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Research Article

A Quantum-Inspired Optimization Strategy for Optimal Dispatch to Increase Heat and Power Efficiency

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Combined heat and power (CHP) systems are widely used in industries for their high energy efficiency and reduced carbon emissions. The optimal dispatch of CHP systems involves scheduling the operation of various equipment to minimize the total operational cost while meeting the heat and power demand of the facility. In this research work, a novel quantum-inspired optimization algorithm is proposed for the first time to solve the optimal dispatch problem of CHP systems. The proposed algorithm combines the principles of quantum mechanics with classical optimization algorithms to achieve a better solution. The algorithm uses quantum gates to perform quantum operations on the optimization variables, which allows for the exploration of a larger search space and potentially better solutions than classical algorithms. The proposed algorithm also incorporates a classical optimizer to refine the numerical evaluations acquired from the quantum operations. The performance of the adopted optimization technique was demonstrated by associating it with various other optimization techniques based on factors such as the speed of convergence, computational time, and the quality of the solution. The comparison is made on two standard CHP systems subjected to various quality and inequality constraints. The simulation results indicate that the quantum-inspired optimization technique surpassed the other algorithms in both solution quality and computational efficiency. The implemented algorithm provides a promising solution to the optimal dispatch problem of CHP systems. Future research can further explore the application of quantum-inspired optimization algorithms in other energy systems and optimize the algorithm's parameters to improve its performance.

1. Introduction of CHPED

The complexity of producing electricity from fossil fuels originates primarily from the process of transforming heat into work by the use of a turbine. Turbines are inefficient at converting incoming heat into useful work for electricity production; therefore, much of the heat that enters the system is wasted as waste heat. Space heating and thermally triggered technology such as absorption chillers are only two examples of where the waste heat stream can be put to good use. Waste heat cannot be provided to consumers at a reasonable cost since central power stations are typically situated many kilometers from them. Typically, customers get their thermal power needs satisfied in two different ways: by buying electricity from the grid and by installing their own heating and cooling systems [1].

The serious concerns raised by the fossil fuel energy sources in the power system by their utilization cause environmental emissions and global warming. On the other hand, the rapid growth in energy demands can cause power system instability with the conventional power system and leads to blackouts. These two significant concerns yield to the researchers and scientists in related disciplines to develop viable solutions to overcome the challenges. Promoting adequate electrical generation infrastructure is a simple approach that can significantly influence lowering energy use and carbon emission problems. Systems that produce heat and electricity simultaneously are known as combined heat and power (CHP) energy systems. As highly effective sources, CHP energy systems have 2 types of productive energy: electricity and heat. In contrast to a conventional power system, which generates energy with an efficacy of approximately 40%, the CHP plant might have an efficiency level of over 85%. Because maximum CHP deployments are in lieu of on-site generating, also called as distributed generation, these solutions decrease energy consumption and boost efficiency by minimizing energy losses [1]. A CHP unit could be as efficient as over 90%, while a traditional unit is just 60% effective at most (with every 100 tons of coal or other fuel it uses, 40 tons are entirely lost). This has substantial financial and ecological benefits. By boosting energy consumption, CHP reduces emission of environmental pollutants such as NOx and SO_2 and other greenhouse gases such as CO_2. CHP is an alternative that can deliver environmental benefits as part of a financially profitable investment. The CHP generation system serves as the most efficient way to make both electricity and heat at the same time. Cogeneration is healthy for the environment and saves much money on energy costs in contrast to heat-only boilers and traditional power plants [2]. The traditional CHP unit with the usage of heat energy and the portion of energy wastage is presented in Figure 1.

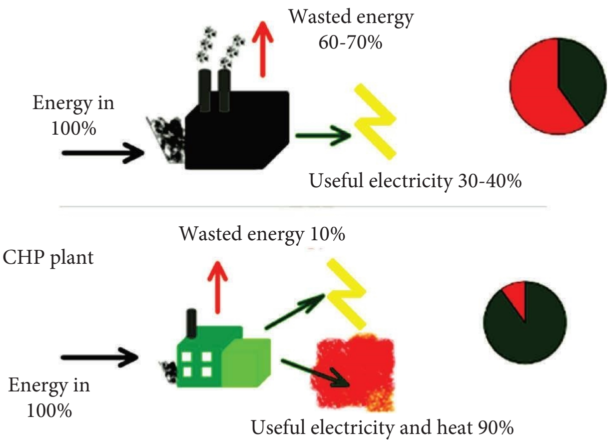


Figure 1: Traditional CHP system.

CHP units are becoming increasingly popular due to the dramatic change occurring in energy because of the deployment of microgrid programs and technology. CHPED generation units include conventional thermal power-only supplying units and CHP thermal power-only generating units (boilers). This dispatch is more complicated than the typical one due to the twofold nonlinear dependence between heat and power outputs, as indicated by the viable operated zones of CHP units. The goal of CHPED is to determine the best time to produce heat and electricity, considering the producing units' electrical and operational limitations. The optimization issue is nonlinear and nonconvex, which demands comprehensive solvers.

2. Comprehensive Literature Review

Many strategies have been employed earlier to address the ED problem. A few of these approaches, referred to as traditional techniques, are primarily derived from mathematical computations. When the limitations of VPLE, RRLs, and POZ are considered, the ED becomes a nonconvex optimization problem that cannot be quickly addressed using conventional methods. Heuristic techniques are employed to address this complicated issue to address this drawback. Heuristic optimization techniques are commonly employed in two forms: original and modified, improved, or hybridized with other algorithms/methods. Over the years, various computational methods that achieve global or near-global solutions for nonlinear optimization problems have been published. During recent decades, development has concentrated on the application of these approaches to CHPED issues since they can handle discontinuities, strong nonlinearities, and nonconvexities in the objective functions and constraints [3]. CHPED is more difficult to implement than the conventional economic dispatch because of the increased complexity of the minimization problem resulting from the merging of heat and power in addition to the additional restrictions that must be met, such as the procurement balance of heat, the bilateral interdependence of power and heat generation in CHP units, and the production limitations of heat-only units [4]. Despite metaheuristics, nature-inspired, heuristic, mathematical approaches, quantum-inspired optimization technique is not implemented to tackle the CHPED issue and the classifications of the optimization taxonomy are presented in Figure 2.

Evolutionary algorithms, which are influenced by biological progression, are a subgroup of inhabitant-based metaheuristic techniques. In evolutionary algorithms, a population is initially formed at random, and then, it is evolved through time to produce the best possible solution [5]. The authors of Ref. [6] put forth an optimization model for a micro-CHP system that utilized fuel cells and employed a genetic algorithm to optimize the system's total electrical efficiency. Another application of GA optimization technique is implemented for the optimal sizing in the CHP plants to save energy sources and reduce energy costs. Another implementation of the GA optimizer is for optimal sizing of CHP plants to save sources of power and minimize energy expenses [7].

