section 3 discusses the creation of a hybrid intelligent MPPT algorithm for maximum power generation under different weather conditions used in the modeling of PV and wind energy systems in a MATLAB environment; iii) Section 4 explains the hybrid intelligent algorithm for battery and load management systems and the proposed hybrid PV and wind systems with energy storage for microgrid integration; and iv) Finally, section 5 presents our conclusions.

2. HYBRID INTELLIGENT ALGORITHM PSO + GWO

Grey wolf optimizer (GWO) mimics grey wolves' hierarchical leadership and hunting strategies. It effectively explores the search space but sometimes struggles with premature convergence. Particle swarm optimization (PSO) models the social behavior of particles to determine optimal solutions. It excels in local exploitation, but may fail to escape local optima. The aim of hybridizing these algorithms is to:

- Combination of the early stages of GWO exploration with a later-stage PSO convergence rate.
- The search process was optimized by adaptively changing the position and velocity updates.
- Improvement in robustness and solution accuracy for complex optimization problems.

$$x_{(t+1)} = \frac{x_1+x_2+x_3}{3} \tag{1}$$

$$X_1 = X_\alpha - A_1 \cdot |C_1 X_\alpha - X| \tag{2}$$

$$X_2 = X_\beta - A_2 .|C_2 X_\beta - X| \tag{3}$$

$$X_3 = X_\delta - A_3 .|C_3 X_\delta - X| \tag{4}$$

Update A, C, a:

$$A = 2a.r1\text{-}a,\ C = 2.r2 \tag{5}$$

a decrease linearly over the iterations to balance exploration and exploitation.

PSO velocity and position updates (exploitation phase). PSO dynamics are introduced in the GWO population by updating the velocities and positions of the particles.

$$V_i\,(t+1) = w.V_i(\text{t}) + C_1.r_1.(P_i\text{-}X_i) + C_2.r_2.(\text{g -}X_i) \tag{6}$$

$$X_i\,(t+1) = X_i(\text{t}) + V_i\,(t+1) \tag{7}$$

Where:
P_i : Personal best position of particle.
g: Global best position.
w is the inertia weight that controls the balance between exploration and exploitation.
C_1 , C_2: Cognitive and social coefficients.
r_1, r_2 : Random numbers in [0, 1].

Hybrid position update. GWO and PSO are blended into a single hybrid position equation as (8):

$$X_i\,(t+1) = X_i(\text{t}) + V_i\,(t+1) + (1\text{-w}).\frac{X_\alpha + X_\beta + X_\delta}{3} \tag{8}$$

where ω: weighting factor for combining GWO and PSO.

- Enhanced hybrid dynamics

To enhance the hybrid algorithm further, we considered the following advanced techniques: adaptive weighting for hybridization:

$$\text{W(t)} = w_{min} + \frac{w_{max} - w_{min}}{max.iter} \text{ . t} \tag{9}$$

Initiate with higher GWO influence (w_{max}) and then decrease it to that of PSO (w_{min}).

Exploration and exploitation dynamic control: If stagnation is observed, restart a portion of the particles/wolves to get away from the local extremities, weighting for hybridization. Start with higher GWO influence (w_{max}) and gradually shift towards PSO (w_{min}).

$$\text{a(t)} = a_{initial}(1 - \frac{t}{max.iter})\text{p} \tag{10}$$

Where p controls the nonlinearity of the reduction.

The novel GWO–PSO hybrid algorithm proposed in this paper combines dynamic role assignment, nonlinear parameter reduction, and a restart mechanism to achieve a balanced and efficient optimization process. A population of 10–30 wolves/particles is initialized, and key parameters are defined, such as the PSO inertia weight between 0.4 and 0.9, cognitive and social coefficients between 1.5 and 2.0, and the GWO leadership structure α, β, δ. The fitness function is set based on the application, such as maximizing power in MPPT or minimizing the energy mismatch for battery/load control. The GWO parameter α normally undergoes a nonlinear reduction using a function like:

$$\text{a(t)=2(1−(t/T)}^{k}) \tag{11}$$

which maintains strong exploration during initial iterations and promotes exploitation as the search progresses. After parameter scheduling, the algorithm evaluates all individuals and sorts them according to fitness. The best individuals occupy the positions of α, β, and δ, and lead the exploitation by GWO update rules. The rest of the population dynamically switches between GWO and PSO according to their performance: if the fitness of an individual improves, it keeps using the GWO update; otherwise, it switches to PSO to benefit from velocity-based exploration. This adaptive behavior enables efficient movement across the search space while refining the promising areas. The algorithm then iteratively checks for stagnation in each update cycle. When no improvement in the global-best fitness has occurred over several iterations, about 10-20% of the poorest individuals are reinitialized by the restart mechanism while keeping the elite solutions. The algorithm terminates when maximum iterations are reached or when convergence is achieved.

