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An Innovative Hybrid Heap-Based and Jellyfish Search Algorithm for Combined Heat and Power Economic Dispatch in Electrical Grids

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Abstract: This paper proposes a hybrid algorithm that combines two prominent nature-inspired meta-heuristic strategies to solve the combined heat and power (CHP) economic dispatch. In this line, an innovative hybrid heap-based and jellyfish search algorithm (HBJSA) is developed to enhance the performance of two recent algorithms: heap-based algorithm (HBA) and jellyfish search algorithm (JSA). The proposed hybrid HBJSA seeks to make use of the explorative features of HBA and the exploitative features of the JSA to overcome some of the problems found in their standard forms. The proposed hybrid HBJSA, HBA, and JSA are validated and statistically compared by attempting to solve a real-world optimization issue of the CHP economic dispatch. It aims to satisfy the power and heat demands and minimize the whole fuel cost (WFC) of the power and heat generation units. Additionally, a series of operational and electrical constraints such as non-convex feasible operating regions of CHP and valve-point effects of power-only plants, respectively, are considered in solving such a problem. The proposed hybrid HBJSA, HBA, and JSA are employed on two medium systems, which are 24-unit and 48-unit systems, and two large systems, which are 84- and 96-unit systems. The experimental results demonstrate that the proposed hybrid HBJSA outperforms the standard HBA and JSA and other reported techniques when handling the CHP economic dispatch. Otherwise, comparative analyses are carried out to demonstrate the suggested HBJSA's strong stability and robustness in determining the lowest minimum, average, and maximum WFC values compared to the HBA and JSA.

Keywords: heap-based algorithm; jellyfish search algorithm; economic dispatch; combined heat and power plants

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1. Introduction

The energy supply in the globe is shifting toward high efficiency, sustainability, and low carbon content [1]. In conventional power units, a large amount of energy is wasted during the conversion of fossil fuels into electricity because of the low efficiency of these conventional plants. However, by utilizing the CHP economic dispatch, the whole fuel cost (WFC) may be reduced by 10–40%, energy efficiency can be increased to 90%, and greenhouse gases (GHG) can be reduced by roughly 13–18% [2]. The heat and electrical energy in the CHP system can be generated from a single source at the same time. The vital optimization challenge for the CHP economic dispatch is to find the minimum WFC of heat and power supply. There are several constraints that should be considered in the CHP economic dispatch, involving a load balance of the system, capacity limitations of generation plants, the valve-point effect of thermal plants, and the heat and power mutual dependency provided by CHP. Two main categories of optimization approaches are explained to solve the CHP economic dispatch problem in recent research, comprising mathematical and heuristic optimization techniques [3,4].

One such task is the economic dispatch of the power system, which entails coordination, planning, and scheduling generators in an efficient manner. Due to the imposed equality and inequality restrictions, the economic dispatch issue exhibits nonlinear behavior. The economic dispatch problem has been highlighted as a multimodal optimization problem that will be difficult to tackle. Because actual issues are multimodal in nature, gradient methods are inapplicable [5]. In [6], an enhanced multi-objective particle swarm optimizer (MOPSO) model was used to manage a bi-objective dispatch framework in order to enhance the power quality and economic costs. In this study, a deep learning approach has been used to improve wind forecast accuracy where uncertainty analysis is a critical component of any assessment of a wind farm's long-term electricity output [7]. In [8], an improved antlion optimizer was presented to search for potential solutions for the economic dispatch issue in power systems with thermal units in order to minimize the generating fuel costs and guarantee that all restrictions are within functioning ranges. In [9], a modified crow search optimization was applied for solving the economic dispatch considering the environmental impacts and high-voltage direct current systems.

Added to that, the CHP economic dispatch has been solved throughout lots of conventional and mathematical approaches. In [10], a decentralized solution based on bender decomposition (BD) was performed for the optimal schedule of the CHP economic dispatch. The Lagrange relaxation (LR) and LR with surrogate sub-gradient (LRSS) have been employed in [11,12] with two levels to find out the optimal solution for studying the CHP economic dispatch. In [13], sequential quadratic programming (SQP) was combined with the LR method, where the LR technique was applied to the optimal CHP scheduling, and SQP was applied on a portion of the CHP problem to check the validity of the acquired operating point inside the trust region. In [14], the envelope-based branch and bound (EBB) approach was utilized for optimal planning of the CHP.

However, to deal with the non-convex objective function of the CHP economic dispatch and to overcome computational time efforts, heuristic approaches have been applied on the mentioned problem, such as the genetic algorithm (GA) [15], opposition teaching learning-based optimization (OTLBO) [16], differential evolution (DE) [17], multi-player harmony search (MPHS) algorithm [18], cuckoo search (CS) [19], and whale optimization algorithm (WOA) [20]. In [21], a greedy randomized adaptive search procedure (GRASP) method was hybridized with DE optimization and applied for the CHP economic dispatch to increase global search capacity while avoiding converging to local minima. In [22], an advanced mutation mechanism was involved in real coded GA and applied to the CHP economic dispatch for minimizing the operation cost, in order to enhance the convergence characteristics. In [23], an improved GA based on a new crossover and mutation was utilized to solve the CHP economic dispatch problem for handling constraints and applied to four cases for assessing the performance of the approach. In [24], a biogeography-based learning PSO (BLPSO) was carried out to improve the solution accuracy and overcome premature convergence where each particle utilized a migration operator to update itself depending on the best position of the whole particles. In addition, a multi-objective PSO has emerged with non-dominated sorting GA [25], and a modified version of shuffle frog leaping (MVSFL) algorithm [26] has been successfully employed on the CHP economic dispatch with limited small-scale applications, which are 5-unit and 7-unit systems.

The authors of [27] presented a combined optimization approach for power systems, which managed energy with power market and active microgrids in electric vehicle parking lots, diverse CHP economic dispatches, power and heat storage units, and distributed production. In [28], a Manta ray foraging optimizer (MRFO) was incorporated with adaptive constraint handling for solving the CHP economic dispatch, whereas the impact of the inclusion of wind power based on the MRFO was investigated in [29]. Moreover, a two-stage mathematical programming has been proposed in [30] to deal with the nondifferentiable portion of valve-point loading influence and attain a convex operating zone in the CHP economic dispatch problem. In [31], the authors investigated the heat in power equipment and the availability of power flexibility in CHP technology from district heating networks.

Recently, two novel algorithms, heap-based algorithm (HBA) and jellyfish search algorithm (JSA), have been introduced to solve global optimization problems. Firstly, the HBA is a powerful metaheuristic optimization that is inspired from organization hierarchy created by Qamar Askari et al. [32]. Its simplicity and effectiveness enforce the research direction into its promising implementations in solving engineering problems. In [33], the HBA was efficiently utilized for parameter estimation of fuel cells, while it was applied for the CHP economic dispatch in [34] and optimal reactive power dispatch in [35]. Secondly, the standard JSA, inspired from jellyfish movements, was created by J.-S. Chou and D.-N. Truong in January 2021 [36]. In [37], the JSA was employed for a spectrum defragmentation algorithm in an elastic optical network. In [38], the JSA was utilized for efficient power system operation based on optimal power flow, whereas it was effectively applied in distribution networks to integrate distributed generators and the static volt-ampere reactive compensator [39]. In this paper, a novel hybrid heap-based and jellyfish search algorithm (HBJSA) is proposed, which combines the benefits of the standard HBA and standard JSA. Compared with the standard HBA and standard JSA, the proposed HBJSA uses an adjustment mechanism to support explorative and exploitative characteristics. The adjustment mechanism is constructed to boost the explorative features at the start of iterations by enhancing the generated solutions via HBA. Furthermore, towards the conclusion of iterations, it augments and enhances the exploitative features by growing the generated solutions via JSA. The efficiency of the HBA, JSA, and the proposed HBJSA is evaluated for solving the CHP economic dispatch by considering various constraints of heat production and power output balance.

The rest of this paper is structured as follows: the CHP economic dispatch problem is characterized in Section 2, whereas Section 3 includes a description of the standard HBA, the standard JSA, and the proposed hybrid HBJSA. Furthermore, Section 4 presents the outcomes of these algorithms and discussion for simulation, while a conclusion is presented in Section 5 of this work.

2. Problem Formulation

The general form of the CHP economic dispatch problem is described in Figure 1. This figure shows the single line diagram of the 24-unit test system for the CHP economic dispatch problem. As shown, different sources of the CHP, heat only, and power-only units supply power and heat are combined together to satisfy the power and heat demands. Heat production and power output balance means that the total power generation equals the total power load and the total heat generation equals the total heat load.

The objective function of the CHP economic dispatch problem can be illustrated as depicted in the following equation [2]:

$$Min\{WFC\} = Min\left\{\sum_{i=1}^{Npp} C_i\left(P_i^{pp}\right) + \sum_{h=1}^{Nhp} C_h\left(H_h^{hp}\right) + \sum_{k=1}^{NCp} C_k\left(P_k^{Cp}, H_k^{Cp}\right)\right\}(\text{USD/h}) \quad (1)$$

The three terms of costs manifested in Equation (1) are explained in Equations (2)–(4) as in [20]. The cost function of a power-only plant involves quadratic and sinusoidal terms, where the sinusoidal term displays the valve-point impacts as signified in Equation (2). Furthermore, the heat-only cost is formulated in Equation (3), while the CHP cost function is represented in Equation (4).

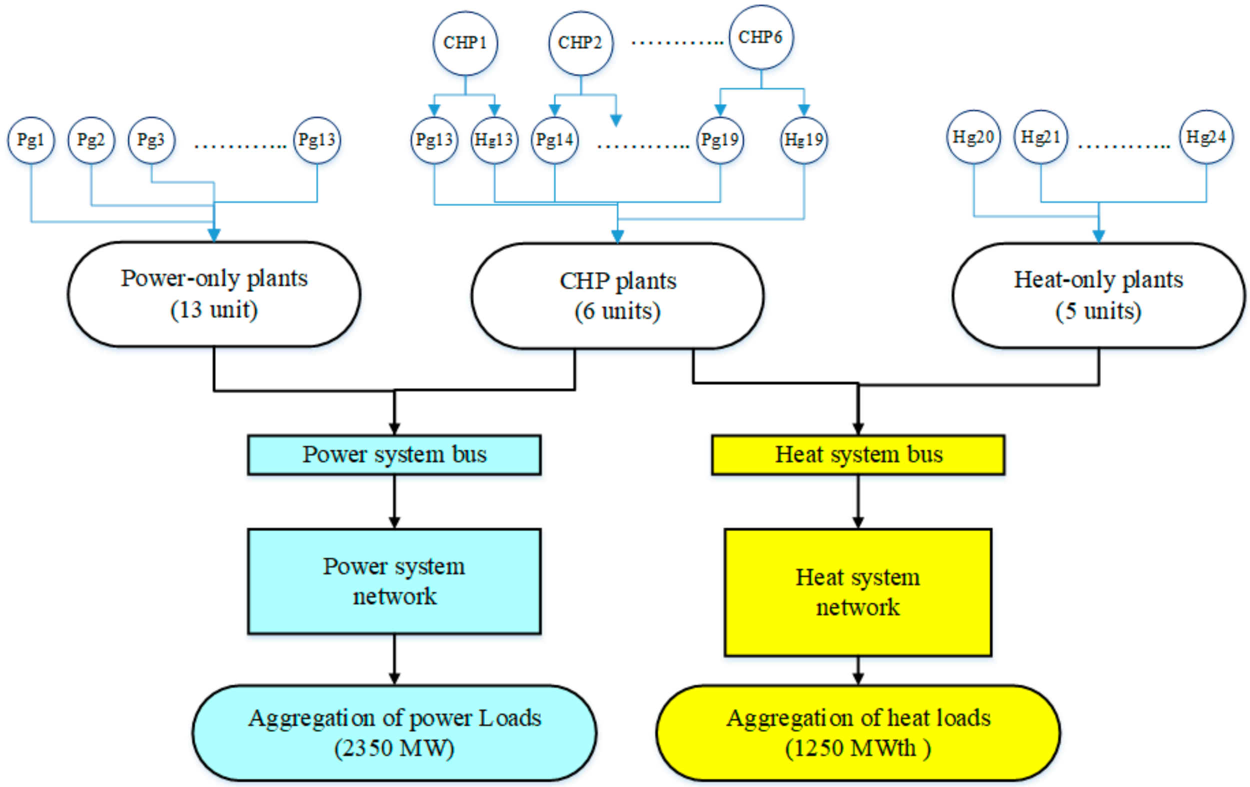


Figure 1. A single line diagram of the CHP economic dispatch problem considering the 24-unit test system.