Another evolutionary algorithm called the differential evolution (DE) method, a form of evolutionary algorithm, was initially introduced in 1997 [8]. To tackle the CHPED problem, an advanced hybrid algorithm was proposed in Ref. [9], which combined the genetic algorithm and evolutionary programming (EP). The DE algorithm was utilized in a test system that comprised two CHP systems, a heat generation unit, and four conventional power generation facilities. The PSO and EP algorithms were also incorporated for comparison, and the results showed that the DE algorithm outperformed both in terms of cost and computation time. However, conventional mathematical techniques such as the Lagrange multiplier, LP, QP, and DP are often limited by local optima [3, 10], making it challenging to achieve highly accurate solutions. In Ref. [11], the SARGA

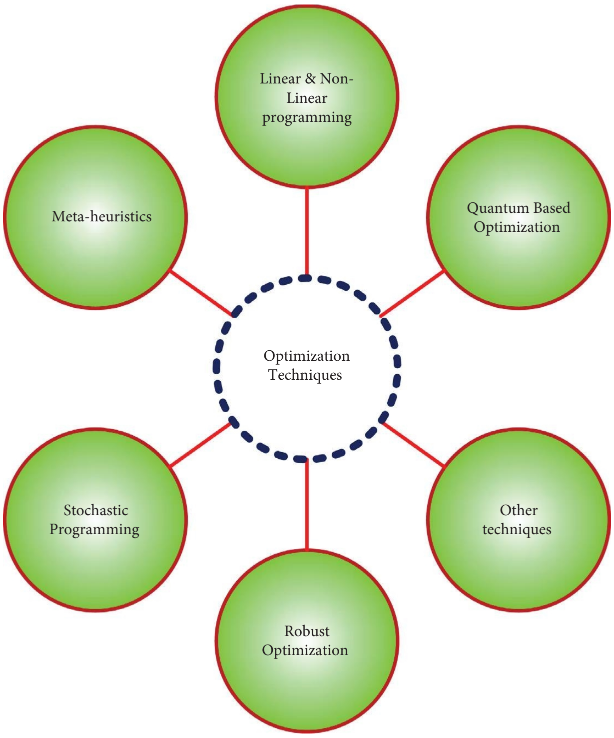


Figure 2: Optimization taxonomy.

optimization technique was implemented to address the nonconvex CHPED problem while satisfying both equality and inequality constraints. A penalty parameter was introduced to handle these constraints. Finally, an improved GA optimization approach was proposed in Ref. [12] for the CHPED problem, which considered a small population count number to achieve better results. Aforementioned previous works focused on the optimization of the operating cost of CHPED problem without considering the network flow constraints and valve point effect. In Ref. [13], the CHPED problem is solved by implementing RCGA optimization technique, which involves the transmission network losses and valve point effect. The multi-objective-based CHPED problem is proposed in Refs. [14, 15] considering different technical parameters such as operating cost, gas emissions, and wind energy sources. The proposed problem is solved by implementing the nature-inspired algorithm PSO, which includes the network loss constraints and valve point effect. The CHPED problem was tackled in Ref. [16] using a hybrid optimization technique. The hybrid HS-GA optimization technique ensures both demands of the heat and power. Few of the research works base on evolutionary algorithms [17–19], metaheuristics [20–22], and nature-inspired algorithms [23]. Numerous studies have attempted to address the CHPED issue by employing heuristic and metaheuristic optimization methods grounded in mathematics. While we acknowledge the abundance of advanced optimization methods in the literature, our literature survey has deliberately focused on highlighting seminal works and influential methodologies that form the foundation of the field. In the provided references, we have cited key studies that have significantly contributed to the discourse on combined heat and power economic dispatch (CHPED) optimization [8, 9, 11–16]. The decision to forefront quantum-inspired optimization, particularly the quantum particle swarm optimization (QPSO) algorithm, was motivated by the identified research gap in applying such techniques to the CHPED problem in the electrical domain. The emphasis on quantum-inspired approaches reflects a conscious choice to explore an innovative avenue that has not been extensively covered in the existing literature.

Prior investigations have predominantly concentrated on heuristic, metaheuristic, and mathematical optimization techniques, including genetic algorithms, evolutionary programming, and differential evolution. Nonetheless, these methodologies frequently face constraints associated with local optima, impeding the attainment of exceedingly precise solutions. Furthermore, the existing body of research has neglected to explore the implementation of quantum-inspired optimization methods within the domain of combined heat and power economic dispatch (CHPED). In contrast, this paper proposes a novel application of the QPSO optimizer to the CHPED problem, considering different test units and corresponding case studies. Quantum-inspired techniques have demonstrated effectiveness in addressing complex problems, and their application in the electrical domain, particularly in CHPED, remains unexplored. A research gap is found since the application of quantum-inspired optimization approaches to complex engineering problems in the electrical domain, especially on the CHPED problems. The main highlight of the implemented optimization approach is that the proposed QPSO optimizer represents a departure from conventional heuristic, metaheuristic, and mathematical optimization techniques, such as genetic algorithms, evolutionary programming, and differential evolution. While these methods face challenges associated with local optima, our approach leverages quantum-inspired optimization to potentially overcome such limitations, offering a new perspective on optimizing the combined heat and power economic dispatch (CHPED) problem. The manuscript introduces a significant contribution by filling a notable research gap in the field of CHPED optimization. By incorporating the quantum particle swarm optimization (QPSO) algorithm, we address the lack of exploration into quantum-inspired optimization methods for complex engineering problems in the electrical domain. This novel application of quantum-inspired techniques to CHPED, coupled with diverse test units and case studies, provides a unique and unexplored dimension in the pursuit of highly accurate solutions. So far, none of the research work is done by implementing the QPSO optimizer on the CHPED problem with different test units and the corresponding case studies. The contribution of the proposed research work is as follows:

(1) The main goal of this investigation is to apply the quantum-inspired PSO method to decrease the combined heat and power units' overall operating

expenses, while simultaneously fulfilling both equality and inequality limitations.

(2) To enhance the efficiency of the QPSO algorithm for the first time in the research studies, this research article implemented QPSO techniques to tackle the CHPED problem. To handle the balance and limiting constraints that are associated with the proposed optimization issue, a penalty parameter is introduced, which penalizes whenever an infeasible solution is obtained during the iterative process.

(3) To assess the effectiveness of the QPSO optimizer, standardized test units were used for comparison with the recently reported optimization approaches. According to the results, the proposed optimization method demonstrated superior performance compared to the aforementioned approaches with regard to the convergence rate, computational efficiency, and solution accuracy.

