OPTIMAL SCHEDULING OF RENEWABLE ENERGY RESOURCES IN ENERGY MANAGEMENT SYSTEMS USING HYBRID GENETIC ALGORITHM AND PARTICLE SWARM OPTIMIZATION

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Highlights

The article presents a novel hybrid optimization method combining Genetic Algorithm and Particle Swarm Optimization to improve the scheduling and integration of renewable energy resources in Energy Management Systems.

Abstract

Emphasizing the importance of Energy Management (EM) systems, the rise in Distributed Generation (DG) and the introduction of multicarrier energy networks have become key factors. An EM is a novel concept introduced in multicarrier energy networks. It enables the transmission, reception, and storage of various types of energy. Thus, this paper presents an enhanced energy hub incorporating various renewable energy-based DG units and heating and power storage systems. It focuses on modeling the operational and organizing elements of the system. In addition, the modeling of optimal planning and scheduling for a multicarrier EM system considers the unpredictable nature of wind and Photovoltaic (PV) units. An effective solution to the EM problem, cost reduction, peak-to-average ratio (PAR), and carbon emission can be achieved through a seamless combination of Renewable Energy Sources (RES) and Power Storage Systems (PSS). This work presents an Optimal Scheduling and Energy Management System utilizing Hybrid Genetic Algorithm and Particle Swarm Optimization (OSEMS-HGA-PSO). This approach combines the strengths of both GA and PSO, resulting in better convergence and superior solutions for optimal scheduling of RES in EM systems. The numerical evaluation assesses the effectiveness of the heuristic algorithms and the proposed system. The results show that the HGA-PSO EM system significantly decreases the cost, PAR, and carbon emission by 58.74%, 57.19%, and 90%, respectively.

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Keywords
energy management; optimal scheduling; renewable energy sources; genetic algorithm; particle swarm optimization.

Introduction and Related Works on RES and EM System

Due to population expansion and development, energy consumption is projected to increase by 4% by the end of 2022 [1]. Fueled by various energy sources, conventional power systems generate about 64.6% of the global electricity supply. These power generators produce a significant quantity of carbon, with the generating and transport sectors accounting for around 45% and 25% of carbon emissions, respectively [14]. The Energy Information Administration (EIA) predicts a potential 2.4% rise in the mean energy bill for U.S. homes next year. The substantial surge in demand and associated expenses would necessitate using alternative energy sources such as solar, thermal, and wind power to create electricity.

Furthermore, to address the rapid growth in energy consumption, mitigate carbon emissions, and achieve cost-effectiveness, researchers have proposed alternative methods of power production using RES. To optimize these RES, it is necessary to transform conventional Power Grids (PGs) into Smart Grids (SGs). Singapore can fulfill increasing requirements and integrate new renewable energy sources simultaneously. SG integrates contemporary communication infrastructure with the current power grid to optimize available energy sources at a specific location [2][25].

Power hubs have emerged as a new and innovative idea in energy optimization in recent years [3]. The researchers have been persuaded by the benefits of this comprehensive idea in the energy sector to suggest future energy systems based on it. The primary challenge of optimizing the EM system is efficiently managing energy resources hourly to meet the needed loads while minimizing costs. Furthermore, the presence of uncertainties in RES adds complexity to the optimization challenge.

Various research has been conducted on optimizing Micro-Grid (MG), focusing on RES and PSS. The main objective of this research is to ascertain the most suitable dimensions of various DG units for supplying electrical loads via different optimization methods. In their study, Bukar et al. [4] introduced a grasshopper optimization method to reduce the overall cost by efficiently managing power generators to ensure that all electrical loads are adequately supplied. The Markov model has been used in [5] to calculate the ideal DG size in an MG. In addition, a multi-objective self-adaptive differential evolutionary algorithm has been used to optimize the integration of various RES and storage devices for batteries in an integrated system. The improvement of RES and PSS has been carried out in an SG [6].

An expedited power flow has been suggested to enhance the efficiency of a microgrid with energy storage. An approach has been described in [29] to determine a home microgrid's optimal capacity, including PV units, wind units, and power storage devices. An optimization technique based on GA has been suggested to identify the most suitable hybrid system configuration for meeting the power requirements of all electrical loads [8]. Zhu et al. [9] used a GA to determine the optimal capacity of several DG units in a solitary MG system. The primary goals of this research are to optimize the use of RES and to minimize the release of harmful pollutants. The neural network has been used to handle day-ahead optimum planning, considering short-term load predictions as well [10].