$$C_i(P_i^{pp}) = a_i(P_i^{pp})^2 + b_i P_i^{pp} + c_i + \left|\lambda_i \sin(\rho_i(P_i^{pp\min} - P_i^{pp}))\right| \text{ (USD/h)} \tag{2}$$

$$C_j(H_j^{hp}) = a_j(H_j^{hp})^2 + b_j P_j^{pp} + c_j \text{ (USD/h)} \tag{3}$$

$$C_k(P_k^{cp}, H_k^{cp}) = a_k(P_k^{cp})^2 + b_k P_k^{pp} + c_k + d_k(H_k^{cp})^2 + e_k H_k^{cp} + f_k H_k^{cp} P_k^{cp} \text{(USD/h)} \tag{4}$$

Diverse constraints for feasible solutions are illustrated for the CHP economic dispatch problem as follows:

$$\sum_{i=1}^{N_{pp}} P_i^{pp} + \sum_{j=1}^{N_{cp}} P_j^{cp} = P_d \tag{5}$$

$$\sum_{j=1}^{N_{cp}} H_j^{cp} + \sum_{k=1}^{N_{hp}} H_k^{hp} = H_d, \tag{6}$$

Furthermore, power-only and heat-only capacity limits are exposed in Equation (7) and Equation (8), respectively. In addition to that, capacity limits of CHP are designated in Equations (9) and (10).

$$P_i^{pp\min} \le P_i^{pp} \le P_i^{pp\max} \quad i = 1, \ldots, N_{pp}, \tag{7}$$

$$H_j^{hp\min} \le H_j^{hp} \le H_j^{hp\max} \quad i = 1, \ldots, N_{hp}, \tag{8}$$

$$P_k^{cp\min}(H_k^{cp}) \le P_k^{cp} \le P_k^{cp\max}(H_k^{cp}) \quad k = 1, \ldots, N_{cp}, \tag{9}$$

$$H_k^{cp\min}(P_k^{cp}) \le H_k^{cp} \le H_k^{cp\max}(P_k^{cp}) \quad k = 1, \ldots, N_{cp}, \tag{10}$$

In the above constraints, Equations (5) and (6) demonstrate the power generated and the power demand balance and the heat generated and the demand balance, respectively.

3. Hybrid HBJSA for CHP Economic Dispatch Problem

3.1. Standard HBA

The standard HBA concept is based on the corporate rank hierarchy (CRH), which states that a team can arrange itself in a hierarchy to fulfill organizational goals [32]. The HBA is classified into three levels: interaction among subordinates, self-contribution of employees and their immediate supervisor, and interaction among colleagues.

In the CRH model, the population is manifested by the full CRH, whereas the heap node is manifested by the search agent. The search agent's fitness is the master of the heap node, and the population index of the search agent is the value of the heap node. The agent position of each search can be updated as:

$$x_i^k(t+1) = B^k + \gamma(2r-1)\left|B^k - x_i^k(t)\right| \tag{11}$$

The kth component of λ vector $\vec{\lambda}$ is represented by:

$$\lambda^k = 2r - 1 \tag{12}$$

γ is computed as follow:

$$\gamma = \left|2 - \frac{(t\ mod\ \frac{t}{C})}{\frac{t}{4C}}\right| \tag{13}$$

The parameter (C) in Equation (14) controls the variation. However, this parameter will complete in T iterations as follows:

$$C = T^{\max}/25 \tag{14}$$

Added to that, the interaction between colleagues is modeled. As manifested in Equation (15), the position of each agent ($\vec{x_i}$) is updated by its arbitrarily selected colleague $\vec{S_r}$:

$$x_i^k(t+1) = \begin{cases} S_r^k + \gamma\lambda^k\left|S_r^k - x_i^k(t)\right|, & f(\vec{S_r}) < f(\vec{x_i}(t)) \\ x_i^k + \gamma\lambda^k\left|S_r^k - x_i^k(t)\right|, & f(\vec{S_r}) \geq f(\vec{x_i}(t)) \end{cases} \tag{15}$$

where the fitness of the search agent can be represented by f.

Additionally modeled is the self-contribution of each employee, where the position of each agent is updated in this level according to the following equation:

$$x_i^k(t+1) = x_i^k(t) \tag{16}$$

Finally, the position updating equations have been emerged. The roulette wheel probabilities, p_1, p_2, and p_3, are selected to balance the exploration and exploitation processes. The search agent updates its position using Equation (16). Selecting the proportion p_1 is carried out by using Equation (17) as:

$$p_1 = 1 - \frac{t}{T^{max}} \tag{17}$$

The search agent updates its position using Equation (11). Selecting the proportion p_2 is carried by using Equation (18) as:

$$p_2 = p_1 + \frac{1-p_1}{2} \tag{18}$$

The search agent updates its position using Equation (17). Selecting the proportion p_3 is carried out by using Equation (19) as:

$$p_3 = p_2 + \frac{1 - p_1}{2} = 1 \tag{19}$$

Hence, the general positions' updating mechanism of the HBA is formulated as in Equation (20):

$$x_i^k(t+1) = \begin{cases} x_i^k(t), & p \le p_1 \\ B^k + \gamma\lambda^k \left| B^k - x_i^k(t) \right|, & p_1 < p < p_2 \\ S_r^k + \gamma\lambda^k \left| S_r^k - x_i^k(t) \right|, & p_2 < p \le p_3 \; and \; f(\vec{S_r}) < f(\vec{x_i}(t)) \\ x_r^k + \gamma\lambda^k \left| S_r^k - x_i^k(t) \right|, & p_2 < p \le p_3 \; and \; f(\vec{S_r}) \ge f(\vec{x_i}(t)) \end{cases} \tag{20}$$

The main steps of the proposed HBA are depicted in Figure 2.

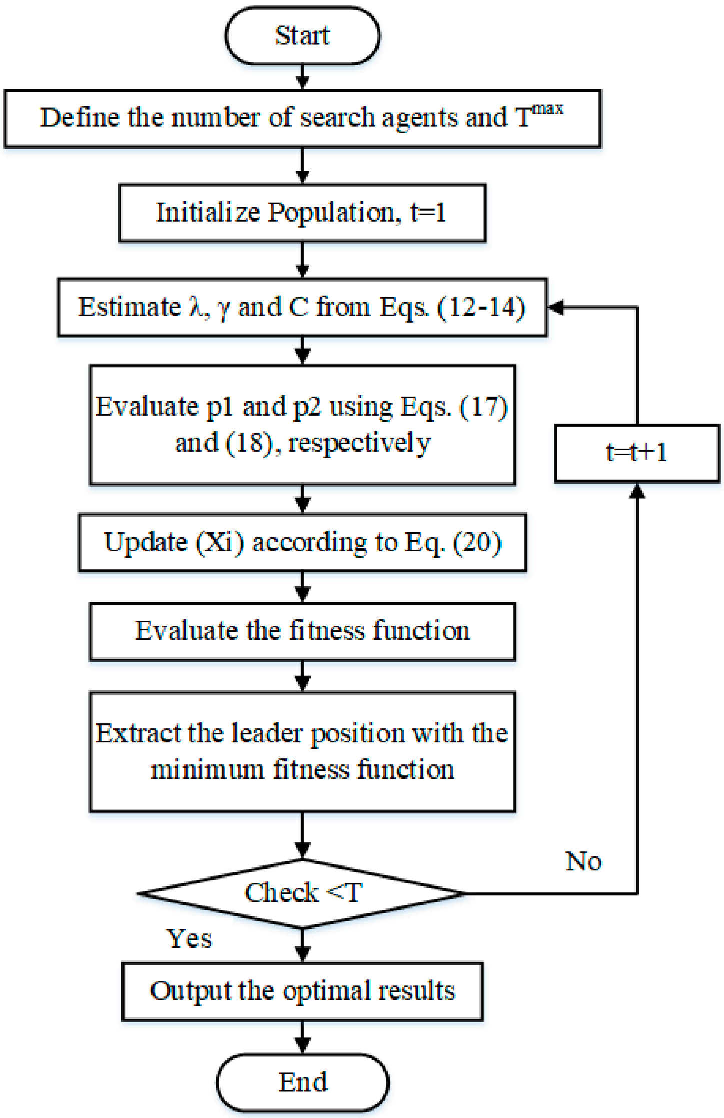


Figure 2. Flowchart of the HBA.