The organization of this research work is as follows: Section 3 describes the mathematical formulation of the proposed objective followed by balance and limiting constraints. Section 4 represents the significance of the QPSO optimizer while solving the complex engineering problems and the related mathematical equations. Section 5 describes the considered standard test systems, numerical evaluations of the corresponding test system, and discussion. Section 6 provides the conclusion of the proposed research problem and its future scope.

3. Mathematical Modelling

The objective of the CHPED optimization problem is to determine the optimal combination of standard power generators, cogeneration units, and heat generation units only for generating both electricity and heat, as represented by equation (1). The aim of this optimization problem is to minimize the total production cost, which is determined by the multiplication of three different cost functions while adhering to both balance and limiting constraints. The optimization objective includes two constraints that necessitate the fulfillment of identical values. The first restriction demands that the sum of electrical power generated by all power generation units should be equivalent to the total required power (Pd), while the second requirement stipulates that it is necessary for the combined heat generated by all heat generation units to be equal to the total heat required (hd). These limitations are represented in equations (2) and (3).

The inequalities involve the combined heat and power units (CHPs) with the optimal production of CHPs requiring to fall within the possible performing zones. The lower and upper limits of all participating units along with the possible FOR in any CHPED are shown in Figure 3 [3, 11, 15, 17] and mathematically represented in equations (4)–(7). In Ref. [22], the CHPED problem is mathematically depicted using the symbols P and H, which refer to the actual power generation and heat production, respectively, of a CHP unit:

$$\mathrm{Min}\, C = \sum_{i=1}^{N_p} C_i\left(\mathrm{P}_i\right) + \sum_{j=1}^{N_c} C_j\left(\mathrm{P}_j, h_j\right) + \sum_{k=1}^{N_h} C_k\left(\mathrm{P}_k\right), \tag{1}$$

$$\sum_{i=1}^{N_p} \mathrm{P}_i + \sum_{j=1}^{N_c} \mathrm{P}_j = \mathrm{P}_d, \tag{2}$$

$$\sum_{i=1}^{N_p} \mathrm{h}_i + \sum_{j=1}^{N_c} \mathrm{h}_j = \mathrm{h}_d, \tag{3}$$

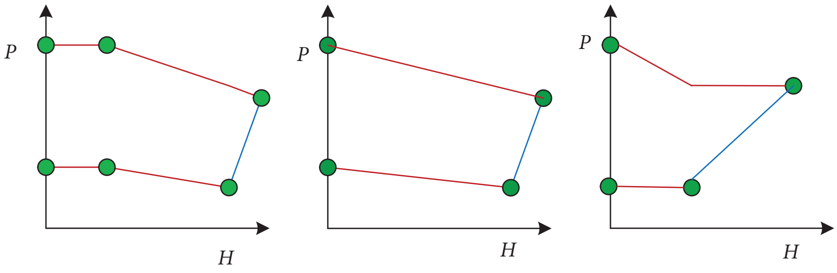
$$\mathrm{P}_i^{\min} \leq \mathrm{P}_i \leq \mathrm{P}_i^{\max}, \quad \text{where}\, i = 1, 2, \ldots, N_p, \tag{4}$$

$$\mathrm{P}_j^{\min\left(h_j\right)} \leq \mathrm{P}_j \leq \mathrm{P}_j^{\max\left(h_j\right)}, \quad \text{where}\, j = 1, 2, \ldots, N_c, \tag{5}$$

$$h_j^{\min\left(\mathrm{P}_j\right)} \leq \mathrm{h}_j \leq h_j^{\max\left(\mathrm{P}_j\right)}, \quad \text{where}\, j = 1, 2, \ldots, N_c, \tag{6}$$

$$\mathrm{h}_k^{\min} \leq \mathrm{h}_k \leq \mathrm{h}_k^{\max}. \tag{7}$$

The operating cost function regarding power and heat units of the proposed problem is represented as follows:



(a) (b) (c)

Figure 3: Possible characteristics of FOR of a CHP.

$$C_i\left(P_i\right) = a_i + b_i P_i + c_i P_i^2, \tag{8}$$

$$C_j\left(P_j h_j\right) = a_j + b_j P_j + c_j P_j^2 + d_j h_j + e_j h_j^2 + f_j P_j h_j, \tag{9}$$

$$C_k\left(h_k\right) = a_k + b_k h_k + C_k h_k^2. \tag{10}$$

To handle the balance and limiting constraints in the CHPED issue, the penalty parameter approach [18] is utilized to transform the problem from a constrained to an unconstrained one. To handle infeasible solutions during the iterative process, a penalty function is utilized, which transforms the constrained CHPED problem into an unconstrained one. The choice of appropriate penalty factor settings requires some experimentation to improve the optimal solutions while staying within the limits. To ensure that all equality and inequality constraints are fulfilled, it is advisable to first normalize each constraint, given their different magnitudes. The penalty factor, as described in Ref. [18], is then incorporated to continuously monitor the compliance of the obtained solution with all constraints.

4. Quantum-Inspired Optimization

The quantum particle swarm optimization (QPSO) algorithm is a quantum-inspired optimization algorithm that is inspired by classical particle optimization algorithms, such as particle swarm optimization (PSO). Quantum-inspired particle swarm optimization (QIPSO) holds significant promise in electrical engineering, providing efficient solutions for intricate optimization problems. In power systems, QIPSO improves optimal power flow, economic dispatch, and voltage stability. For smart grids, it optimizes energy distribution and load balancing. In power systems, QIPSO aids in fault detection and classification, enhancing the overall reliability. Furthermore, it proves valuable in optimizing renewable energy systems, electronic circuit designs, antenna array configurations, and telecommunication network planning. Its versatility extends to the optimizing electric vehicle charging infrastructure, underscoring its efficacy in addressing diverse challenges within the electrical engineering domain.

QPSO employs the principles of quantum mechanics, including superposition and entanglement, to efficiently navigate the solution space of an optimization problem. The basic idea of the QPSO algorithm is to represent the candidate solutions of an optimization problem as quantum states. These quantum states are then evolved over time using a quantum circuit that consists of quantum gates, such as the Hadamard gate, phase gate, and controlled-NOT gate.

The classical representation of the quantum bits is shown in Figure 4. The QPSO algorithm can be formulated as follows:

Initialization. Initialize a set of qubits to represent the quantum state of each candidate solution. The quantum state of each qubit is initialized to a superposition of 0 and 1, which is represented by the Hadamard gate.

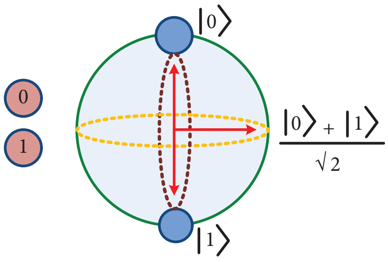
Encoding. Encode the candidate solutions into the quantum states of the qubits. This is done by applying a sequence of gates that depends on the problem being solved.

