

Optimizing Combined Heat and Power Economic Dispatch Using a Differential Evolution Algorithm

K Mahender¹, Gundala Srinivasa Rao², Gangula Kamalakar³, S. Venkateshwarlu⁴, Swathi polasa⁵, and Harish Pulluri^{6*}

¹Associate Professor, Department of EEE, Geethanjali College of Engineering and Technology, Hyderabad, TS, India,

²Department of EEE, CMR College of Engineering & Technology, Hyderabad, TS, India,

³Professor, Department of EEE, CVR College of Engineering, Hyderabad, TS, India.

⁴Department of Electrical and Electronics Engineering, Anurag University, Hyderabad, T.S., India

⁵Senior Lecturer in Electrical and Electronics Engineering, Government Polytechnic Nirmal.

⁶Department of EEE, Anurag University, Hyderabad, T.S., India

Abstract. The electrical load dispatch (ELD) optimizes the scheduling of various power plants to deliver the necessary power at the lowest operational cost. Implementing combined heat and power (CHP) units in contemporary power systems enhances energy efficiency and generates less environmental pollution compared to conventional units by producing electricity and heat at the same time. As a result, the ELD issue, including CHP units, transforms into a non-linear and non-convex challenge called CHP economic dispatch (CHPED), which aims to meet electrical and thermal demands at the lowest operational cost. The CHPED issue is examined by applying the Differential evolution (DE) approach. The algorithm's efficacy on 24-unit, 48-unit, and 96-unit systems is detailed. The results acquired are compared with other algorithms to evaluate the effectiveness of the DE algorithm. The findings proved the efficacy of the DE algorithms compared to other evolutionary algorithms.

1 Introduction

Currently, energy conservation and pollution reduction are crucial problems, particularly in industrialized civilizations. Consequently, technologies that significantly contribute in this context receive considerable focus. The quantity of fossil energy is limited, and its use results in significant environmental degradation; thus, the effective utilization of these resources is crucial in electricity generation. The CHP unit is an appealing approach for optimizing energy use, as it concurrently generates electricity and heat within a system [1] and it achieves an energy efficiency of up to 90% [2] by the concurrent generation of two energy types, markedly enhancing the efficiency by around 30% compared to conventional plants [3]. In

* Corresponding author: mahi9vkb@gmail.com

CHPs, fuel prices are diminished by 10–40% [4], while pollution output is reduced by 13–18% [5]. Minimizing operating expenses arising from the substantial expenditures associated with constructing new plants remains a primary concern in the operation power plants. From the decades extensive research has been done save operational expenses using effective optimization methods. Consequently, optimizing power systems, particularly in the power production sector with the inclusion of new technologies like CHP, is a significant and compelling subject. Utilizing more advanced optimization techniques and identifying lowered operational expenses will substantially decrease power generation costs, allowing for cost savings to be allocated toward the development of new projects and the replacement of outdated equipment with newer alternatives. In a comprehensive framework where thermal plants play a crucial role, incorporating CHP is an efficient strategy for improving the effectiveness of power generation and it is known as CHPED issue [6-7]. The CHPED problem aims to reduce the total operational costs while satisfying all constraints [8]. Key factors that complicate the CHPED problem comprises the valve points of thermal units and the interdependence between power and heat generation in CHP units, known as the feasible operating region (FOR) [10].

Different classical methods like Lagrangian relaxation (LR), linear program (LP), semi-definite method are used to solve CHPED problem. These approaches are derivative-based methods and exhibit significant sensitivity to the initial conditions and characteristics of the objective function [11].

Effectively resolving the CHPED problem only by traditional methods is exceedingly challenging, if not unfeasible, particularly when accounting for the diverse objective functions and numerous limitations. To overcome the drawbacks of classical techniques many evolutionary techniques are developed namely grey wolf optimization [12], improved genetic algorithm [13], crisscross optimization [14, 15], Gaussian Cauchy mutation [16], social network search [17], marine predators [18], These algorithms may avoid local minima solutions but cannot assure the discovery of the optimal solution, lack significant metrics concerning the proximity to the global optimum, and are prone to premature convergence [19].

It is important to acknowledge that alternative heuristic methods, termed meta-heuristics, have been proposed to address complex optimization problems. They consist of a collection of methodologies aimed, at least partially, at automating the design of heuristic approaches for addressing complex computational search issues and pertain to a search methodology or learning mechanism for selecting or generating heuristics to resolve these computational challenges. More details on this subject can be found in [20-22].

CHPED constitutes an optimization issue that necessitates the consideration of several objectives and constraints for the solution. The main challenges in this problem are modelling the VPLE of thermal power units and the interdependent relationship between heat and electricity production in CHP units. The solution must satisfy the constraints. The proposed study addressed the intricate CHPED problem utilizing a proficient Differential Evolution algorithm and validated the method's effectiveness through testing on three case studies: Two medium test cases, a 24-unit system, and a 48-unit system, and one large test case, a 96-unit system.