3. HYBRID GWO/PSO-BASED MPPT ALGORITHM FOR PV SYSTEM

This paper presents a novel algorithm that integrates GWO and PSO to determine the optimal duty cycle for MPPT in photovoltaic (PV) systems. The process is initiated with parameter configuration for both algorithms, including iterations, number of wolves and particles, and search space range. The GWO employs the hunting strategy of wolves to perform a coarse search for the duty cycle and evaluate fitness using a power-based function. The three top wolves were designated as alpha, beta, and delta, with the values updated in each iteration. PSO refines the results by identifying a potential solution using GWO. During PSO, each particle updates its position and velocity based on its best solution and the best solution identified by the other particles, as indicated by the GWO. This methodology balances exploration and exploitation within a solution space. The fitness function computed the simulated power output for the maximum power of the PV system. Following nested optimization loops, the algorithm selects the duty cycle to produce the optimal solution. Helper functions constrain the positions within the search space and adjust the fitness and positions of the wolves and particles, ensuring effective convergence to the optimal duty cycle. Figure 1 shows the flowchart for hybrid GWO and PSO-based PV and PV MPPT power waveforms under various irradiations.

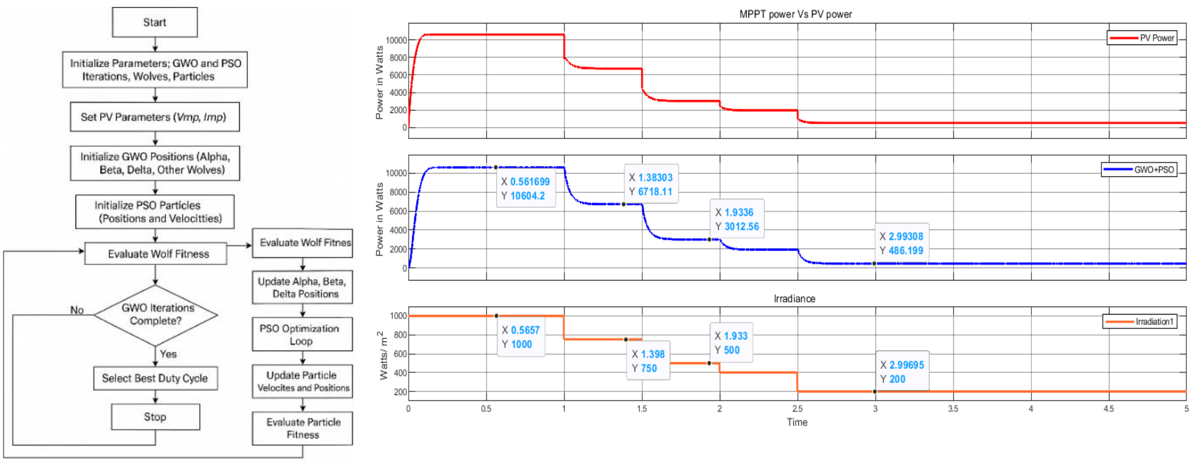

Figure 1. Flowchart for hybrid GWO and PSO-based PV and PV MPPT power waveforms under various irradiation conditions

The hybrid MPPT algorithm includes GWO and PSO.

i) The function of GWO is to:
- GWO looks at the entire search space worldwide to find where the highest quality is most likely to be found.
- It runs automatically for a number of specified iterations (GWO-iterations).
- GWO keeps three best solutions (alpha, beta, delta) and updates the positions of all the wolves subsequently.
- After GWO ends, the best solution (s) are provided which will start the process in PSO.

ii) Transition point:
- GWO finishes an iteration before being replaced by PSO.
- The top wolf's or alpha wolf's positions (one if single top wolf, many if top wolves are a group) chosen among the wolves are used as the initial location(s) of the particles.

iii) Function and purpose of a PSO:
- Now, PSO works in this region and focuses more on finding a better solution within it.
- Velocity updating and using personal and global best solutions guide its progress towards the solution.
- The result is faster convergence and the ability to bypass local minima issues.
- It is clear from able1 that the grey wolf + PSO gets a better score than GA+PSO, mostly because it provides better solar tracking abilities. Comparative analyses of Various intelligent MPPT algorithms for PV presented in Table 1.