Evolution. Evolve the quantum states over time using a quantum circuit that consists of a sequence of gates. The evolution is governed by a Hamiltonian that is derived from the optimization problem.

Measurement. Measure the quantum state of each qubit to obtain a classical bit string that represents a candidate solution. The probability of measuring each bit string is proportional to the square of the amplitude of the corresponding quantum state.

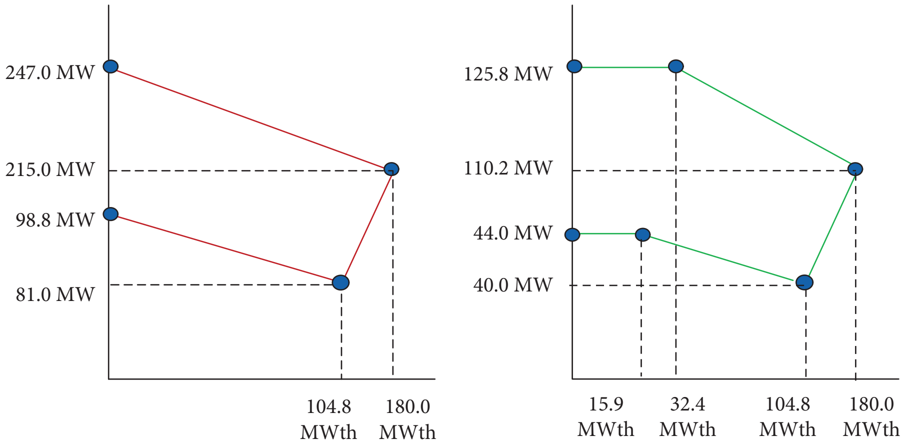
Update. Update the quantum states based on the results of the measurements. This is done using a classical algorithm that is inspired by the PSO algorithm.

In solving various optimization problems, such as constrained optimization, continuous optimization, and combinatorial optimization, the QPSO algorithm has demonstrated its effectiveness. The QPSO's mathematical equations and contraction-expansion coefficients are obtained from Ref. [24]. Figure 5 illustrates the iterative process of the QPSO algorithm in a step-by-step manner. The CHPED system parameters are initially established based on the framework, and 50 preliminary samples are produced to confirm the solution space feasibility and associated decision variables. Subsequently, the fitness value of each solution is calculated to set individual and collective standards, with a maximum of 200 iterations being carried out. To prevent premature convergence, the contraction-expansion



(a) (b)

Figure 4: (a) Classical bit representation and (b) quantum bit representation.



(a) (b)

Figure 5: (a) CHP unit 2. (b) CHP unit 3.

coefficient can be adjusted to optimize performance. The algorithm enhances population diversity by employing the mean best approach of each iteration. The convergence and maximum allowable number of iterations determine the stopping criteria for the method. Figure 6 describes the proposed optimization approach steps to tackle the CHPED problem in a flowchart format.

5. Numerical Evaluation and Discussion

This section examines a well-known standard test system previously described in the literature. The setup comprises a traditional power unit, two CHP units, and a heat unit. The proposed CHPED problem is solved by a well-established nature-inspired algorithm integrated with quantum mechanics called the quantum particle swarm optimizer. The integration of numerous distributed energy resources makes power system problems more intricate in nature, increasing the system's complexity. After comparing the QPSO optimizer to various heuristics, metaheuristics, and other advanced algorithms, the findings demonstrate that the suggested CHPED problem was successfully solved. The efficiency of the recommended algorithm is determined by its fast convergence rate, short computational time, and high solution quality.

5.1. Test Case 1. In this research, two standard CHP test systems, represented in Figures 5(a) and 5(b), have been analysed. The test systems are composed of four units, which include one traditional unit (unit 1), two CHP units (unit 2 and unit 3), and one heat unit (unit 4). The conventional unit has a power output range of 0 to 150 MW, while the heat unit has a range of 0 to 2690 MWth. The feasible operating regions of the two CHP units are illustrated in the figures. The power output limits of the test units range between 150 MW and 200 MWth, for the maximum and minimum values, respectively. The following equations represent the mathematical models of the standard test units:

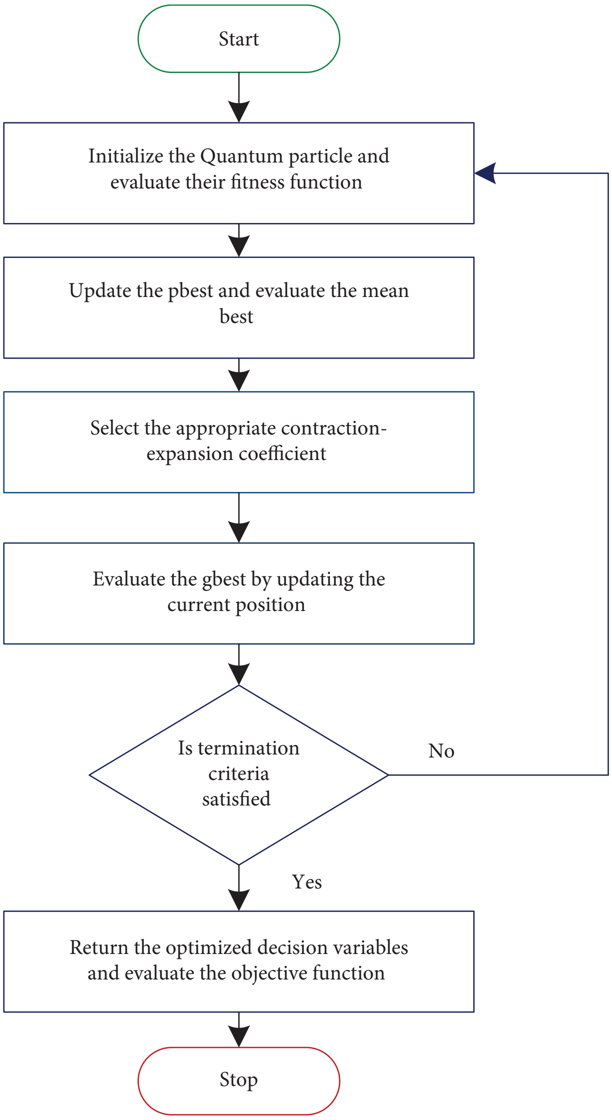


FIGURE 6: Flowchart of the QPSO optimizer.

$$C_1(P_1) = 50P_1, \tag{11}$$

$$C_2(P_2, h_2) = 2650 + 14.5P_2 + 0.0345P_2^2 + 4.2h_2 + 0.030h_2^2 + 0.031P_2h_2, \tag{12}$$

$$C_3(P_3, h_3) = 1250 + 36.0P_3 + 0.0435P_3^2 + 0.6h_3 + 0.027h_3^2 + 0.011P_3h_3, \tag{13}$$

$$C_4(P_4) = 50P_4. \tag{14}$$

Equations (15) and (16) depict the equality and inequality constraints of the test units being considered. Equation (17) represents the upper and lower bounds of the CHP test unit.