A unique planning approach has been presented to simultaneously tackle the dependability and budgetary limitations using the Monte Carlo simulation [11]. The stochastic management method in [12] has been designed to include a larger proportion of RES while considering chance limits. Chaturvedi et al. [13] have developed a novel approach using power pinch analysis to determine the optimal size of hybrid systems for minimizing overall cost. An ideal operation for a zero-carbon design has been suggested, considering domestic loads, PV units, and electrical and thermal ESSs [30]. A novel EM method has been suggested to determine the most efficient operation of the RES and PSS by using Mixed-Integer Linear Programming (MILP). The algorithm takes into account the demand response as well [15].

Liu et al. [16] have introduced an approach that utilizes a Mixed-Integer Linear Programming (MILP) problem to achieve optimum planning for the system management issue. This project aims to reduce the yearly costs associated with both the initial investment and ongoing operation of the system. Liu et al. [16] have presented a framework for the optimum design and management of pooled PSS using cost-benefit analysis. The optimization aim is to minimize the cost of procuring power for the retailer. In [17], a multi-criteria optimization method was created to build and manage distributed power plants that use various energy sources [20]. The primary goals of the described study are to assess the entire yearly cost, quantify the CO2 emissions, and evaluate the level of grid reliance.

Kim et al. [18] devised a resilient and efficient EM plan for a MG system, incorporating a wind turbine, PV arrays, microturbine, and diesel engine. An EM-based approach combining cost-based and incentive-based demand responses is presented to decrease the load during peak periods while maintaining system stability. Gao et al. [19] have proposed an economical EM optimization method for achieving optimum scheduling and organizing of an MG system, which includes a compressed air PSS. Rokni et al. [31] have presented a distributed EM system to optimize the scheduling of RES in an MG system. The main goal of the described effort is to reduce the operating cost of the MG.

Using SG technology, users can lower their power expenses by incorporating RESs. The authors in [21][22] examined a model that utilizes an Artificial Neural Network (ANN) to integrate RESs to lower expenses and limit carbon emissions. Consequently, the consumer's power cost is decreased by 35.5%. Nevertheless, they neglected to include the fusion of PSS and user convenience in their work. In their study, the authors proposed using both GA and Whale Optimization Algorithm (WOA) and then conducted a comparative analysis of the outcomes. The findings indicated a decrease of 30.2% in the bill cost and a reduction of 36.6% in the PAR. Nevertheless, they have neglected the incorporation of RESs in their academic endeavors.

A combined programmable home EM system has been presented in [23][26], combining PSO and GA algorithms. Nevertheless, the consideration of thermal comfort and Combined Heat and Power (CHP) production was omitted. They aimed to decrease expenses, PAR, and include RES in the EM system architecture. They have successfully achieved a decline of 60.1% in bill cost and a decrease of 18.02% in PAR. An optimum load scheduling for an EM system, using a Hybrid Gray Wolf-modified Enhanced Differential Evolutionary (HGWmEDE) algorithm, has been proposed in [24]. The home load was planned using the output generated by the forecaster module.

This literature analysis examines several optimization approaches and algorithms to schedule RES in EM systems for best results. Optimizing the use of RES is essential for sustainable EM, and effectively managing the timing of these resources is vital in attaining this objective. To summarize, effectively scheduling RES in EM systems is an intricate and demanding issue requiring sophisticated optimization approaches. By persisting in the exploration and advancement of inventive optimization algorithms, we may enhance the effectiveness, dependability, and sustainability of EM systems while optimizing the utilization of RES.

Optimal Scheduling and Energy Management Systems Utilizing a Combination of Genetic Algorithm and Particle Swarm Optimization (OSEMS-HGA-PSO)

In a residential neighborhood, a Smart Home (SH) is linked to an SG network. The SH is equipped with smart meters that use the suggested HGA-PSO algorithm to operate and manage their energy consumption [7][27][28]. The OSEMS includes several components: electrical household appliances, UC signals (indicating appliance choices), local RES such as PV and wind power, CHP systems fueled by biomass, and energy storage devices such as PSS. Intelligent appliances would establish communication with a controller over a home area network, and the OSEMS will regulate the scheduling of these appliances according to the suggested system.