3.2. Standard JSA

The JSA is inspired by the jellyfish movements whether they move in the ocean current or within their swarm [36]. The jellyfish population can be mathematically modeled as:

$$X_i(t+1) = 4P_0(1 - X_i), \quad 0 \leq P_0 \leq 1 \tag{21}$$

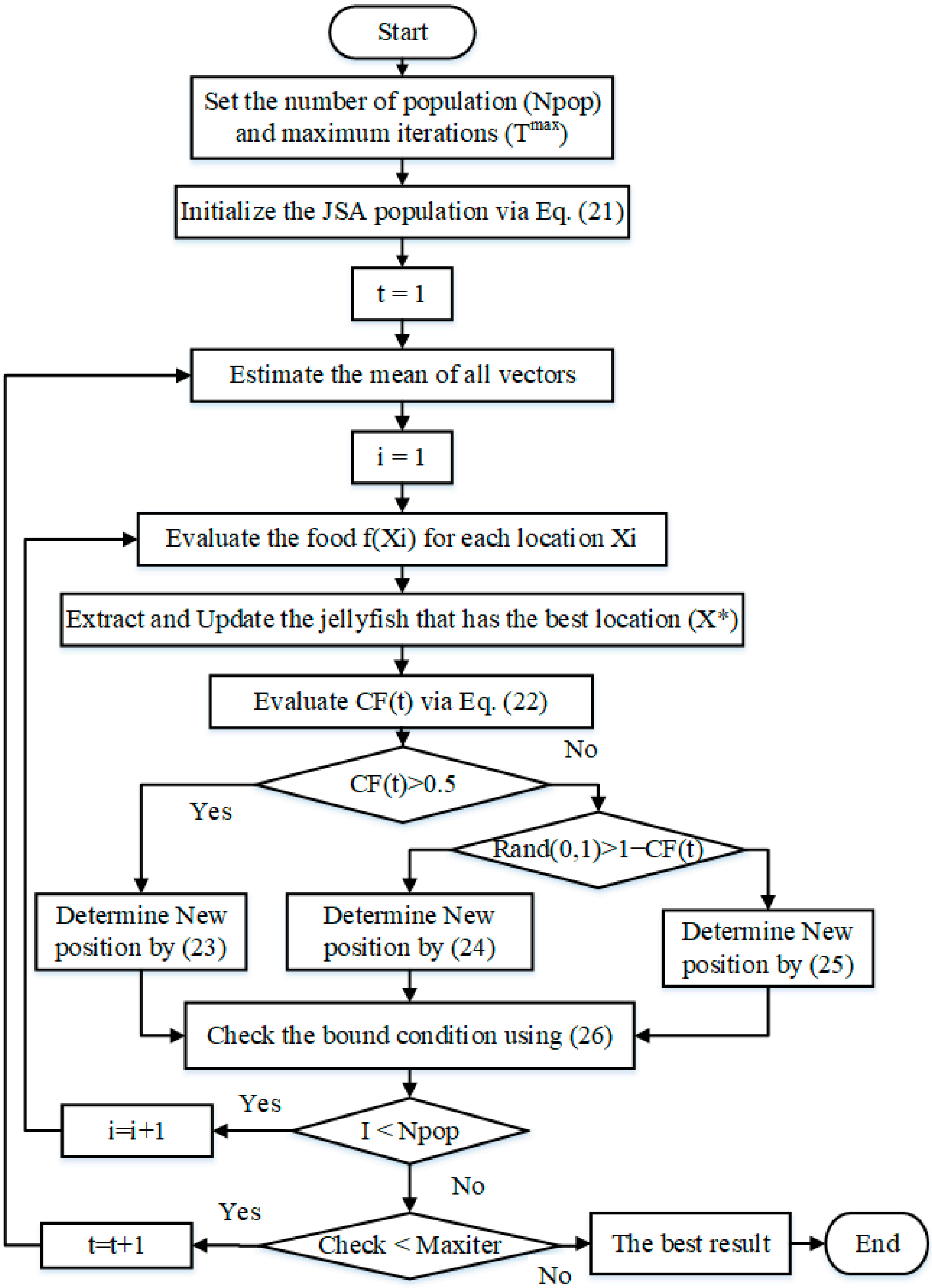


Figure 3. Flowchart of the JSA.

The time control function $CF(t)$ value is assessed as described in Equation (22), and it is varied from 0 to 1 over time:

$$CF(t) = \left| \left(1 - \frac{t}{T^{\max}}\right) \times (2 \times rand(0,1) - 1) \right| \quad (22)$$

If the CF is greater than the constant CO_o (to be 0.5), the new location of each jellyfish can be formulated as demonstrated in Equation (23)

$$X_i(t+1) = R \times (X^* - 3 \times R \times \mu) + X_i(t) \quad (23)$$

If CF value is more than CO_o, each jellyfish location is updated depending on the movement within the swarm, as clarified in Equations (24) and (25).

$$X_i(t+1) = 0.1 \times R \times (U_b - L_b) + X_i(t) \quad (24)$$

$$X_i(t+1) = \begin{cases} X_i(t) + R \times (X_j(t) - X_i(t)) & if \;\; f(X_i) \geq f(X_j) \\ X_i(t) + R \times (X_i(t) - X_j(t)) & if \;\; f(X_i) < f(X_j) \end{cases} \quad (25)$$

As soon as a jellyfish moves at the back of the search zone boundaries, it will go back, as is demonstrated in Equation (26), to the reverse boundary.

$$\begin{cases} X'_{i,d} = (X_{i,d} - U_{b,d}) + L_b(d) & if \quad X_{i,d} > U_{b,d} \\ X'_{i,d} = (X_{i,d} - L_{b,d}) + U_b(d) & if \quad X_{i,d} < L_{b,d} \end{cases} \quad (26)$$

where $X_{i,d}$ expresses the ith jellyfish location in dth dimension. The main steps of the JSA are depicted in Figure 3.

3.3. Proposed Hybrid HBJSA

In this sub-section, a hybrid HBJSA is proposed to combine the benefits of the standard HBA and standard JSA. Compared with standard HBA and standard JSA, the proposed HBJSA employs an adjustment mechanism to support the explorative and exploitative characteristics. This mechanism is constructed to boost the explorative feature at the start of iterations by enhancing the generated solutions via HBA. Furthermore, toward the conclusion of iterations, it augments and enhances the exploitative feature by growing the generated solutions via JSA. The adjustment mechanism is executed by employing an adaptive coefficient (φ) designed as follows:

$$\varphi = \frac{t}{2 \times T^{\max}} \quad (27)$$

From this equation, the coefficient (φ) is correlated positively with the number of iterations increases until it reaches 0.5 at the highest quantity of iterations. The more the value of the coefficient (φ) increases, increasing of the generated solutions via JSA will be updated by Equation (28) as follows:

$$x_i^k(t+1) = R \times (Leader^k - 3 \times R \times \mu) + x_i^k(t) \quad (28)$$

where *Leader* is the leader position of the search agents, which achieves the minimum fitness value.

Another point of view for handling the CHP economic dispatch problem, the objective function in Equation (1) is updated to incorporate penalized terms of the power and heat units constraints as follows:

$$OF = WFC + Pen_v \sum_{j=1}^{N_c} B_v \left(P_j^C(H_j^C) - P_j^{CLimit}(H_j^C) \right) \quad (29)$$

where the term (P_j^{CLimit} (H_j^C)) is the power limit to the CHP j heating output; ψ_v is a penalized coefficient for CHP operating violating; Bv equals 1 when there is violation or 0 when there is not. Accordingly, the farthest violated operating point will have a greater penalty.

Figure 4 illustrates the main steps of the proposed hybrid HBJSA for handling the CHP economic dispatch problem. For more information about the proposed HBJSA, the main steps can be summarized as follows:

- Define the parameters of HBJSA.
- Randomly initialize the control parameters that involve the output of power and heat of the committed units and keep it within the accepted boundaries. They are checked versus its acceptable bounds' mechanism. Both units began inside their respective limitations, and if either of them is violated throughout the repetitions, it is reset to the nearest limit.
- Evaluate the fitness function of the CHP problem that minimizes the overall cost using Equation (28).

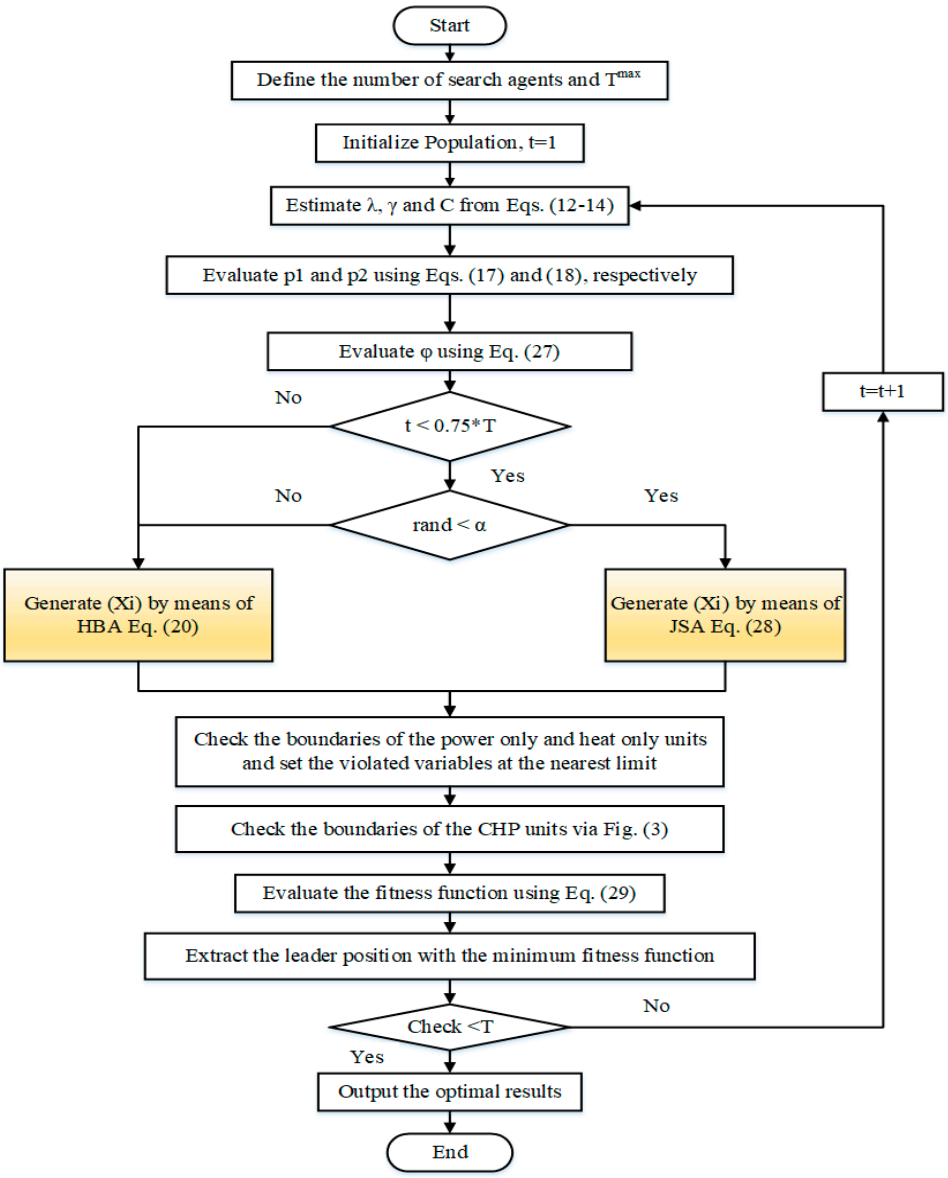


Figure 4. Flowchart of the proposed HBJSA.

Figure 3 shows the second type of mutually dependent CHP unit. They are dealt with as the penalty function that is added in the considered fitness function (OF) in Equation (29). As shown in Figure 3, when an operational point is inside the limits, it has a Bv value of zero, while the infeasible locations have a Bv value of one. On the other side, the greater the penalty amount, the farther the infeasible point is from the nearest border.

As a result, the proposed hybrid HBJSA has a greater capacity for looking for suitable locations. Furthermore, a stopping condition is used in which the ideal result is attained if the maximum number of iterations is reached. HBA penalizes infeasible solutions to varying degrees based on their distance from the next feasible point.

4. Simulation Results

The proposed HBJSA, the standard HBA, and JSA are employed on four test systems. The first two test systems are medium-scale 24-unit and 48-unit systems, whereas the second two test systems are large-scale 84-unit and 96-unit test systems. The number of iterations (T) and population size (n_{pop}), which are the main two parameters of the standard HBA, the standard JSA, and the proposed HBJSA account for 3000 and 100, respectively, for all systems. MatlabR2017b is utilized to carry out the simulations using CPU (2.5 GHz) Intel(R)-Core (TM) i7-7200U and 8 GB of RAM.