(a) Equality constraints:

$$\begin{cases} P_1 + P_2 + P_3 = 20, \\ h_2 + h_3 + h_4 = 115. \end{cases} \tag{15}$$

(b) Inequality constraints of the two CHP units:

$$\begin{cases} 0.178191h_2 - P_2 - 105.7446 \leq 0, \\ 0.17777h_2 + P_2 - 247.000 \leq 0, \\ -0.16984h_2 - P_2 + 98.8000 \leq 0, \\ 1.15841h_3 - P_3 - 46.881188 \leq 0, \\ 0.15116h_3 + P_3 - 130.6976 \leq 0, \\ -0.0676818h_3 - P_3 + 45.07614 \leq 0 \; h_3 \geq 15.9, \\ 44 - P_3 \leq 0 \; h_3 \leq 15.9, \end{cases} \tag{16}$$

$$\begin{cases} 0 \leq P_1 \leq 150, \\ 81 \leq P_2 \leq 247, \\ 0 \leq h_2 \leq 180, \\ 40 \leq P_3 \leq 125.8, \\ 0 \leq h_3 \leq 135.6, \\ 0 \leq h_4 \leq 2695.2. \end{cases} \tag{17}$$

The above-considered test unit of the CHPED system is solved for the first time by implementing a nature-inspired algorithm integrated with quantum mechanics called the quantum-inspired particle swarm optimization. The proposed algorithm is compared with the existing heuristics and metaheuristics, and other recently reported optimization algorithms. The proposed optimization approach demonstrates excellent performance in several aspects, including faster convergence rate, higher computational efficiency, and better quality of the solution obtained. The proposed algorithm code has been implemented in a MATLAB R2023a environment and executed with the system configuration of 12 GB RAM, 2.2 GHz Intel core i7 processor. The evaluated decision variables, such as fuel costs, heat demand, total operating cost, and computational time, are given in Table 1. The maximum iterations of all the implemented optimization approaches are considered as 200 in all the test cases 8.

The analysis of the convergence of the proposed optimization approach shows outstanding performance in various aspects, such as the rate of convergence, efficiency in computation, and the quality of the solution obtained. Figure 7 shows the convergence characteristics of the proposed QPSO algorithm. Figure 5 describes the possible FOR of the considered test units.

5.2. Numerical Evaluation of Test Unit 2. The test system being analysed comprises a total of five units, which includes 1 power unit, 3 CHP units, and a heat unit. The heat and power output ranges of the conventional power unit are shown in Figure 8 and are limited to 35 MW and 135 MW, respectively. On the other hand, the heat unit's power output range is restricted between 0 MWth and 60 MWth.

The considered test units will be evaluated with three different scenarios, namely,

(i) $P_d = 300\,\text{MW}, h_d = 150\,\text{MWth}$
(ii) $P_d = 250\,\text{MW}, h_d = 175\,\text{MWth}$
(iii) $P_d = 150\,\text{MW}, h_d = 220\,\text{MWth}$

The mathematical representation of the three considered test unit cost functions is represented as follows:

$$C_1(P_1) = 254.886 + 7.6997P_1 + 0.00172P_1^2 + 0.000115P_1^3, \tag{18}$$

$$C_2(P_2, h_2) = 1250 + 36.0P_1 + 0.0435P_2^2 + 0.6h_2 + 0.027h_2^2 + 0.011P_2h_2, \tag{19}$$

$$C_3(P_3, h_3) = 2650 + 34.5P_3 + 0.1035P_3^2 + 2.203h_3 + 0.025h_3^2 + 0.051P_3h_3, \tag{20}$$

$$C_4(P_4, h_4) = 1565 + 20P_4 + 0.072P_4^2 + 2.3h_4 + 0.02h_4^2 + 0.04P_4h_4, \tag{21}$$

$$C_5(P_5, h_5) = 950 + 2.0109h_5 + 0.038h_5^2. \tag{22}$$

The proposed optimization problem of the considered test unit 2 is mathematically represented as follows:

$$\begin{aligned} \min C = {} & C_1(P_1) + C_2(P_2, h_2) + C_3(P_3, h_3) \\ & + C_4(P_4, h_4) + C_5(P_5, h_5). \end{aligned} \tag{23}$$

The equations (24) and (25) specify the subjective equality and inequality constraints; Equation (26) specifies the boundary restrictions, and the following are the relevant limits within which the FOR of the test units is under consideration.

Equality constraints:

Table 1: Comparison simulation results of test system 1.

Optimization technique	P_1 (MW)	P_2 (MW)	P_3 (MW)	h_2 (MWth)	h_3 (MWth)	h_4 (MWth)	TOC	C. time (sec)
IACS	0.0800	150.9300	49.0000	48.8400	65.7900	0.3700	9452.20	5.26
MADS-PSO	0.0092	157.9392	42.0516	42.4459	72.5522	0.0019	9301.38	7.56
MADS-LHS	0.0017	159.8000	40.2014	42.4042	72.3904	0.2054	9277.13	7.04
ABC	0.2400	158.7800	40.9600	39.5800	75.2300	0.1800	9276.70	NA
GAPF	0	159.2300	40.7700	39.9400	75.0600	0	9267.28	4.32
PSO	0.0500	159.4300	40.5700	39.9700	75.0300	0	9265.10	3.09
DE	0.0200	159.9400	39.9300	40.0200	74.9900	0.0600	9258.90	NA
LR	0	160.0000	40.0000	40.0000	75.0000	0	9257.10	3.98
B&B	0	160.0000	40.0000	40.0000	75.0000	0	9257.10	4.27
EP	0	160.0000	40.0000	40.0000	75.0000	0	9257.10	7.96
FA	0.0014	159.9986	40.0000	40.0000	75.0000	0	9257.10	NA
IGAMU	0	160.0000	40.0000	39.9900	75.0000	0	9257.09	5.53
HS	0	160.0000	40.0000	40.0000	75.0000	0	9257.07	4.21
SARGA	0	159.9900	40.0100	39.9900	75.0000	0	9257.07	3.76
CSO	0	160.0000	40.0000	40.0000	75.0000	0	9257.07	1.18
IWO	0	160.0000	40.0000	40.0000	75.0000	0	9257.07	11.21
GSA	0.0003	159.4494	40.5494	38.8850	75.4736	0.6414	9269.14	7.26
CSA	0	160.0000	40.0000	40.0000	75.0000	0	9257.07	5.62
SFS	0	160.0000	40.0000	40.0000	75.0000	0	9257.07	3.78
QPSO	0	159.9982	40	40.0394	74.9833	0	9254.59	1.78