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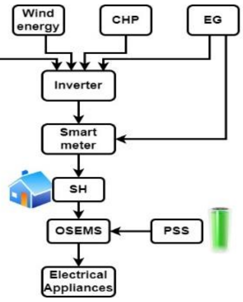

Figure 1. System design of SH using the proposed framework

An OSEMS is used at the externally grid-connected SH to collect the following information: (i) User Comfort (UC) signal on the load patterns (such as planned or urgent), including their operating durations, acceptable delays, and arrival times, as well as comfort levels. (ii) The output of PV power generation and the constraints associated with it, (iii) The wind turbine output, (iv) The values of CHP production and the associated limitations, (v) the power levels of both sources, (vi) The real-time price indications for electrical power and the limitations imposed by the external EG. After receiving the above data, the OSEMS uses the suggested algorithm to ascertain the most efficient schedule and oversee the EM and PSS. All OSEMS actions are presumed to be conducted within set time intervals, with each operation carried out per time slot. Additionally, all important information is safely and promptly sent via a communications network. Various wireless communication options, including Wi-Fi, ZigBee, Z-Wave, and a wired house plug protocol, are available for communication needs in SG. Figure 1 illustrates a simple system design of SH using the proposed framework.

PV System

Solar power production from PV panels relies mostly on solar radiation and the total projected radiation. The production of solar electricity is contingent upon the quantity of radiation, the orientation of the panels, and the efficiency of energy transmission. The energy produced in every window over 24 hours is first allocated to the planned load and may be described using Equation (1).

$$P_{PV}(\mathrm{t}) = P_{PV}\ Sa_{PV}R(t)(1-0.05)(T(t)-25) \quad \forall t \tag{1}$$

Where P_{PV}, Sa_{PV} and $R(t)$ denotes the power efficiency, surface area of solar panels, and solar radiance. $T(t)$ denotes the ambient temperature in $°C$ at time t. The spectrum of hourly irradiation from the sun often exhibits a bimodal pattern, which may be quantified as a linear combination of two unimodal distribution functions. The Weibull probability density has been used to illustrate the above function.

Wind Energy

The power generated by wind turbines results from the kinetic energy of wind velocity. Therefore, electrical power generation from wind turbines is mainly influenced by climatic conditions and the course of the wind's movement. The quantity of energy obtained from a wind turbine is often calculated using the following formula:

$$E_{WE}(t) = (1/2) * Ad * A * V(t) \tag{2}$$

Where Ad, A, and $V(t)$ are the air density, area of turbine, and velocity of wind in m/s.

CHP

To fulfill the power needs of the SH construction, it is assumed that the building will obtain energy from its controllable micro-CHP generation system. The CHP framework has the following specifications: on a typical basis, it utilizes 33% reduced fuel for power production, resulting in a 50% reduction in carbon emissions. CH4 biogas can be utilized for heat generation, power production, or as a fuel for transportation. The effectiveness of the CHP framework can be determined using Equation (3).

$$\gamma = [U_{po} + \sum O_{th}]/I_f \tag{3}$$

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Where γ is the effectiveness of the entire system, U_{po} is the usable power output, O_{th} is the thermal output, and I_f is the fuel input.

Biomass, mostly derived from forests, is the crucial CHP energy source. The anaerobic breakdown of organic materials in regulated tanks or landfills produces biogas. CH4 is the primary constituent of biogas. The content of CH4 typically falls between the range of 35% to 60%. The CH4 component of biogas may be used for generating thermal and electrical power and fuelling transportation. Biogas is a proactive method of generating renewable energy, making it a crucial contributor to energy production and environmentally benign. Urban regions have several sources of biogas, such as waste from factories, agricultural waste, and municipal solid waste.

Optimization using the Proposed HGA-PSO

HGA-PSO for optimal scheduling of RES in EM systems involves integrating the exploration capability of GA with the exploitation capability of PSO.

1. Initialization

- Initialize population PP for GA and particle swarm SS for PSO with random solutions within the search space.
- Set the maximum number of iterations $max\_iterations$, population size pop_size, and swarm size $swarm\_size$.
- Set parameters for GA: crossover rate CR, mutation rate MR, and elitism rate ER.
- Initialize the inertia weight w, cognitive parameter $c1$, and social parameter $c2$ for PSO.