The mean is 10608.07, and it has a very low standard deviation of about 0.82, which means that there is little variation from run to run presented in Table 2. The best-case seen is 10609, and the worst case is 10607, giving a very small performance range of only 2 units. All these measures as a whole indicate that the algorithm provides consistent and reliable results under repeated runs.

Table 1. Comparative analyses of various intelligent MPPT algorithms for PV

Irradiance	GWO	PSO	GA	GA+PSO	Grey wolf + PSO
1000	8669.78	9763.28	8662.36	10549.1	10607
750	4848.65	5496.51	4687.97	6444.94	6717.41
500	2076.45	2466.7	2046.22	3029.9	3159.62
400	1435.96	1574.84	1369.72	1944.42	1977.28
200	368.628	397.62	361.309	519.579	546.268

Table 2. Statistical metrics

Irradiance	Grey wolf + PSO
Mean	10608.7
Standard deviation	0.82
Best case	10609
Worst case	10607

4. HYBRID GWO/PSO-BASED MPPT ALGORITHM FOR WIND SYSTEM

A metaheuristic GWO-PSO was implemented to optimally determine the duty cycle that maximizes the output power in a wind energy system using parameters such as wind voltage and current. The algorithm sets the following parameters for GWO and PSO: number of iterations, wolves in GWO, and particles in PSO. The search space is quantized in two dimensions: the duty cycle and another system parameter, with the positions and velocities initialized randomly. The GWO phase conducts optimization by mimicking wolf hunting behavior. A fitness function assesses the position of each wolf by indicating how well it optimizes the power output. Wolves are ranked by fitness, and the three fit tests are selected iteratively to create new packs moving towards the solution space. This phase produces an alpha position, which represents the best candidate solution.

The PSO phase refines the solution by imitating the social and cognitive behaviors of the particles. The velocity and position of each particle are determined by its best-known position, the alpha position from the GWO, and a randomly weighted component that promotes diverse solutions. After updating, the particle fitness values were re-evaluated, and the best-known positions were updated accordingly. GWO is incorporated into a loop that contributes to the global search, whereas PSO fine-tunes the local environment. Among the optimal solutions, the optimal duty cycle was selected as the final solution. This process includes a sortie variable; fitness evaluation; alpha, beta, and delta positions; clamping particle positions; and examining duty cycle-power relationships. The algorithm structure is well-defined; however, the fitness evaluation function, wind system modelling function, and constraints must be developed for a specific wind energy system. Figure 2 (see Appendix) the flowchart for hybrid GWO and PSO for wind system. Figure 3 shows the power waveform of hybrid GWO and PSO-based wind MPPT. Figure 4 displays the simulated voltage and current waveform of hybrid GWO and PSO-based wind MPPT.