4.1. Simulation Results of the 24-Unit Test System

The data for the obtained system are mentioned in [40], which illustrates that 2350 MW and 1250 MWth are the load demand and heat demand, respectively, and it has five heat units, 13 thermal units, and six CHP units. The HBA, JSA, and proposed HBJSA are applied on this test system, and the corresponding MW, MWth for each unit, and WFC are demonstrated in Table 1. It can be manifested that the proposed HBJSA provides the optimal solution for WFC minimization, which accounts for USD 57,968.5399, while the standard HBA and the standard JSA account for USD 57,994.51 and USD 58,739.5241, respectively.

Moreover, convergence characteristics of the proposed HBJSA versus the standard HBA and the standard JSA for the 24-unit test system of the CHP economic dispatch problem are depicted in Figure 5. It is seen from that figure that the proposed hybrid HBJSA is capable of improving the solution quality compared to the standard HBA and the standard JSA. At the last 400 iterations, the proposed hybrid HBJSA provides a higher exploitative feature and, finally, reaches the lowest WFC of USD 57,968.5399. Additionally, the standard HBA, the standard JSA, and the proposed HBJSA effectively achieve all constraints with 100% accuracy, as illustrated in Table 1.

In addition, a comparison between the HBA, JSA, and the proposed HBJSA is conducted in Table 2 for the 24-unit system of CHP economic dispatch with respect to reported techniques such as PSO [40], time-varying acceleration coefficients-PSO (TVAC-PSO) [40], group search optimization (GSO) [41], and improved GSO (IGSO) [42], MRFO [28], and supply demand algorithm (SDA) [34]. In this table, ranking order is evaluated in ascending order based on the minimum WFC. From this table, the proposed hybrid HBJSA achieves the first rank with the lowest WFC. On the other side, the standard HBA occupies the second rank, while the standard JSA occupies the last rank. This table demonstrates that the proposed HBJSA overwhelmed the standard HBA, the standard JSA, and the reported recent techniques for achieving minimum WFC.

Table 1. Comparison between HBA, JSA, and the proposed HBJSA for the 24-unit test system of CHP economic dispatch problem.

Unit	JSA	HBA	HBJSA
P 1	449.27558	538.55874	448.81809
P 2	149.67888	300.2175	299.21886
P 3	202.56201	301.08256	300.72118
P 4	109.86032	159.77793	60.109633
P 5	109.93156	63.21736	159.74512
P 6	159.73642	60.688903	159.77696
P 7	160.00828	160.20653	159.77184
P 8	159.74295	111.5383	60.000007
P 9	109.83449	161.25396	159.75102
P 10	77.389984	40	77.411833
P 11	77.406979	40.000266	40.001098
P 12	92.367201	55.657936	55.008621
P 13	92.395174	55.284533	55.661102
P 14	115.82103	87.944171	85.844198
P 15	40.964462	41.266255	42.751997
P 16	114.87371	84.034893	95.888699
P 17	69.301243	43.143672	44.468374
P 18	10.133787	11.08247	10.046228
P 19	48.715961	35.04403	35.005125
H 14	124.27642	108.69733	107.49154
H 15	75.711188	76.092716	77.376451
H 16	123.80751	106.47628	113.15577
H 17	100.29358	77.714606	78.85075
H 18	40.003606	40.464341	40.020006
H 19	26.210361	20.020468	20.001274
H 20	399.97537	460.53782	453.10933
H 21	59.9258	60	60
H 22	59.902038	60	59.998827
H 23	119.91378	119.99644	119.99649
H 24	119.98035	120	119.99957
Sum (Pg)	2350.0000	2350.0000	2350.0000
Sum (Hg)	1250.0000	1250.0000	1250.0000
WFC	58,739.5241	57,994.5150	57,968.5399

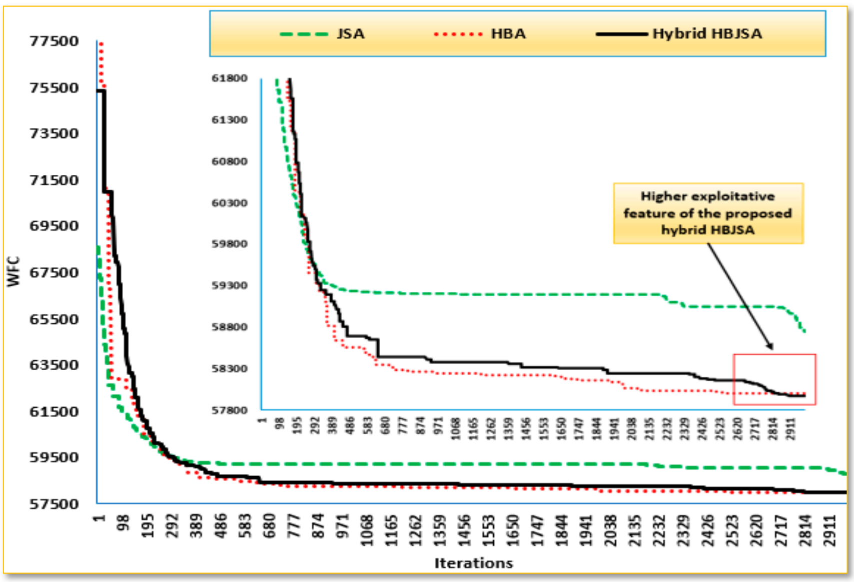


Figure 5. Convergence characteristics of the proposed HBJSA versus the HBA and JSA for the 24-unit system of CHP economic dispatch.

Table 2. Comparison between HBA, JSA, and HBJSA with respect to reported techniques for the 24-unit system of CHP economic dispatch.

Method	Sum (Pg)	Sum (Hg)	WFC	Rank
GSO [41]	2350	1250	58,225.745	7
IGSO [41]	2350	1250	58,049.01	3
PSO [40]	2349.9	1250	59,736.26	8
TVAC-PSO [40]	2350.0002	1250	58,122.74	5
MRFO [28]	2350	1250	58,173.93	6
SDA [34]	2350	1250	58,061.477	4
JSA	2350	1250	58,739.5241	9
HBA	2350	1250	57,994.515	2
Proposed hybrid HBJSA	2350	1250	57968.54	1

4.2. Simulation Results of the 48-Unit Test System

Table 3. Comparison between HBA, JSA, and the proposed HBJSA for the 48-unit test system of CHP economic dispatch problem.

Output	HBA	JSA	HBJSA	Output	HBA	JSA	HBJSA
P 1	628.31969	538.55876	628.31847	P 33	89.741692	93.956738	92.056329
P 2	301.64745	166.31944	298.49068	P 34	45.760605	63.520906	44.496057
P 3	297.56062	299.2078	298.71921	P 35	93.563713	98.369246	95.721078
P 4	60.025209	109.86692	162.17614	P 36	54.117683	64.357184	46.047531
P 5	60.891955	159.73312	60	P 37	10.89958	16.476816	11.179988
P 6	115.51041	109.86683	60.187387	P 38	35	47.149532	36.636756
P 7	60	109.87111	60.000003	H 27	109.52988	130.11379	112.92198
P 8	112.29664	109.86759	61.265074	H 28	77.887623	76.952262	80.359207
P 9	163.79819	109.86802	60.012628	H 29	106.94451	118.12661	112.31166
P 10	84.337266	77.40216	40.077792	H 30	79.211207	102.05398	78.341268
P 11	44.380157	77.405413	77.401957	H 31	42.302628	42.775213	40.213152
P 12	92.442285	92.402577	92.236557	H 32	21.949409	24.616716	20.01776
P 13	92.547707	92.400831	55.000005	H 33	108.80007	112.07165	111.00119
P 14	538.58181	359.03989	628.66001	H 34	79.972231	95.305162	78.407382
P 15	150.5131	149.62114	299.67572	H 35	111.85121	114.54771	112.98988
P 16	302.48049	299.20217	224.39881	H 36	87.186384	96.027118	80.220448
P 17	159.0721	109.86997	160.3726	H 37	40.316118	42.776163	40.506134
P 18	159.48447	110.38702	110.74399	H 38	19.999898	25.522939	20.698728
P 19	60.042597	109.86649	159.34188	H 39	442.02953	399.58888	445.84515
P 20	60.163088	109.86727	60	H 40	59.963929	59.999977	60
P 21	160.27015	109.8666	60.001242	H 41	60	59.999861	59.99996
P 22	158.67694	159.73453	162.0577	H 42	119.87507	119.99992	120
P 23	40	77.402895	78.899748	H 43	119.99995	119.99993	119.99952
P 24	40.430825	77.408107	40	H 44	452.35143	399.52269	446.16766
P 25	55.283719	92.400956	55	H 45	59.829479	59.999808	59.99892
P 26	55.000343	92.649622	55.003382	H 46	59.999794	59.999907	60
P 27	89.427389	126.10612	95.4717	H 47	119.99989	119.99982	120
P 28	43.348156	42.260587	46.55662	H 48	119.99975	119.9999	120
P 29	84.844588	104.74609	94.384639	Sum (Pg)	4700	4700	4700
P 30	44.879351	71.338822	43.869636	Sum (Hg)	2500	2500	2500
P 31	15.371858	16.474563	10.500572	WFC (USD)	116,439.96	117,365.09	116,140.34
P 32	39.288183	45.156162	35.038114				

The data for the obtained system are mentioned in [40], which illustrates that 4700 MW and 2500 MWth are the load demand and heat demand, respectively, and it has 10 heat units, 26 thermal units, and 12 CHP. The HBA, JSA, and proposed HBJSA are applied to this test system, and the corresponding MW, MWth for each unit, and WFC are demonstrated in Table 3. It can be manifested that the proposed HBJSA provides the optimal solution for WFC minimization, which accounts for USD 116,140.34, while the standard HBA and the standard JSA account for USD 116,439.96 and USD 117,365.09, respectively.

Moreover, convergence characteristics of the proposed HBJSA versus the standard HBA and the standard JSA for the 48-unit test system of the CHP economic dispatch problem are depicted in Figure 6. It is seen from that figure that the proposed hybrid HBJSA is capable of improving the solution quality compared to the standard HBA and the standard JSA. After 900 iterations, the suggested hybrid HBJSA delivers more exploitative features and ultimately achieves the lowest WFC of USD 116,140.34. Additionally, the standard HBA, the standard JSA, and the proposed HBJSA effectively achieve the power and heat balance constraints with 100% accuracy, as illustrated in Table 3.