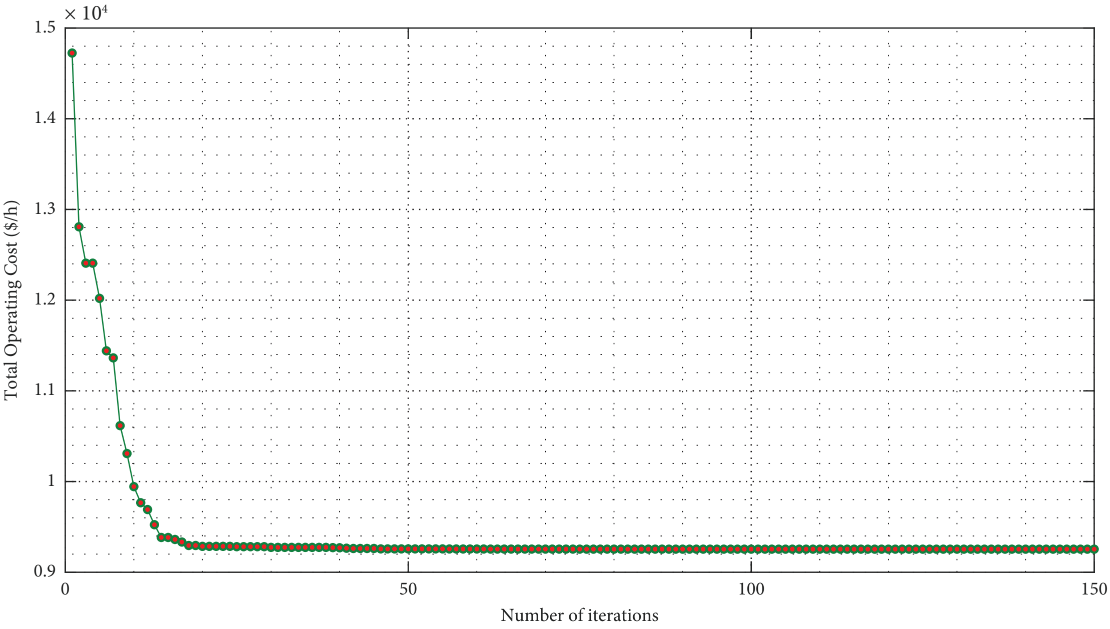
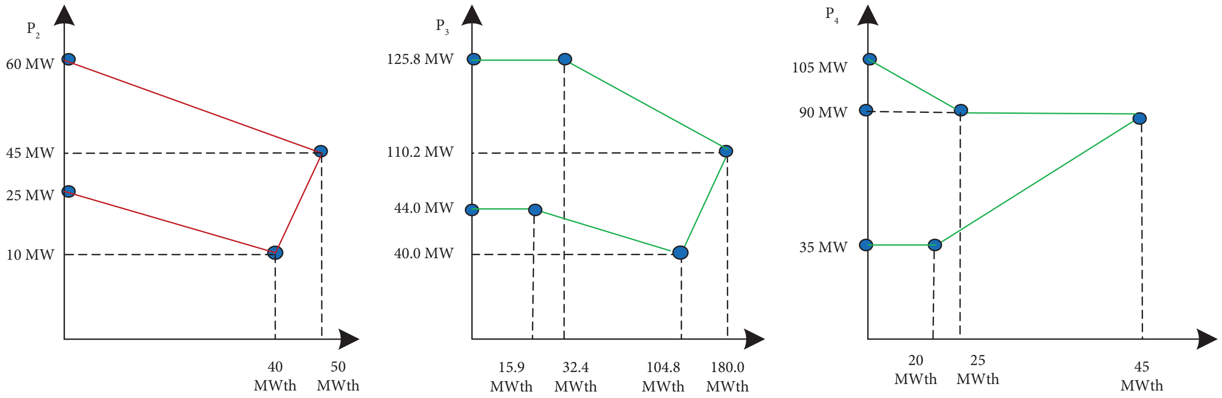


Figure 7: Convergence characteristics of test unit 1.



(a) (b) (c)

FIGURE 8: Test system 2. (a) First CHP unit (unit 2). (b) Second CHP unit (unit 3). (c) Third CHP unit (unit 4).

TABLE 2: Numerical results and comparison evaluations of case study 1 (test system 2).

Optimization technique	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	h_2 (MWth)	h_3 (MWth)	h_4 (MWth)	h_5 (MWth)	TOC
GA	135.0000	70.8100	10.8400	83.2800	80.5400	39.8100	0.0000	29.6400	13779.50
RCGA	134.9904	49.9525	25.0827	89.9744	73.5089	35.8519	1.2916	39.3476	13776.14
HS	134.7400	48.2000	16.2300	100.8500	81.0900	23.9200	6.2900	38.7000	1372320
CPSO	135.0000	40.7309	19.2728	105.0000	64.4003	26.4119	0.0000	59.1955	13692.52
IWO	134.7300	40.0000	20.8600	104.4100	75.0000	37.6000	0.0000	37.4000	13683.65
FA	134.7400	40.0000	20.2500	105.0000	75.0000	27.8700	0.0000	47.1200	13683.22
TVAC-PSO	135.0000	41.4019	18.5981	105.0000	73.3562	37.4295	0.0000	39.2143	13672.89
COA	135.0000	40.7687	19.2313	105.0000	73.5956	36.7760	0.0000	39.6284	13672.83
SFS	135.0000	40.7689	19.2311	105.0000	73.5955	36.7766	0.0000	39.6279	13672.83
QPSO	135.000	40.0498	19.9947	104.9671	70.7783	34.8284	0.0000	44.3938	13669.09

TABLE 3: Numerical results and comparison evaluations of case study 2.