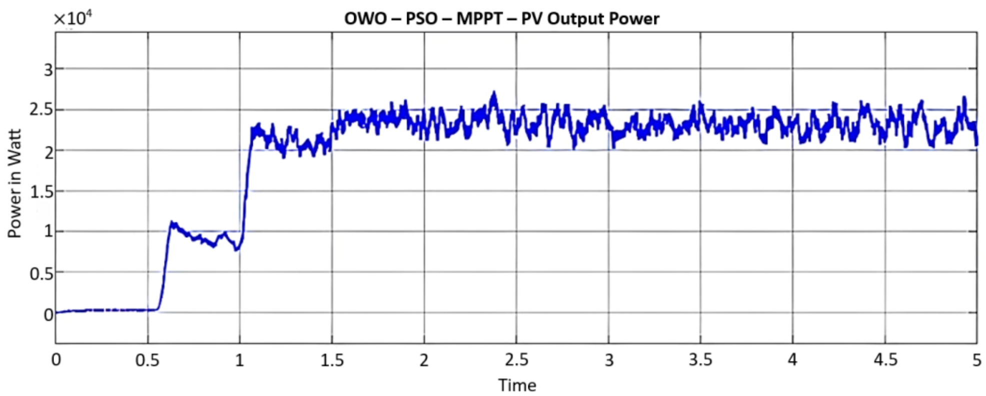

Figure 3. Hybrid GWO and PSO-based wind MPPT power waveform

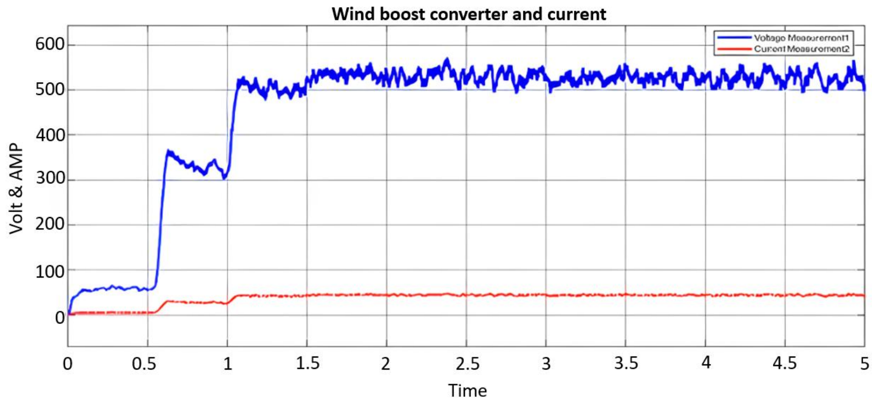

Figure 4. Hybrid GWO and PSO-based wind MPPT voltage and current waveform

5. LOAD AND BATTERY MANAGEMENT

The function manages the load with GWO and uses the GWO algorithm to dispatch among three loads categorized by priority based on available renewable power. These loads are divided into high-, medium-, and low-priority loads with power demands of 1000 W, 10,000, and 18,000 W, respectively. The algorithm aims to fully utilize renewable power and avoid idle power by determining the positions of three circuit breakers (CB1, CB2, and CB3). The GWO algorithm randomly places a group of wolves (possible solutions) where each position corresponds to the power distribution of the three loads. Load 1, a high-priority load, is always on with constant power ratings. Load 2 activates at an intermediate power level when the renewable power exceeds 10,000 W, whereas low-priority load 3 activates only when the renewable power is at least 18,000 W. These constraints indicate load scheduling based on the available power. For each GWO iteration, the objective function indicated the amount of unused renewable power for each wolf. The wolves are sorted according to this overlooked capacity, and the algorithm declares the first three resolutions: alpha, beta, and delta. These best wolves impose their plans on others in subsequent iterations, whereas a linearly decreasing term (A) balances exploration and exploitation. The best optimized values were obtained by updating the wolf positions based on the GWO equations emulating the encircling and hunting of grey wolves. Following the optimization process, the algorithm assesses the appropriate circuit breaker conditions corresponding to each load given the power distribution of the optimum solution (α). Circuit breaker CB1 is always on, as a high-priority load must be provided. As mentioned previously, CB2 and CB3 are enabled only if their respective loads connected to the alpha solution receive power. Thus, it guarantees effective priority-based control of renewable power for the three loads in the system and avoids waste. Figure 5 shows the proposed hybrid microgrid with power management.

The duty cycle is determined by the GWO-BMS function using grey wolf optimization (GWO), which assesses renewable power availability and load demand. It defines the proportion of time a power system operates within specified parameters. If renewable power exceeds the load demand, the algorithm aims to optimize energy usage; otherwise, it minimizes the energy deficiency. The GWO algorithm initially sets parameters: number of wolves (n), maximum iterations (max-iterations), and initial wolf positions in the search space (0, 1) [3], which are potentially correlated with the duty cycle. It initializes the alpha wolf and its score, setting it high for minimization. The optimization target is based on a comparison of the renewable and load power. With a higher renewable power, the aim is a high-duty cycle; otherwise, it is a low-duty cycle. GWO's main loop runs for specified iterations. Each iteration evaluates the 'fitness' of each wolf (duty cycle) using a fitness function. This function assesses how well the current duty cycle meets the target, optimizing extra energy usage for high-duty cycle targets or controlling energy discrepancies for low-duty cycle targets. The alpha wolf is updated if a better solution is obtained. After evaluating the fitness of everyone, they were ranked by similarity to the alpha wolf. The positions of other wolves are updated according to the real wolf hunting behavior. This update follows the GWO equations, where coefficient a reduces linearly to balance exploration and exploitation. The values are clamped to the [0, 1] search space and new positions are obtained accordingly. At the end of the iterations, the program outputs the duty cycle to the alpha wolf as the solution to this iteratively formulated optimization algorithm. This solution is optimal in terms of renewable power supply and load requirements to guarantee the management of energy in the system. Figures 6 and 7 shows the Flowchart for load management and BMS. Figures 8 and 9 shows the flowchart GWO + PSO-based power management system and distribution voltage and current waveform.

Figure 10 (see Appendix) and Table 3 gives the THD values for voltage and current in R, Y and B phases and the Y-phase voltage has the highest distortion, amounting to 6.17%.