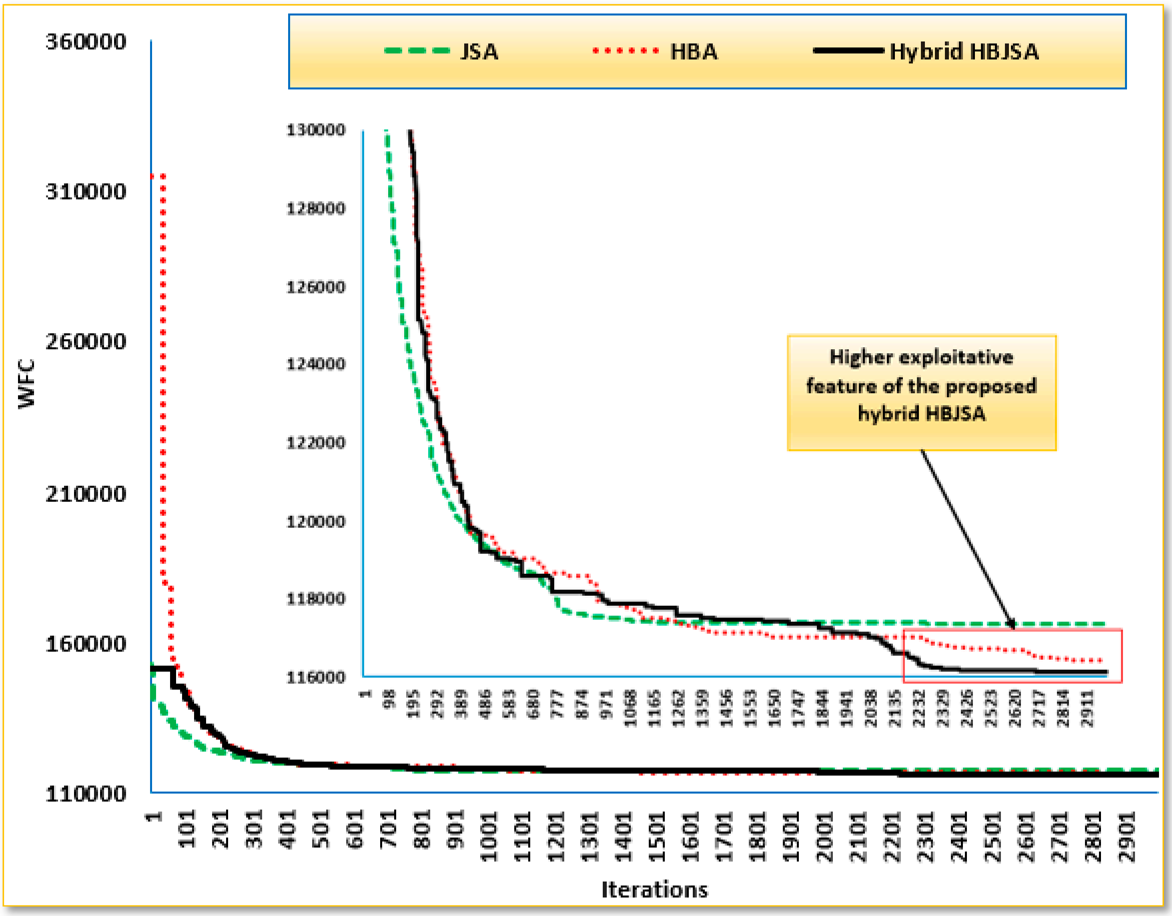


Figure 6. Convergence characteristics of the proposed HBJSA versus the HBA and JSA for the 48-unit system of CHP economic dispatch.

In addition to this, a comparison between the HBA, JSA, and proposed HBJSA is conducted in Table 4 for the 48-unit system of CHP economic dispatch with respect to other reported techniques such as MRFO [28], SDA [34] TVAC-PSO [40], CPSO [40], GSO [43], modified PSO [44], OTLBO [16], and MGSO [43] and gravitational search algorithm (GSA) [45]. Additionally, crow search algorithm (CSA) [46], grey wolf algorithm (GWA) [47], salp swarm algorithm (SSA) [48], multi-verse algorithm (MVA) [49], DE [50], MPA [51–53], civilized swarm optimization CSO [54] and Powell's pattern search PPS [54] are applied to the CHP economic dispatch for this system.

Table 4. Comparison between HBA, JSA, and HBJSA with respect to reported techniques for the 48-unit system of CHP economic dispatch.

Optimizer	WFC (USD)	Rank	Optimizer	WFC (USD)	Rank
SDA [34]	116,620.61	7	Modified PSO [44]	116,465.54	3
MRFO [28]	117,336.9	9	TVAC-PSO [40]	118,962.54	14
CSA [28]	122,953.5	20	GSA [45]	119,775.9	15
GWA [28]	122,583.3	19	MPA [42]	116,860.6	8
SSA [48]	120,174.1	16	CSO and PPS [54]	117,367.09	12
MVA [28]	117,657.9	13	MGSO [43]	117,366.09	11
DE [28]	120,482.7	17	HBA	116,439.96	2
GSO [43]	116,578.475	6	JSA	117,365.09	10
OTLBO [16]	116,579.24	4	Proposed hybrid HBJSA	116,331.21	1
PSO [40]	120,918.92	18			

In this table, ranking order is evaluated in ascending order based on the minimum WFC. From this table, the proposed hybrid HBJSA achieves the first rank with the lowest WFC. On the other side, the standard HBA occupies the second rank, while the standard JSA occupies the tenth rank. This table demonstrates that the proposed HBJSA overwhelmed the standard HBA, the standard JSA, and reported recent techniques for achieving minimum WFC.

4.3. Simulation Results of the 84-Unit Test System

The data for the tested system are mentioned in [20]. The power and heat demands equal 12,700 MW and 5000 MWth, respectively, and it has 20 heat units, 40 thermal units, and 24 CHP. The HBA, JSA, and proposed HBJSA are investigated to this test system, and the corresponding MW, MWth for each unit, and WFC are demonstrated in Table 5. It can be manifested that the proposed HBJSA provides the optimal solution for WFC minimization, which accounts for USD 288,820.7, while the standard HBA and the standard JSA account for USD 289,822.4 and USD 290,323.8, respectively.

Moreover, convergence characteristics of the proposed HBJSA are depicted in Figure 7 versus the standard HBA and the standard JSA for the 84-unit test system of the CHP economic dispatch problem. It is seen from that figure that the proposed hybrid HBJSA is capable of improving the solution quality compared with HBA and JSA. At the last 950 iterations, the proposed hybrid HBJSA provides a higher exploitative feature and, finally, reaches the lowest WFC of USD 288,820.7. Additionally, the standard HBA, the standard JSA, and the proposed HBJSA effectively achieve all constraints with 100% accuracy, as illustrated in Table 5.

In addition, a comparison study between the HBA, JSA, and proposed HBJSA is conducted in Table 6 for the 84-unit system of CHP economic dispatch with respect to reported techniques such as WOA [20], MRFO [28], marine predators algorithm (MPA) [42], improved MPA (IMPA) [42], and SDA [34]. In this table, ranking order is evaluated in ascending order based on the minimum WFC. From this table, the proposed hybrid HBJSA achieves the first rank with the lowest WFC. On the other side, the standard HBA occupies the second rank while the standard JSA occupies the fifth rank. This table demonstrates that the proposed HBJSA overwhelmed the standard HBA, the standard JSA, and reported recent techniques for achieving minimum WFC.

Table 5. Comparison between HBA, JSA, and the proposed HBJSA for the 84-unit test system of CHP economic dispatch problem. (a) Power outputs from power only and CHP units. (b) Heat outputs from CHP and heat-only units.

(a)

Unit	HBA	JSA	HBJSA	Unit	HBA	JSA	HBJSA
Pg1	114	111.1626385	113.9718986	Pg33	181.7205	159.7499057	185.8014921
Pg2	113.11556	112.5520392	112.0171823	Pg34	199.99998	199.9449699	199.988706
Pg3	103.83725	107.7765112	98.99471338	Pg35	182.91598	199.6705009	181.7649853
Pg4	184.80695	179.7375644	179.6906294	Pg36	200	199.991963	199.9921324
Pg5	89.505208	87.78776144	94.40847581	Pg37	109.99936	89.86684403	109.9315908
Pg6	106.64827	139.9948775	138.9511133	Pg38	110	109.9917663	104.3481595
Pg7	256.25545	266.7806527	260.1628409	Pg39	89.839986	94.16960534	109.9999047
Pg8	297.05131	290.8186132	299.6320704	Pg40	550	511.3076161	517.5996621
Pg9	299.99539	284.6025908	288.5380215	Pg41	126.91167	132.3982552	110.3909623
Pg10	130	207.4135385	130	Pg42	126.65154	144.4049507	136.7428407
Pg11	169.30903	243.5827337	242.0952346	Pg43	115.3838	88.99398926	134.0103426
Pg12	306.09411	318.3996454	168.8036849	Pg44	133.27883	105.2551322	117.7366501
Pg13	394.50082	304.5241963	394.2779192	Pg45	42.80197	93.63589835	49.34154951
Pg14	393.7356	304.5184491	394.2937412	Pg46	43.679119	49.07352085	43.51922726
Pg15	305.53666	394.322214	396.1931056	Pg47	77.280238	76.78719074	59.37920101
Pg16	394.45006	304.521412	394.3233195	Pg48	74.818416	55.66222673	50.7813389
Pg17	500	489.2867798	489.4316065	Pg49	99.519272	167.415806	100.5621492
Pg18	490.89205	399.4800955	493.0301498	Pg50	116.0936	170.7899652	105.6288952
Pg19	514.62594	511.432115	511.337944	Pg51	109.31998	167.4168782	114.6635218
Pg20	525.35426	511.3041636	550	Pg52	106.01984	125.329591	133.3378228
Pg21	550	523.3475504	523.296119	Pg53	60.72298	60.42436073	70.08052756
Pg22	548.52995	523.2824448	527.9275831	Pg54	52.580944	79.5458983	67.82445444
Pg23	550	523.2914355	549.9999949	Pg55	43.691272	56.36733616	52.91754938
Pg24	521.61373	523.3169144	536.3000349	Pg56	56.186778	66.27287672	55.44283757
Pg25	522.56351	523.306813	526.3906729	Pg57	12.98492749	10.52629429	24.879583
Pg26	549.31974	523.2792844	523.3095942	Pg58	29.50082157	13.96655832	13.325097
Pg27	14.540184	10.00833641	11.43580483	Pg59	10.22458212	10.24231125	12.523674
Pg28	10.098278	10.00401295	11.56317354	Pg60	13.31866365	18.41685747	12.214388
Pg29	10.909877	10.02394824	10.00000666	Pg61	37.73118881	46.39822013	58.063135
Pg30	96.999939	96.95242919	89.71504585	Pg62	55.41904721	77.24184524	47.952259
Pg31	180.39147	181.241749	188.3825144	Pg63	38.52470481	53.47372752	35.709818
Pg32	189.8298	189.9953502	189.9818368	Pg64	58.3696072	57.21827797	45.08951

(b)