Optimization technique	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	h_2 (MWth)	h_3 (MWth)	h_4 (MWth)	h_5 (MWth)	TOC
GA	119.220	45.1200	15.8200	69.8900	78.9400	78.9400	18.4000	54.9900	1232737
HS	134.670	52.9900	10.1100	52.2300	85.6900	85.6900	4.1800	45.4000	12284.45
IWO	134.590	40.0000	10.9400	64.4700	75.0000	75.0000	8.8100	52.2100	1213433
CPSO	135.000	40.3446	10.0506	64.6060	70.9318	70.9318	4.0773	60.0000	12132.86
FA	134.810	40.0000	10.0000	65.1800	75.0000	75.0000	16.9700	43.0200	12119.86
TVAC-PSO	135.000	40.0118	10.0391	64.9491	74.8263	74.8263	16.1867	44.1428	1211739
GSA	135.000	39.9998	10.0000	64.9807	74.9844	74.9844	17.8939	42.1095	1211737
COA	135.000	40.0000	10.0000	64.9910	75.0000	75.0000	14.4001	45.6000	12116.60
CSA	135.000	40.0000	10.0000	65.0000	75.0000	75.0000	14.4046	45.5954	12116.60
DE	135.000	40.0000	10.0000	64.9998	75.0000	75.0000	14.3984	45.6018	12116.61
ABC	135.000	40.0488	16.2528	58.7008	74.3491	74.3491	18.7334	39.2381	12178.49
SARGA	135.000	40.2096	10.2792	64.5112	71.9024	71.9024	16.0870	48.1273	12123.81
SFS	135.000	40.0000	10.0000	65.0000	75.0000	75.0000	14.4043	45.5957	12116.60
QPSO	135.000	40.000	11.3599	63.6516	79.0644	45.5972	9.5391	41.0702	11573.10

TABLE 4: Numerical results and comparison evaluations of case study 3 (test system 2).

Optimization approach	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	h_2 (MWth)	h_3 (MWth)	h_4 (MWth)	h_5 (MWth)	TOC
GA	37.9800	76.3900	10.4100	35.0300	106.0000	38.3700	15.8400	59.9700	11837.40
HS	41.4100	66.6100	10.5900	41.3900	97.7300	40.2300	22.8300	59.2100	11810.88
1WO	35.5972	57.3554	10.0070	57.0587	89.9767	40.0025	30.0232	60.0000	11781.37
CPSO	42.1660	64.6523	10.0000	43.1817	96.2810	40.0000	23.7190	60.0000	11758.64
FA	42.1433	64.6271	10.0001	43.2295	96.2593	40.0001	23.7404	60.0000	11758.06
TVAC-PSO	42.1497	64.6342	10.0000	43.2161	96.2654	40.0000	23.7346	60.0000	11758.06

Table 4: Continued.

Optimization approach	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	h_2 (MWth)	h_3 (MWth)	h_4 (MWth)	h_5 (MWth)	TOC
GSA	42.2652	64.7630	10.0112	42.9706	96.3766	40.0005	23.6230	59.9990	11758.09
COA	42.1454	64.6294	10.0000	43.2252	96.2613	40.0000	23.7387	60.0000	11758.06
QPSO	65.000	40.000	10.000	35.000	96.2841	49.2769	30.8324	44.3471	10182.750

Table 5: Control parameters of PSO and QPSO algorithms.

Algorithm	Control parameters
PSO	Cognitive factor and social factor are 1.4, inertia weight, w, 0.9~0.4, random values r1 and r2 [0, 1], no. of particles is 30, and maximum iterations are 200
QPSO	Contraction and expansion coefficient is 0.75, and maximum iterations are 200

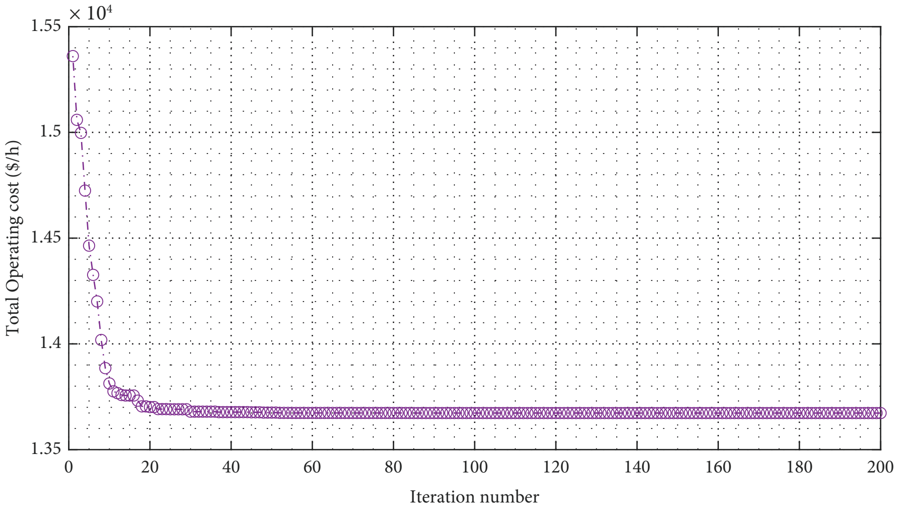


Figure 9: Convergence characteristics of case 1 (second test system).

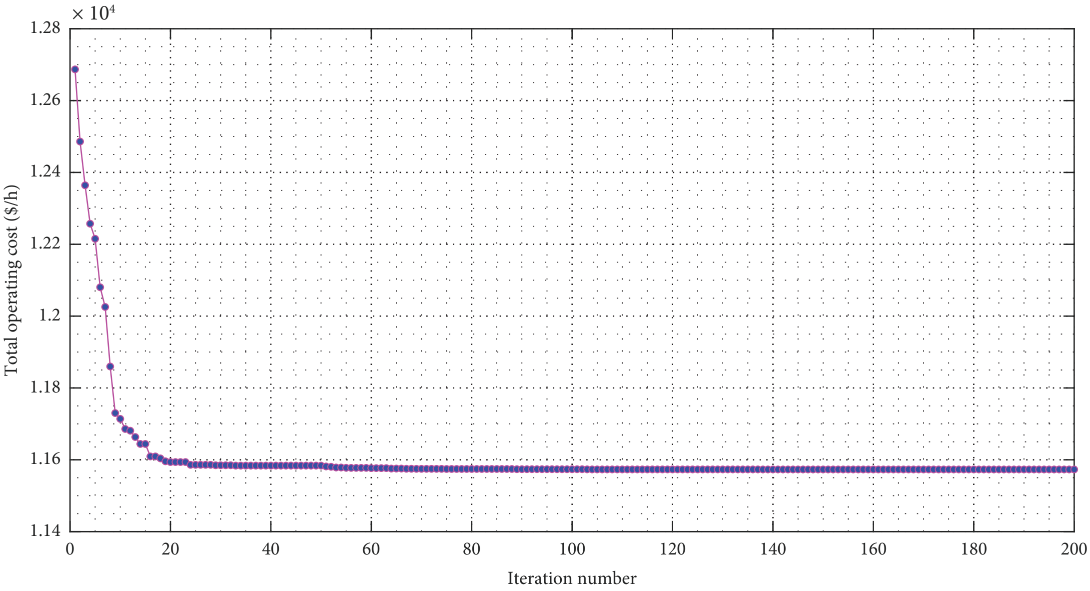


Figure 10: Convergence characteristics of case 1 (second test system).