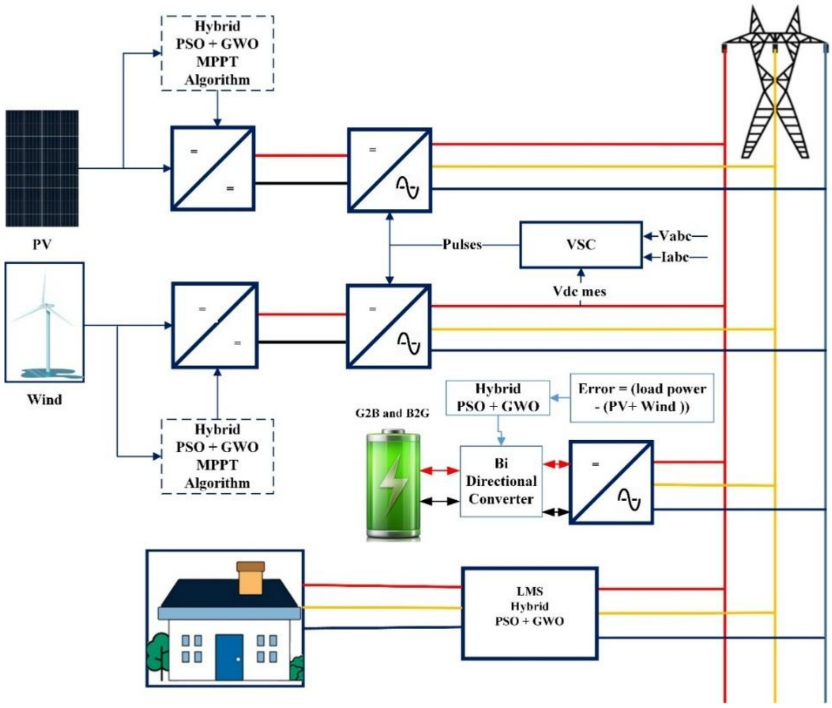

Figure 5. Proposed hybrid microgrid with power management

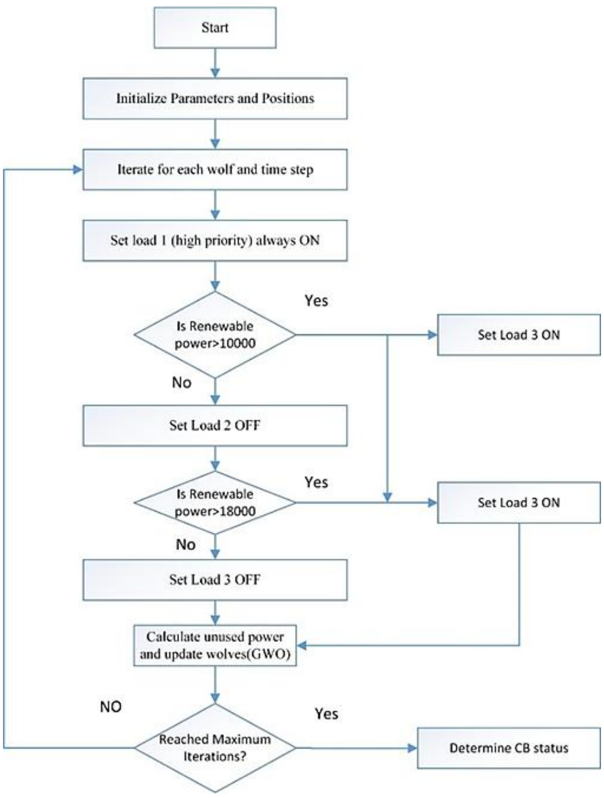

Figure 6. Flowchart for load management

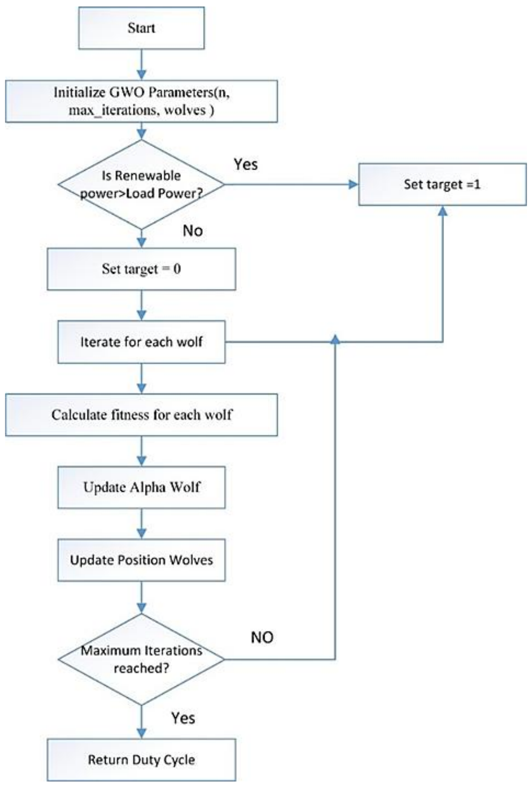

Figure 7. Flow chart for BMS

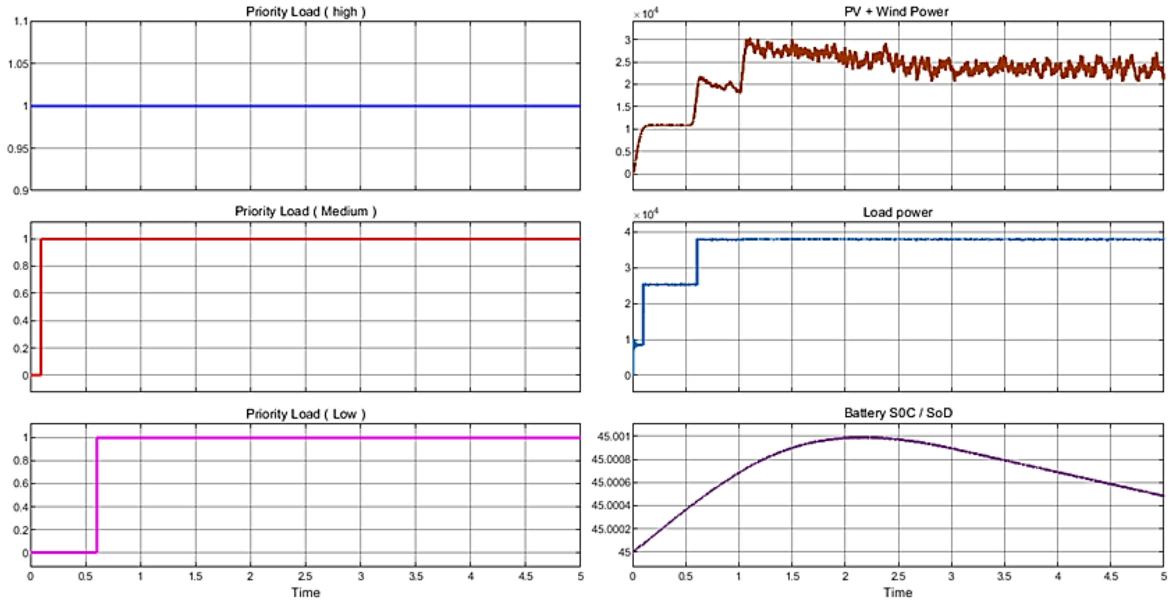

Figure 8. GWO + PSO-based power management system

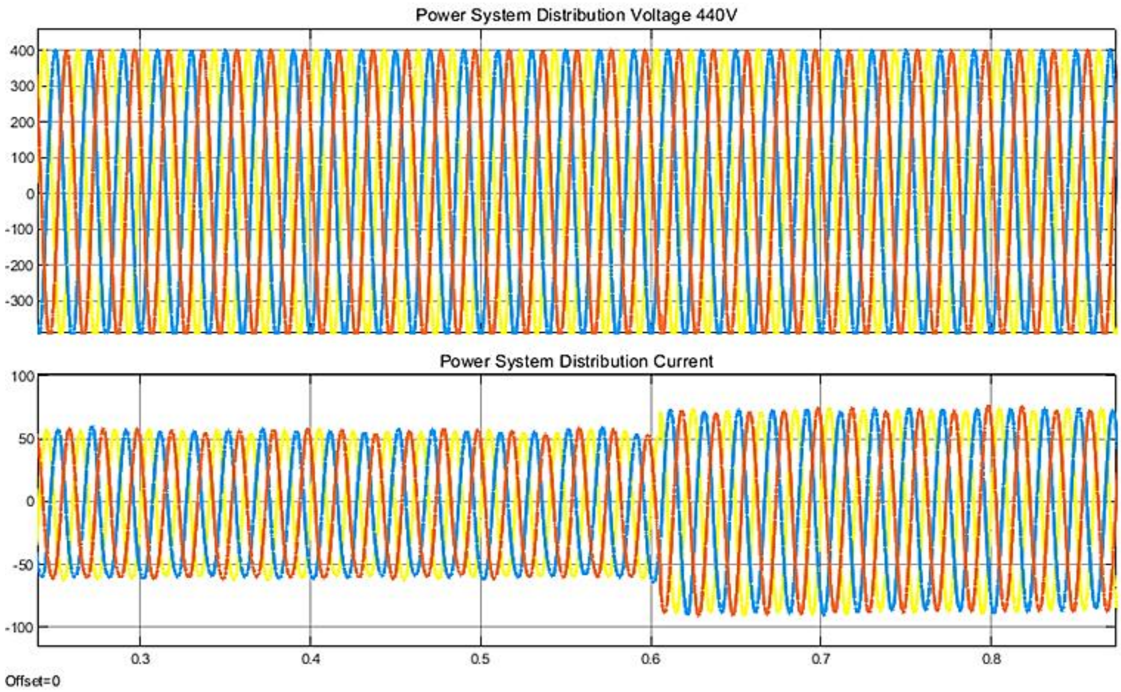

Figure 9. Distribution voltage and current waveform

Table 3. Total harmonics distortions in three phases

Profile	R – Phase	Y – Phase	B – Phase
Voltage	2.83	6.17	3.43
Current	1.72	1.53	1.89

6. CONCLUSION

This paper presents an in-depth analysis of a hybrid photovoltaic (PV) and wind power system with energy