Unit	HBA	JSA	HBJSA	Unit	HBA	JSA	HBJSA
Hg41	130.3604684	133.6418007	121.29	Hg65	397.9644411	347.8697453	409.80933
Hg42	130.2202223	140.381546	136.07204	Hg66	394.0861183	349.5293932	397.46604
Hg43	123.5432156	109.2841022	134.528	Hg67	400.2039596	349.7318595	413.03126
Hg44	134.1352577	118.4055739	125.13589	Hg68	401.4451605	344.0636931	366.65675
Hg45	77.30525496	121.3009135	83.04628	Hg69	59.9999999	59.99488855	59.953414
Hg46	78.02176698	82.83206972	78.035694	Hg70	59.3632427	59.97703456	59.988637
Hg47	107.1826963	106.7556784	88.175722	Hg71	59.86117224	59.99220729	59.466048
Hg48	105.056327	88.52055969	84.30425	Hg72	60	59.81462736	59.836488
Hg49	115.192982	153.2842745	113.88524	Hg73	58.88396654	59.98307532	60
Hg50	124.3738069	155.1483245	118.16811	Hg74	59.5417115	59.99915877	60
Hg51	120.69336	153.2958557	123.68397	Hg75	59.81273203	59.90067694	60
Hg52	118.7925953	129.3907541	133.9953	Hg76	60	59.98083928	59.999977
Hg53	92.88987192	92.63077153	100.95165	Hg77	120	119.9950741	119.99872
Hg54	85.7914299	109.1376617	99.009779	Hg78	120	119.9939719	117.44199
Hg55	78.18666618	89.12490012	86.055856	Hg79	119.9528822	119.9953091	119.99999
Hg56	88.97404025	97.67717242	88.298905	Hg80	120	119.9308343	120
Hg57	41.27968283	40.22573511	46.369847	Hg81	119.9999728	119.9583146	119.99954
Hg58	48.35748487	41.69903249	41.415021	Hg82	119.4423968	119.9958398	120
Hg59	40.09624275	40.10312819	41.063184	Hg83	119.999888	119.9968772	116.18205
Hg60	41.2298315	43.60456849	40.943192	Hg84	111.9564926	119.9957398	119.08122
Hg61	21.18412326	25.17541074	29.921693	Sum (Pg)	12702	12701	12704
Hg62	27.1688682	39.19892893	25.868861	Sum (Hg)	5000	5000	5000
Hg63	21.60258212	28.38461052	19.393777	WFC (USD)	289,822.392	290,323.818	288,820.7
Hg64	25.84708597	30.09746698	21.476288				

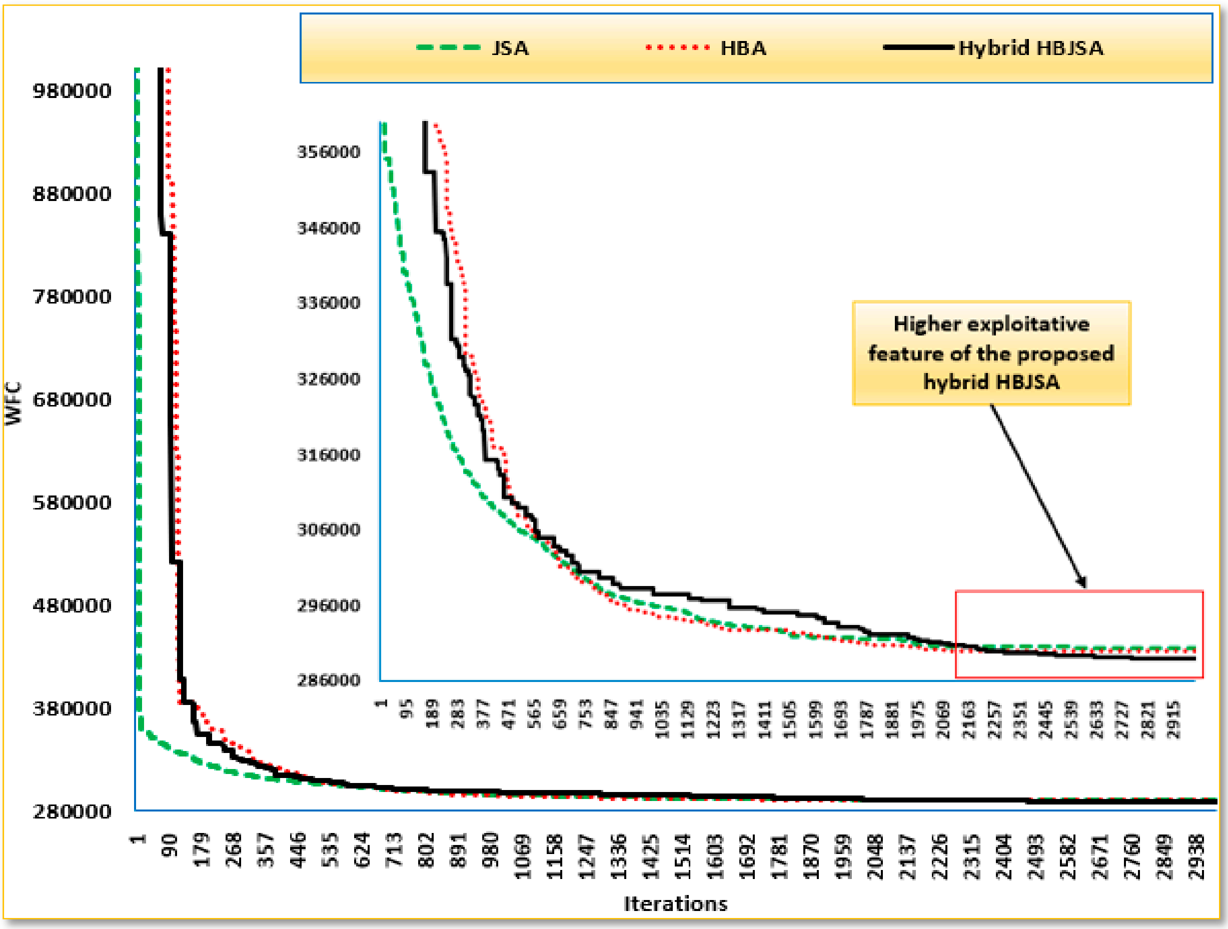


Figure 7. Convergence rates of the proposed HBJSA versus the HBA and JSA for the 84-unit system of CHP economic dispatch.

Table 6. Comparison between HBA, JSA, and HBJSA with respect to reported techniques for the 84-unit system of CHP economic dispatch.

Optimizer	WFC (USD)	Rank
WOA [20]	290,123.97	4
SDA [34]	292,788.5	7
MPA [42]	294,717.7	8
IMPA [42]	289,903.8	3
MRFO [28]	291,225.6	6
HBA	289,822.4	2
JSA	290,323.8	5
Proposed hybrid HBJSA	288,820.7	1

4.4. Simulation Results of the 96-Unit Test System

The data for the obtained system are mentioned in [20], which illustrates that 12700 MW and 5000 MWth are the load demand and heat demand, respectively, and it has 20 heat units, 52 thermal units, and 24 CHP units. The standard HBA, standard JSA, and proposed HBJSA are applied to this test system, and the corresponding MW, MWth for each unit, and WFC are demonstrated in Table 7. It can be manifested that the proposed HBJSA provides the optimal solution for WFC minimization, which accounts for USD 234,836.04, while the standard HBA and the standard JSA account for USD 235,102.65 and USD 235,277.05, respectively.

Table 7. Comparison between HBA, JSA, and the proposed HBJSA for the 96-unit test system of CHP economic dispatch problem. (a) Power outputs from power only and CHP units. (b) Heat outputs from CHP and heat-only units.

(a)

Unit	HBA	JSA	HBJSA	Unit	HBA	JSA	HBJSA
Pg1	537.254715	628.137415	448.717297	Pg39	92.65458803	92.39186824	92.49373328
Pg2	341.5738074	224.3852587	299.2517474	Pg40	448.3942915	448.8085979	442.7202304
Pg3	151.1408777	224.523037	224.1274655	Pg41	297.8196029	150.3797127	299.2207761
Pg4	109.0977628	109.8640106	111.2441868	Pg42	146.2329552	299.2034647	299.2279809
Pg5	64.10866612	109.8714738	62.37611714	Pg43	110.6346294	111.2974761	160.3281579
Pg6	110.0480942	159.7649454	179.2961575	Pg44	161.7767837	110.3086384	60.04191249
Pg7	94.33638081	159.7332315	99.67889937	Pg45	61.66518066	159.5162729	60.0000011
Pg8	60.00000879	110.0519045	117.6713057	Pg46	108.9737886	109.8987507	160.4436803
Pg9	108.2875293	110.3981768	156.6263679	Pg47	110.4947542	109.9034171	60.69590696
Pg10	115.4310336	110.6273109	78.02377234	Pg48	109.9050818	110.2078249	115.9607595
Pg11	49.01342421	77.48642225	78.94705246	Pg49	42.02833221	77.39752348	40.52730593
Pg12	92.02655803	92.39805239	92.1778521	Pg50	72.25178996	77.33236811	76.26902551
Pg13	55.18840658	92.42912952	88.05166676	Pg51	93.0608812	92.76312061	86.46078517
Pg14	360.9754061	358.9389673	538.5168446	Pg52	92.57317097	93.12310103	82.99448914
Pg15	299.3860657	224.471123	224.6561836	Pg53	104.4403419	104.9831519	93.34146328
Pg16	359.9221971	227.8984155	149.8696746	Pg54	47.60359863	45.13159323	52.66559089
Pg17	159.7120077	109.9684494	60	Pg55	88.44497134	100.2247131	106.2115994
Pg18	109.3602599	109.9616018	60	Pg56	50.14389995	51.71950188	65.28739078
Pg19	110.4137284	109.8707063	154.0137736	Pg57	12.03402877	19.00938769	10.16852035
Pg20	101.8946306	110.4372778	109.7933677	Pg58	45.6270289	56.30321085	37.30026155
Pg21	109.8648707	109.96827	60	Pg59	91.41295489	125.4849027	110.4459566
Pg22	179.4592083	109.861271	159.8078912	Pg60	51.86266145	51.90216163	56.35148968
Pg23	40.13034648	114.7915897	40.00785124	Pg61	110.2162351	91.18311611	93.67867133
Pg24	77.22962911	77.44476922	40.00084287	Pg62	47.62594622	54.14716313	42.99511003
Pg25	66.61283247	92.41354325	92.2948894	Pg63	18.272772	34.655934	20.975389
Pg26	91.02277492	92.44381223	94.51903986	Pg64	45.155884	75.627888	35.029188
Pg27	359.4498313	359.4658937	629.8475952	Pg65	88.829361	148.19343	107.83001
Pg28	299.4259674	149.5651638	151.507932	Pg66	43.74986	75.326734	51.732368
Pg29	289.8301184	224.7535524	359.9646486	Pg67	95.340679	100.58341	87.64695
Pg30	161.92495	109.9432458	109.8286727	Pg68	67.297804	42.252459	52.983829
Pg31	107.7669533	109.7440166	60.38342883	Pg69	11.638244	17.202374	10.380566
Pg32	159.4640725	109.899657	109.8614158	Pg70	35.028678	47.915618	37.11649
Pg33	162.5783378	112.3437083	160.9958816	Pg71	87.384128	99.938915	110.78998
Pg34	159.9001838	118.7834711	159.7427634	Pg72	53.523651	67.954604	44.094744
Pg35	60.03756814	109.9579597	109.7936225	Pg73	106.28473	88.257959	99.595259
Pg36	113.7051781	114.8045459	120	Pg74	65.916093	53.319524	62.695199
Pg37	114.3819608	77.49926496	40.00494973	Pg75	12.449246	11.427801	10.796383
Pg38	94.29271341	92.63059511	86.65823591	Pg76	35.002312	47.191073	44.243458

(b)