2. Objective Function

- Define the objective function $f(x)$ that represents the solution's fitness, considering factors such as energy cost, renewable energy utilization, and system constraints.

3. Hybridization of GA and PSO

- For $t = 1\ to\ max\_iterations$:

a. Perform GA Operations

i. Selection: Select individuals from the population based on their fitness.
ii. Crossover: Apply crossover operation to create new offspring.
iii. Mutation: Apply mutation operation to introduce diversity.
iv. Elitism: Select the best individuals from the current population.

b. Perform PSO Operations

i. Update particle velocity and position using the cognitive and social components.
ii. Update the global best position found by the swarm.
iii. Combine the solutions obtained from GA and PSO to form a combined population.
iv. Evaluate the fitness of each solution in the combined population.
v. Select the best solutions to form the new population for the next iteration.

4. Stopping Criterion

- Terminate the algorithm if the maximum number of iterations is reached or if convergence is achieved.

a. Objective Function

$$f(x) = Cost(x) + Penalty(x) \tag{4}$$

Where: $Cost(x)$ represents the energy cost associated with the scheduling solution x. $Penalty(x)$ represents any penalties imposed due to violations of system constraints.

b. Crossover Operation (GA):

- Single Point Crossover:

```
\begin{cases}
\text{Parent}_1[i] & \text{if } \text{random}(0, 1) > \text{CR} \text{ or } i
> \text{Crossover\_point} \\
\text{Parent}_2[i] & \text{otherwise}
\end{cases} \]
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c. Mutation Operation (GA):

- Bit Flip Mutation:

\begin{cases}
1 − \text{Offspring}_i & \text{if } \text{random}(0, 1) < \text{MR} \\
\text{Offspring}_i & \text{otherwise}
\end{cases} \]

d. Velocity Update (PSO):

$$vi(t+1) = w \cdot vi(t) + c1 \cdot rand(0,1) \cdot (pBesti(t) - xi(t)) + c2 \cdot rand(0,1) \cdot (gBest(t) - xi(t)) \quad (5)$$

e. Position Update (PSO):

$$xi(t+1) = xi(t) + vi(t+1) \quad (6)$$

Integration with Energy Management Systems

Renewable Energy Scheduling

- Use the hybrid GA-PSO algorithm to optimize the scheduling of renewable energy resources based on energy demand, cost, and system constraints.

System Optimization

- Optimize the operation of EM systems by incorporating the scheduling solution obtained from the hybrid algorithm.

Dynamic Adaptation

- Dynamically adjust the scheduling solution in response to changes in energy demand, renewable energy availability, and system constraints.

This hybrid approach combines the exploration capability of GA with the exploitation capability of PSO, leading to improved convergence and solution quality for optimal scheduling of renewable energy resources in energy management systems.

Results and Discussion

This section presents the results and computer-generated models of the proposed OSEMS-based EM model. The evaluation and discussion on the effectiveness of the RES, PSS, and suggested HGA-PSO algorithm are conducted in our system model. MATLAB simulation software has been employed to conduct simulations. To examine the proposed OSEMS, we assumed that there is a smart house equipped with five appliances that can be adjusted and three sources of energy: EG, RES, and PSS. The proposed HGA-PSO has been compared with standalone GA, PSO, and WOA for the OSEMS framework.