storage for power management in a microgrid. The proposed methodology employs a hybrid intelligent optimization technique using a grey wolf optimizer (GWO) and particle swarm optimization (PSO) for maximum power point tracking (MPPT) in PV and wind systems, battery management, and priority-based load management. This research concentrates on three main aspects: GWO-PSO for MPPT in PV and wind systems, GWO-PSO for battery management, and GWO-PSO for priority-based load management. The system performance was simulated in MATLAB under different conditions, and the results were compared with those of other methods and benchmarked against the IEEE 516 standard. The hybrid intelligent optimization methodology exhibits superior performance in terms of power generation, energy consumption, and system stability and can be considered as a potential solution for power management in hybrid renewable energy microgrids.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
R. Indumathi	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
S. A. Lakshmanan		✓		✓		✓		✓	✓	✓	✓	✓	✓	

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

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available from the corresponding author, [SAL], upon reasonable request.

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APPENDIX

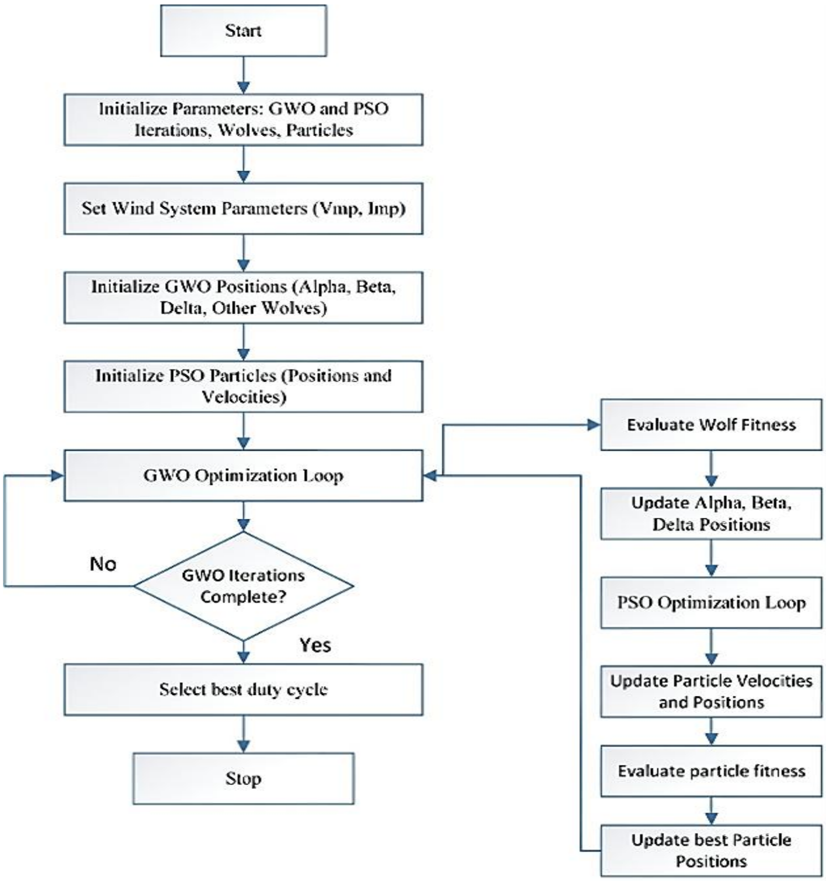
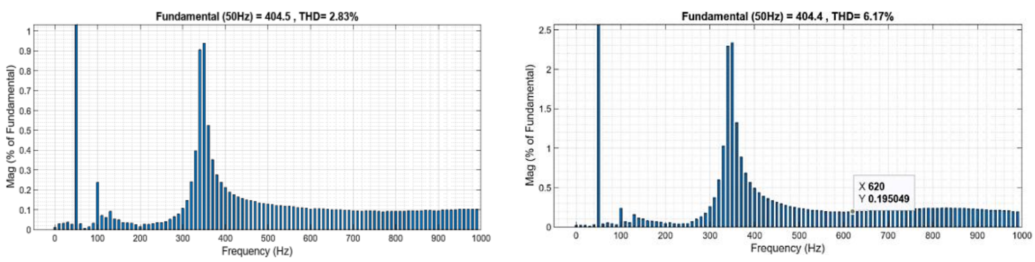