Unit	HBA	JSA	HBJSA	Unit	HBA	JSA	HBJSA
Hg53	117.8187	118.25717	111.65705	Hg77	385.57459	400.14747	390.26983
Hg54	81.187872	79.425882	85.919458	Hg78	59.99772	59.999812	56.453332
Hg55	108.9226	115.58344	118.85523	Hg79	60	59.922567	59.999913
Hg56	83.024668	85.11551	96.801938	Hg80	118.82035	119.99872	119.42771
Hg57	40.490709	43.852427	40.05269	Hg81	119.99892	119.97171	119.96065
Hg58	24.658925	29.679309	15.297858	Hg82	438.22049	402.77116	436.82909
Hg59	109.94761	129.76254	116.53145	Hg83	60	59.993989	59.982729
Hg60	83.140535	85.274518	89.077417	Hg84	59.858041	59.997954	59.888563
Hg61	120.77066	110.51193	111.89757	Hg85	119.95149	119.99343	119.76019
Hg62	81.226938	87.148267	77.525341	Hg86	118.46015	119.99908	119.9878
Hg63	39.67663	50.561873	44.68415	Hg87	450.50341	399.42417	429.43143
Hg64	23.984424	38.46521	19.947464	Hg88	59.784083	59.977283	60
Hg65	108.20515	142.50587	119.75308	Hg89	59.830588	59.991776	59.830142
Hg66	77.96514	105.49604	85.12105	Hg90	119.99947	119.9983	120
Hg67	112.78318	115.78643	108.31842	Hg91	118.32769	119.99419	119.89929
Hg68	98.469051	76.943631	85.900861	Hg92	451.81766	398.46975	449.27757

Table 7. *Cont.*

(b)							
Unit	**HBA**	**JSA**	**HBJSA**	**Unit**	**HBA**	**JSA**	**HBJSA**
Hg69	40.664318	43.086924	40.158344	Hg93	60	59.998636	59.693249
Hg70	18.721909	25.870776	20.947021	Hg94	59.916361	59.985181	59.957398
Hg71	106.59216	115.42154	121.3902	Hg95	119.99988	119.98799	119.99901
Hg72	86.491633	99.131229	78.521522	Hg96	119.83914	119.99335	119.9259
Hg73	118.09871	108.86068	115.18485	Sum (Pg)	9400	9400	9400
Hg74	97.014286	86.491059	94.56892	Sum (Hg)	5000	5000	5000
Hg75	40.89038	40.610943	37.166946	WFC	235,102.65	235,277.05	234,836.04
Hg76	18.353784	25.540248	24.147382				

Moreover, convergence characteristics of the proposed HBJSA versus the standard HBA and the standard JSA for the 96-unit test system of the CHP economic dispatch problem are depicted in Figure 8. From this figure, the proposed hybrid HBJSA is capable of improving the solution quality compared to the standard HBA and the standard JSA. At the last 1000 iterations, the proposed hybrid HBJSA provides a higher exploitative feature and, finally, reaches the lowest WFC of USD 234,836.04. Additionally, the standard HBA, the standard JSA, and the proposed HBJSA effectively achieve all constraints with 100% accuracy, as illustrated in Table 7.

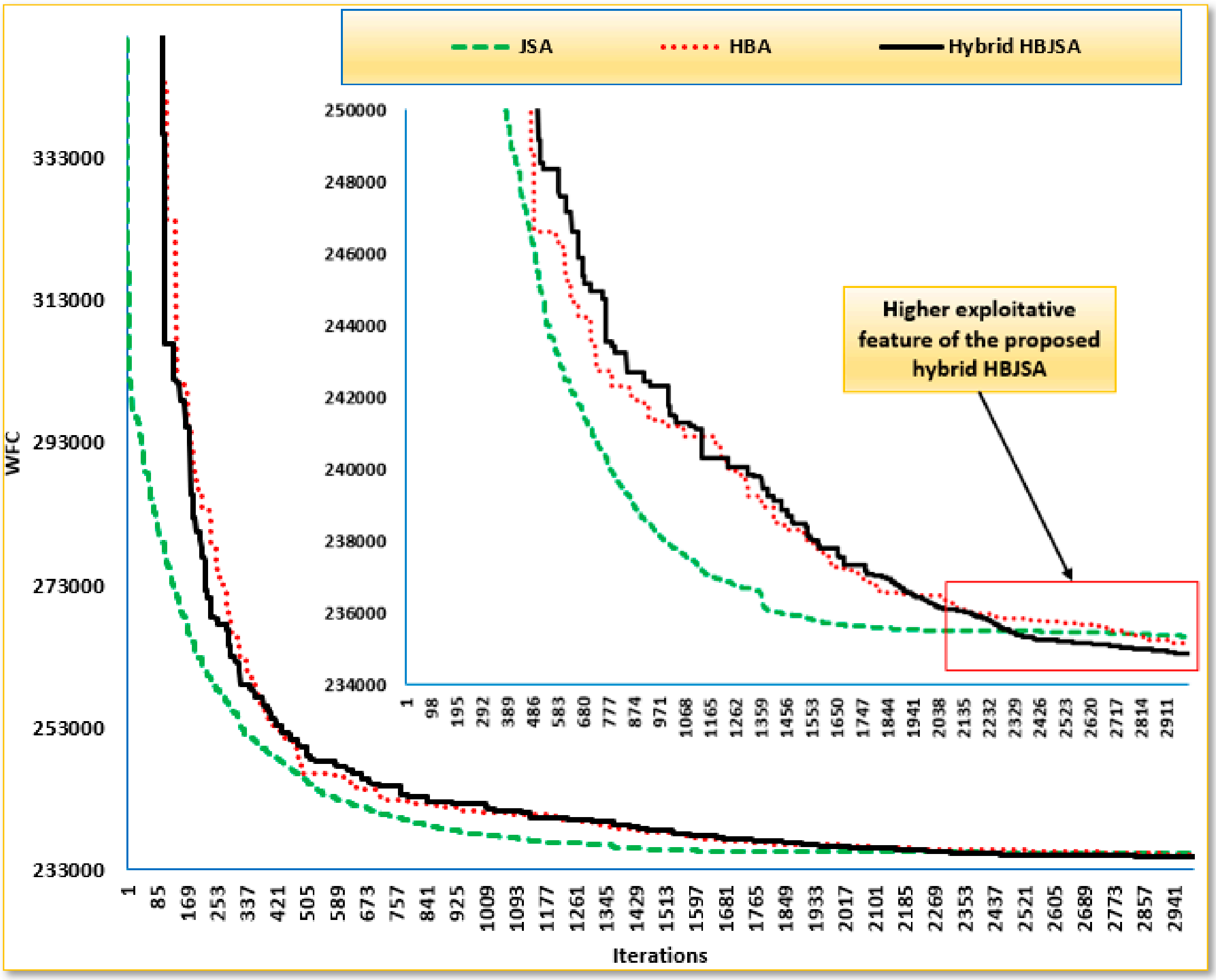


Figure 8. Convergence characteristics of the proposed HBJSA versus the HBA and JSA for the 96-unit system of CHP economic dispatch.

In addition, a comparison study between the standard HBA, JSA, and the proposed HBJSA is conducted in Table 8 for the 96-unit system of CHP economic dispatch with respect to reported techniques such as WVO-PSO [55], WOA [20], MPA [42], IMPA [42], MRFO [29], and SDA [34]. In this table, the ranking order is evaluated in ascending order based on the minimum WFC. From this table, the proposed hybrid HBJSA achieves the first rank with the lowest WFC. On the other side, the standard HBA occupies the second rank, while the standard JSA occupies the fourth rank. Additionally, this table demonstrates that the proposed HBJSA overwhelmed the standard HBA and the standard JSA and reported recent techniques for achieving minimum WFC.

Table 8. Comparison between HBA, JSA, and HBJSA with respect to reported techniques for the 96-unit test system of CHP economic dispatch problem.

Optimizer	Sum (Pg)	Sum (Hg)	WFC (USD)	Rank
WOA [20]	9400.033	5000	236,699.15	8
WVO-PSO [55]	9399.99	4999.99	238,005.79	9
SDA [34]	9400	5000	236,185.18	6
MRFO [29]	9400	5000	235,541.4	5
MPA [42]	9400	5000	236,283.1	7
IMPA [42]	9400	5000	235,260.3	3
HBA	9400	5000	235,102.65	2
JSA	9400	5000	235,277.05	4
Proposed hybrid HBJSA	9400	5000	234,836.04	1

4.5. Statistical Assessment of HBA, JSA, and Proposed Hybrid HBJSA for CHP Economic Dispatch

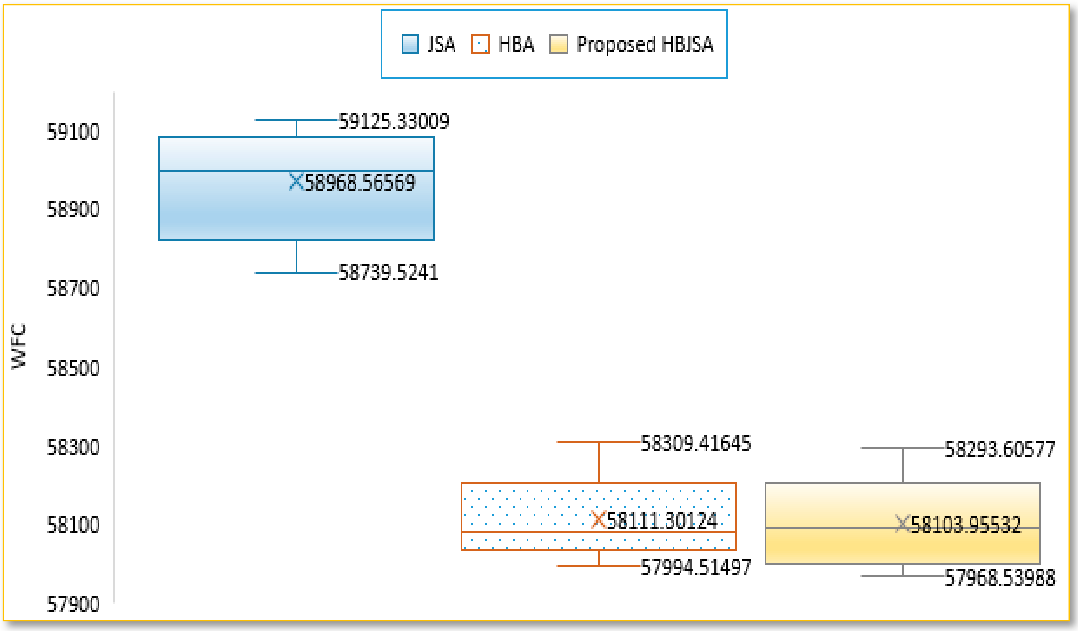
For all test systems, the proposed hybrid HBJSA, HBA, and JSA are run several times, and the corresponding whiskers box plots are drawn in Figure 9. For the 24-unit system, as shown in Figure 9a, the proposed hybrid HBJSA outperforms HBA and JSA in finding the lower minimum, average, and maximum WFC values. The proposed hybrid HBJSA achieves minimum, average, and maximum WFC values of USD 57,968.539, USD 58,103.95, and USD 58,293.6, respectively. On the other side, the HBA achieves minimum, average, and maximum WFC values of USD 57,994.51, USD 58,111.3, and USD 58,309.416, respectively, whereas the JSA obtains counterparts of USD 58,739.524, USD 58,968.565, and USD 59,125.33, respectively.