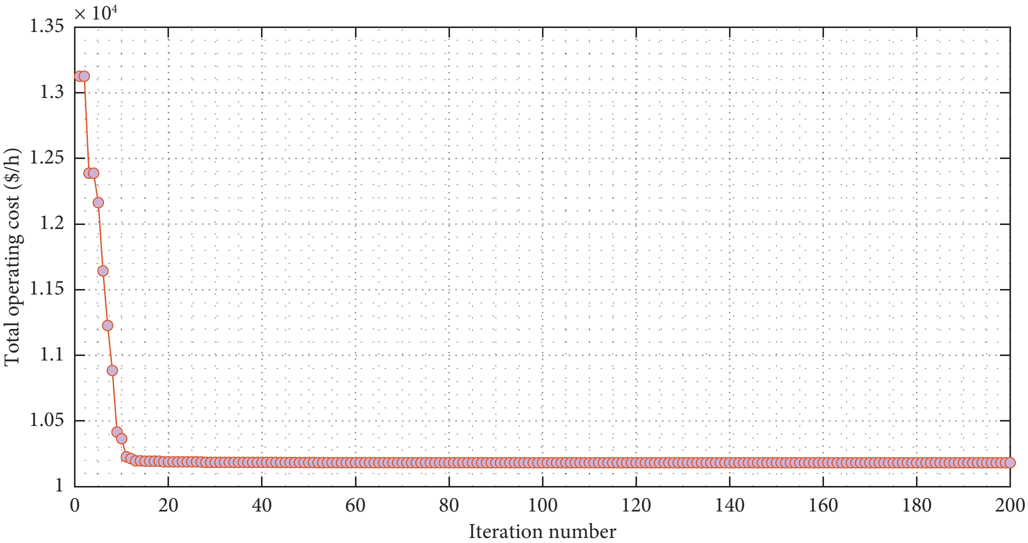


Figure 11: Convergence characteristics of test system 2 (case 3).

$$\begin{cases} P_1 + P_2 + P_3 + P_4 + P_5 = P_d, \\ h_2 + h_3 + h_4 + h_5 = h_d. \end{cases} \tag{24}$$

Inequality constraints:

$$\begin{cases} P_2 + 0.151162791 h_2 - 130.6976744 \le 0\, h_2 \ge 32.4, \\ P_2, -125.8 \le 0\, h_2 \le 32.4, \\ -P_2, +1.158415842 h_2 - 46.88118818 \le 0, \\ -P_2, -0.067681895 h_2 + 45.07614213 \le 0\, h_2 \ge 15.9, \\ 44 - P_2 \le 0\, h_2 \le 15.9, \\ P_3 + 0.272727272 h_3 - 60 \le 0, \\ -P_3 - 0.25 h_3 + 20 \le 0, \\ P_3 + 2.333 h_3 - 83.333 \le 0, \\ P_4 + 0.60 h_4 - 105 \le 0\, h_4 \le 25, \\ -P_4 + 2.20 h_4 - 9 \le 0. \end{cases} \tag{25}$$

Boundary restrictions:

$$\begin{cases} 35 \le P_1 \le 135, \\ 40 \le P_2 \le 125.8, \\ 10 \le P_3 \le 60, \\ 35 \le P_4 \le 105, \\ 0 \le h_2 \le 135.6, \\ 0 \le h_3 \le 55, \\ 0 \le h_4 \le 45, \\ 0 \le h_5 \le 60. \end{cases} \tag{26}$$

Simulation results of case 1, case 2, and case 3 and the corresponding optimization technique comparison of the CHPED problem are tabulated in Tables 2–4.

From the above observations, the proposed QPSO optimizer shows the better performance in terms of rate of convergence, the best quality of the global solution, and computational time. The optimum total operating costs can be obtained by using QPSO optimizer as well as compared with other heuristics metaheuristics and other mathematical computational optimization approaches. The proposed optimizer avoids being stuck with local minima for obtaining global optimum solution. The algorithm tuning parameters of the proposed algorithms QPSO and PSO are tabulated in Table 5. The intended optimization technique is compared with the recently reported global optimization methods and the result shows that the QPSO algorithm is superior in terms of best global solution. Figures 9–11 show the convergence characteristics of the QPSO optimizer.

6. Discussion and Conclusion

The proposed CHPED optimization problem is solved by implementing the QPSO optimizer. The CHPED formulation models the simultaneous generation of electrical power and thermal energy as a nonconvex, nonlinear optimization problem with the aim of minimizing the operating expenses of heat and power generation units subject to a number of inequality and equality limitations as well as interdependent limitations. In this research work, the authors implement penalty factors to deal with the equality and inequality restrictions, compensating an infeasible solution at each iteration of the transformation from a constrained to an unconstrained CHPED problem. Two widely used test systems from the CHPED literature have been utilized to ensure the accuracy and performance of the proposed optimization technique. The proposed QPSO optimizer is compared with different global optimization approaches. The obtained simulation results show that the proposed optimization approach QPSO is superior in terms of rate of convergence, convergence characteristics, and quality of the best global optimal solution. The proposed QPSO optimizer minimizes the total running cost of the CHPED test unit systems using minimum sufficient and conventional power.The obtained optimum global solution is summarized in Tables 1, 2, 3, and 4.. The suggested technique has achieved enhanced near-global optimal solutions with minimal computing time, and it is robust in acquiring the superior testified possible solutions for varied systems and case studies. The conclusion of the implemented optimization approach has several potential future research directions. The QPSO recommends further exploration of quantum-inspired optimization techniques in addressing complex engineering challenges within the electrical domain, emphasizing scalability and robustness. Dynamic conditions and adaptability to evolving scenarios in combined heat and power economic dispatch (CHPED) systems are highlighted for investigation. In addition, the practical implementations and real-world case studies are suggested to validate the proposed quantum particle swarm optimization (QPSO) algorithm. These future directions aim to advance the practical utility and understanding of quantum-inspired optimization in addressing electrical engineering complexities.

Abbreviations

IACS:	Improved ant colony search
MADS-PSO:	Mesh adaptive direct search and particle swarm optimization
MADS-LHS:	Mesh adaptive direct search and Latin hypercube sampling
ABC:	Artificial bee colony
GAPF:	GA-based penalty function
PSO:	Particle swarm optimization
DE:	Differential evolution
LR:	Lagrangian relaxation
B&B:	Branch and bound algorithm
EP:	Evolutionary programming
FA:	Firefly algorithm
IGAMU:	Improved genetic algorithm with multiplier updating
HS:	Harmony search
SARGA:	Self-adaptive real-coded genetic algorithm
CSO:	Crisscross optimization algorithm
IWO:	Invasive weed optimization
GSA:	Gravitational search algorithm
CSA:	Cuckoo search algorithm
SFS:	Stochastic fractional search.

Data Availability

No underlying data were collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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