Figure 2. Flowchart for hybrid GWO and PSO for wind system



(a) (b)

Figure 10. Voltage and current harmonics in distribution grid: (a) voltage THD measurement at phase–1 and (b) voltage THD measurement at phase –2

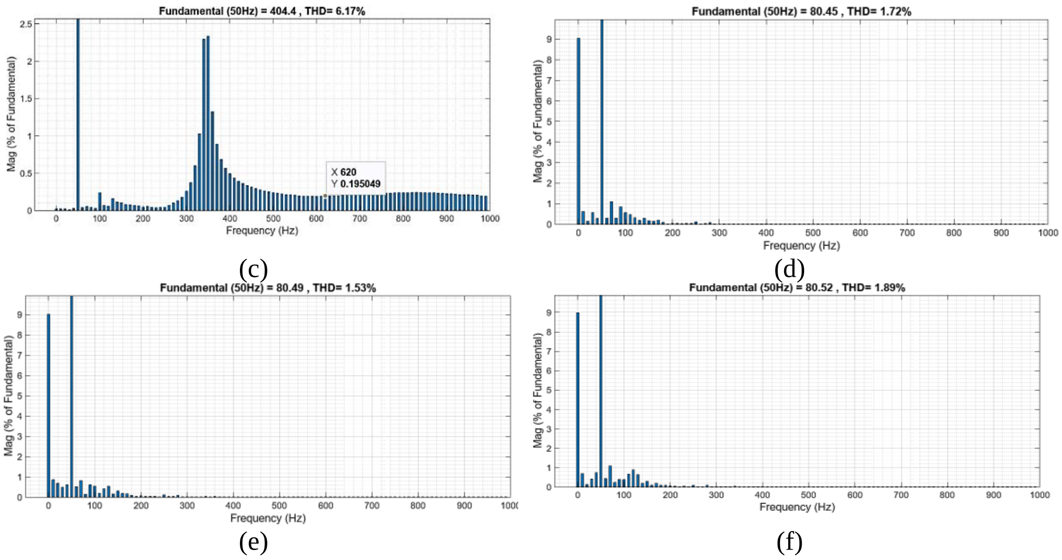


Figure 10. Voltage and current harmonics in distribution grid: (c) voltage THD measurement at phase –3, (d) current THD measurement at phase–1, (e) current THD measurement at phase–2, and (f) current THD measurement at phase–3.

BIOGRAPHIES OF AUTHORS

R. Indumathi (member, IEEE) received her B.E. degree in electrical and electronics engineering from Anna University and her M.E. degree in power systems from AVIT, VMU. She is currently pursuing a Ph.D. at the Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Chennai. She can be contacted at email: r_indumathi@ch.students.amrita.edu.

S. A. Lakshmanan (member, IEEE) received the B.E. degree in electrical and electronics engineering from Madras University, the M.E. degree in power electronics and drives from the College of Engineering-Guindy, Anna University, and the Ph.D. degree from the Indian Institute of Technology Mandi (IIT Mandi) with a specialization in power electronics applications in grid-connected systems. He is currently an assistant professor [Sl.Gr] with the Department of ECE, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Chennai Campus. His research interests include the modeling of power converters for electric vehicle applications, digital signal processing, and AI and ML techniques. He can be contacted at email: sa_lakshman@ch.amrita.edu.