For the 48-unit system, as shown in Figure 9b, the proposed hybrid HBJSA outperforms HBA and JSA in finding the lowest minimum WFC value of USD 116,140.335. Compared to the HBA, the proposed hybrid HBJSA obtains lower maximum WFC values of USD 117,848.43 where the HBA obtains USD 117,980.55, while both acquire comparable WFC values of USD 116,952.6 and USD 116,946.22 for the proposed hybrid HBJSA and HBA, respectively. Compared to the JSA, the proposed hybrid HBJSA presents great superiority, since the JSA obtains minimum, average, and maximum WFC values of USD 117,365.09, USD 117,911.105, and USD 118,456.98, respectively.

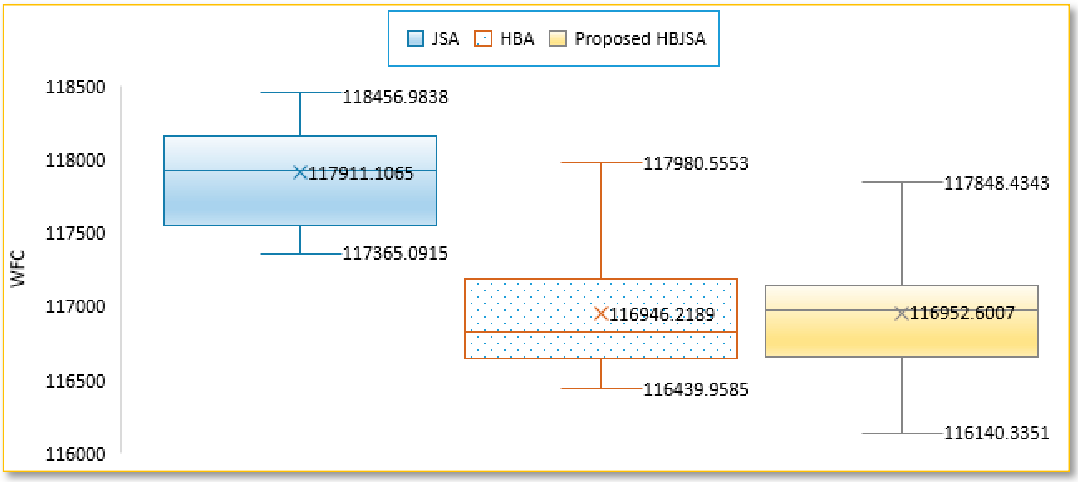
For the 84-unit system, as shown in Figure 9c, the proposed hybrid HBJSA outperforms HBA and JSA in finding the lower minimum, average, and maximum WFC values. The proposed hybrid HBJSA achieves minimum, average, and maximum WFC values of USD 288,820.68, USD 289,813.827, and USD 291,251.73, respectively. On the other side, the HBA achieves minimum, average, and maximum WFC values of USD 289,822.392, USD 290,891.01, and USD 292,342.51, respectively, whereas the JSA obtains counterparts of USD 290,323.82, USD 292,366.86, and USD 293,747.44, respectively.

For the 96-unit system, as shown in Figure 9d, the proposed hybrid HBJSA outperforms HBA and JSA in finding the lower minimum, average, and maximum WFC values. The proposed hybrid HBJSA achieves minimum, average, and maximum WFC values of USD 234,836.0389, USD 235,646.129, and USD 235,967.06, respectively. On the other side, the HBA achieves minimum, average, and maximum WFC values of USD 235,102.65, USD 2,356,921.613, and USD 239,119.46, respectively, whereas the JSA obtains counterparts of USD 235,277.05, USD 236,688.76, and USD 237,940.189, respectively.

All these comparative assessments illustrate the high stability and robustness of the proposed HBJSA in finding the lowest minimum, average, and maximum WFC value compared with the HBA and JSA.

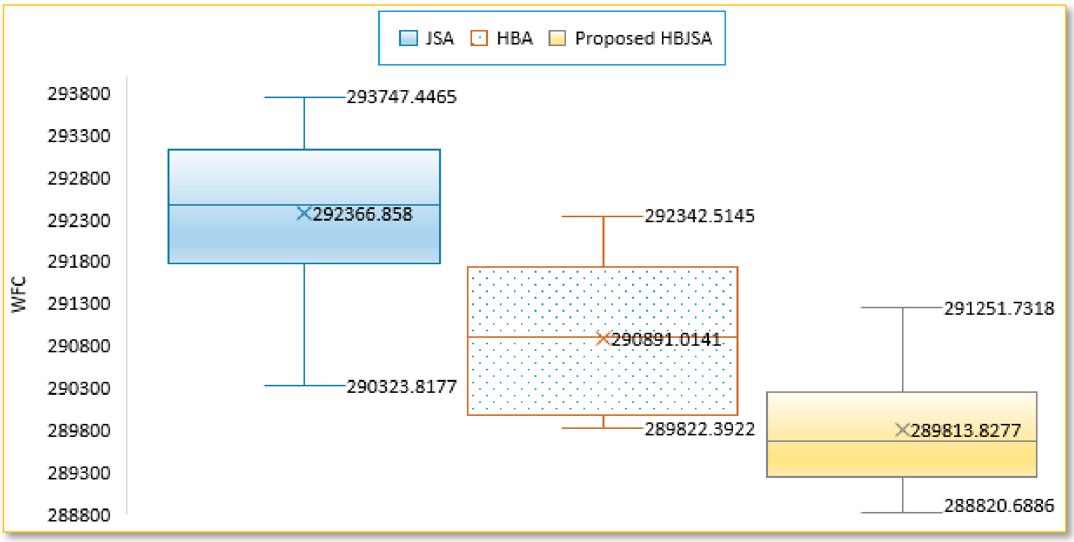


(**a**) 24-unit test system.

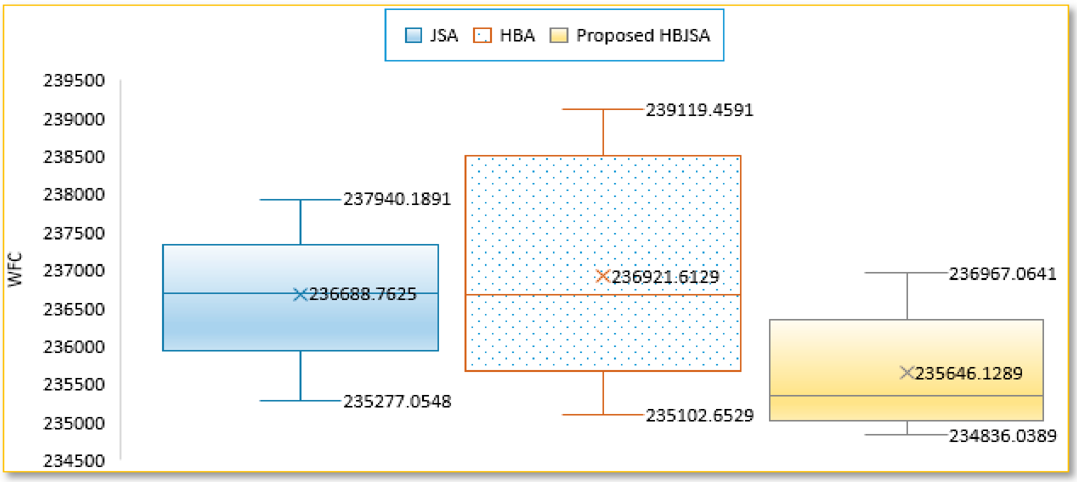


(**b**) 48-unit test system.

Figure 9. *Cont.*



(**c**) 84-unit test system.



(**d**) 96-unit test system.

Figure 9. Whiskers box plot for the proposed HBJSA versus HBA and JSA for solving the CHP economic dispatch problem.

From these implementations, the practical use of the HJBSA for a larger scale as 84-unit and 96-unit test systems do not require cloud solutions. It requires the input data of the system as follows:

- The data of the power and heat loads.
- The data of the power limits of power-only units.
- The data of the heat production limits of heat-only units.
- The data of the power and heat characteristics curves of the CHP units.

5. Conclusions

In this paper, an innovative hybrid heap-based and jellyfish search algorithm (HBJSA) is presented for solving the CHP economic dispatch problem. The proposed hybrid heap-based and jellyfish search algorithm (HBJSA) combines the benefits of the standard HBA and standard JSA. Compared with standard HBA and standard JSA, the proposed HBJSA uses an adjustment mechanism in order to support the explorative and exploitative characteristics. In the proposed HBJSA, an adjustment mechanism has been constructed to boost the explorative feature at the start of iterations by enhancing the generated solutions via HBA. Furthermore, towards the conclusion of iterations, it augments and enhances the exploitative feature by growing the generated solutions via JSA. Besides, the HBA, JSA, and the proposed HBJSA have been utilized to solve the complex CHP economic dispatch problems with hard constraints, which are the feasible operating area of CHP units and valve-point effects. They are applied on two medium systems, which are 24-unit and 48-unit systems, and two large systems, which are 84-unit and 96-unit systems.

The major contributions of this paper are:

- A novel hybrid HBJSA is proposed, for the first time, in order to enhance the performance of the standard HBA and JSA for solving the CHP economic dispatch problem.
- Significant improvements via the proposed HBJSA are achieved in terms of the solution quality with high exploitative convergence characteristics for all systems studied.
- High superiority of the proposed hybrid HBJSA has been satisfied compared with several competitive algorithms in the literature.
- High robustness and stability of the proposed hybrid HBJSA with respect to standard HBA and JSA in finding the lowest minimum, average, and maximum WFC objectives.

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Nomenclature

a_k, b_k, c_k, d_k, e_k and f_k	Cost coefficients of the kth unit
a_j; b_j and c_j	Cost coefficients of jth heat plant
a_i, b_i and c_i	Cost coefficients of ith power plant
WFC	Whole fuel cost
$C_i\left(P_i^{pp}\right)$	Fuel cost of power unit i
$C_j\left(H_j^{hp}\right)$	Fuel cost of jth heat plant
$C_k\left(P_k^{cp}, H_k^{cp}\right)$	The operational cost of kth cogeneration unit
$P_k^{cp_{Limit}}\left(H_k^{cp}\right)$	Power bound for the set heat-output of cogenerator (k)
BI	Binary coefficient
N_{pp}	Number of power-only plants
H_d	System heat load
N_{cp}	Number of cogenerators
N_{hp}	Number of heat-only units
P_d	System power load
H^c	Heat output of CHP
P^c	The power output of CHP
ψ_v	Penalty coefficient
λ_i and ρ_i	Valve-point cost coefficients
CRH	Corporate rank hierarchy
t	Current iteration

k	kth vector component
$\mid \ \mid$	Absolute value
$(2r-1)$	kth component of vector $\overrightarrow{\lambda}$
r	Random number from the range [0,1]
f	Fitness of the search agent
p	Produced randomly number [0,1]
C	User-defined parameter which its unit is (iteration)
CO_o	Constant equals 0.5
X_i	ith jellyfish logistic chaotic value
TC	Time control
$CF(t)$	Time control function
t	Iteration number
$T^{\max}$	Maximum iterations' numbers
μ	Mean for all jellyfish locations in the swarm
P_0	The initial jellyfish population, $P_0 \in (0,1), P_0 \notin \{0.0, 0.25, 0.75, 0.5, 1.0\}$.
R	A random number from [0–1]
X^*	Best location of currant jellyfish
f	Objective function
U_b	Search spaces upper limit
L_b	Search spaces lower limit
$X_{i,d}$	ith jellyfish location in dth dimension

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