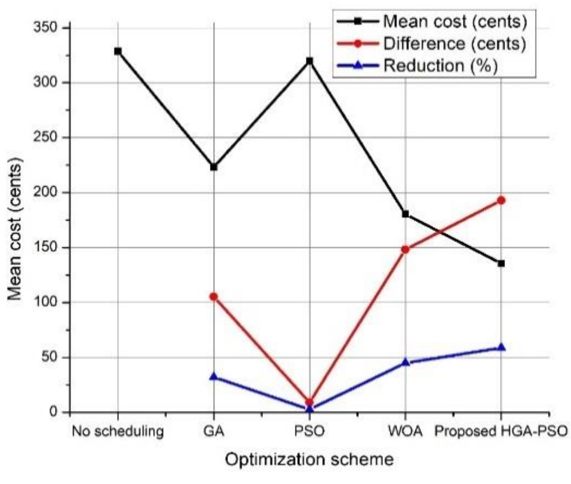

Figure 2. Cost analysis of various optimization schemes for OSEMS framework

Figure 2 illustrates a cost analysis of several optimization strategies for the OSEMS framework. Several optimization techniques led to substantial cost savings compared to the situation without any schedule. The GA attained an average cost of 223.4 cents, resulting in a decrease of 32.04% compared to the absence of scheduling. Furthermore, using PSO led to a noteworthy reduction in the average cost to 319.7 cents, resulting in a savings of 2.74%. The WOA attained an average cost of 180.5 cents, resulting in a cost reduction of 45.09%. The proposed HGA-PSO demonstrated superior performance to other methods by obtaining the lowest average cost of 135.6 cents. The proposed HGA-PSO represents a significant decrease of 58.75% compared to the absence of scheduling.

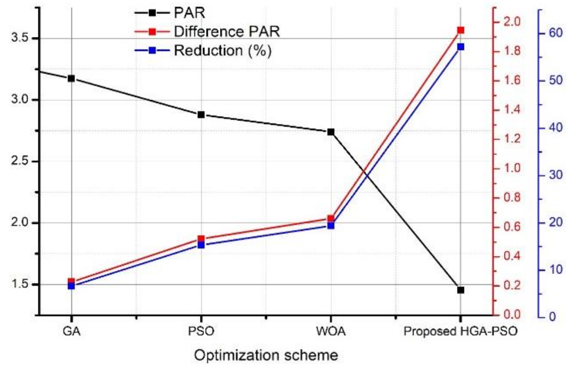

Figure 3. PAR analysis of various optimization schemes for OSEMS framework

Figure 3 depicts a PAR study of several optimization strategies for the OSEMS framework. When comparing the scenario without scheduling to each optimization strategy, there was a noticeable decrease in PAR, suggesting a performance improvement. The GA obtained a PAR of 3.174, indicating a decrease of 6.67% compared to the unscheduled algorithm. Furthermore, PSO and WOA obtained reductions in PAR of 15.35% and 19.41% respectively. However, the HGA-PSO demonstrated superior performance to other methods, obtaining a PAR of 1.456, which corresponds to a significant decrease of 57.19% compared to the absence of the scheduling scheme.

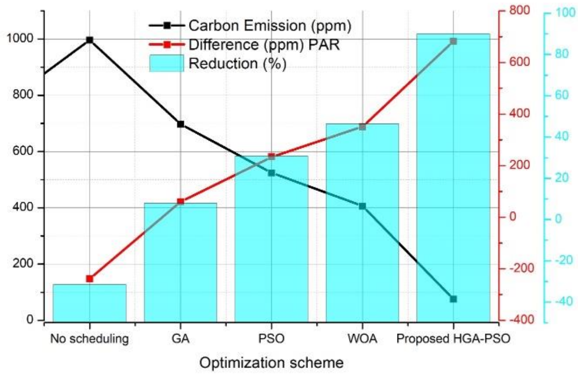

Figure 4. Carbon emission level (ppm) of various optimization schemes for OSEMS framework

Figure 4 displays the Carbon Emission levels (measured in parts per million, ppm) of several optimization strategies used in the OSEMS framework. Each optimization technique led to a substantial decrease in carbon emissions compared to the overall CO2 emissions. Without any schedule, the amount of carbon emissions reached 996.4 ppm. However, significant reductions in carbon emissions were achieved via the optimization process. The GA successfully reduced carbon emissions to 698 ppm, resulting in a decrease of 7.92%. PSO and WOA yielded much higher reductions of 30.80% and 46.35%, respectively. The HGA-PSO suggested in this study achieved the lowest carbon emission level of 75.8 ppm, which is a significant decrease of 90% compared to the absence of a scheduling algorithm.

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Conclusion

A seamless integration of RES and PSS may address the EM issue, reduce costs, lower the PAR, and minimize carbon emissions. This study introduces an Optimal Scheduling and Energy Management System that combines Genetic Algorithm and Particle Swarm Optimization (OSEMS-HGA-PSO). This technique synergistically harnesses the advantages of both GA and PSO, leading to enhanced convergence and improved solutions for the optimum scheduling of RES in EM systems. The numerical assessment measures the efficacy of the heuristic algorithms and the suggested system. The findings unequivocally demonstrate that implementing the EM system with HGA-PSO substantially reduces cost, PAR, and carbon emission by 58.74%, 57.19%, and 90%, respectively.

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