2 Problem Formulation

The CHPED seeks to ascertain the optimal power and heat output of units to optimize fuel costs while satisfying power and heat demand along with other restrictions.

2.1 Objective Function

The purpose of this task is to minimize the following mathematical function:

$$\text{Minimize } C = C_T^{TH} + C_T^{CHP} + C_T^H \quad (1)$$

$$C_T^{TH} = \sum_{i=1}^{N_{TH}} C_i(p_i^{TH}) = \sum_{i=1}^{N_{TH}} [a_i + b_i p_i^{TH} + c_i p_i^{TH^2} + |e_i \sin \{f_i (p_i^{TH,m} - p_i^{TH})\}|] \quad (2)$$

$$\begin{aligned} C_T^{CHP} &= \sum_{j=1}^{N_{CHP}} C_j(p_j^{CHP}, h_j^{CHP}) \\ &= \sum_{j=1}^{N_{CHP}} [a_j + b_j p_j^{CHP} + c_j p_j^{CHP^2} + d_j h_j^{CHP} + e_j h_j^{CHP^2} + f_j p_j^{CHP} h_j^{CHP}] \end{aligned} \quad (3)$$

$$C_T^H = \sum_{k=1}^{N_H} C_k(h_k^H) = \sum_{k=1}^{N_H} [a_k + b_k h_k^H + c_k h_k^{H^2}] \quad (4)$$

$C_T^{TH}, C_T^{CHP}, C_T^H$, symbolize total cost, of PoU, CHP, HoU units respectively, N_{TH}, N_{CHP}, N_H indicate number of PoU, CHP, HoU individually; p_i^{TH}, p_j^{CHP} indicates power generated by PoU, CHP individually; h_j^{CHP}, h_k^H power generated by CHP and HoU respectively. a_i, b_i, c_i, d_i, e_i indicates cost characteristics of i^{th} PoU; a_j, b_j, c_j, d_j, e_j cost characteristics of j^{th} PoU; a_k, b_k, c_k indicates cost characteristics k^{th} HoU.

2.2 Constraints

2.2.1. Equality Constraints

The power consumed by POUs and CHPs should satisfy the heat and power demand as shown in (5) & (6).

$$\sum_{i=1}^{N_{TH}} p_i^{TH} + \sum_{j=1}^{N_{CHP}} p_j^{CHP} = p_d \quad (5)$$

$$\sum_{j=1}^{N_{CHP}} h_j^{CHP} + \sum_{k=1}^{N_H} h_k^H = h_d \quad (6)$$

2.2.2. Inequality Constraints:

The power generated by POUs should satisfy the lower and higher limits of the plant, as shown in (7). Similarly, the heat generated by HOUs should satisfy the limits of the plant, as shown in (8). The cogeneration plant should generate the power and heat that satisfies limits, as shown in (9,10).

$$p_i^{TH, \min} \leq p_i^{TH} \leq p_i^{TH, \max}; i = 1, 2, \dots, N_{TH} \quad (7)$$

$$p_j^{CHP, \min} (h_j) \leq p_j^{CHP} \leq p_j^{CHP, \max} (h_j) \quad (8)$$

$$j = 1, 2, \dots, N_{CHP}$$

$$h_j^{CHP, \min} (p_j) \leq h_j^{CHP} \leq h_j^{CHP, \max} (p_j); \quad (9)$$

$$j = 1, 2, \dots, N_{CHP}$$

$$h_k^{H,min} \leq h_k^H \leq h_k^{H,max}; k = 1,2, \dots, N_H \quad (10)$$

3 Proposed Differential Evolution to Solve CHPED Issue

Storn and Price [23] introduced an innovative EA for numerical problems termed as DE technique. This approach is named for its unique differential operator used to produce offspring from parent solutions, unlike the conventional crossover, mutation techniques.

Like Genetic Algorithms, the Differential Evolution technique is a population-based method that utilizes selection, crossover, and mutation, procedures. The primary distinctions among the Genetic Algorithm (GA) and the Differential Evolution (DE) lie in their mutation and selection processes.

3.1 Initialization

The initial population always generated between their higher and lower values using (11).

$$x_{i,j}(0) = x_j^l + rand(0,1) \cdot (x_j^u - x_j^l) \quad (11)$$

3.2 Mutation

In every run, a donor chromosome $v_i(t)$ is generated to modify the parent chromosome $x_i(t)$. The mechanism for constructing the donor chromosome distinguishes among different DE methods. Donor vector is created as shown in (12). Differentiation constant F ranges from 0.4 – 1.

$$v_{i,j}(t + 1) = x_{r1,j}(t) + F(x_{r2,j}(t) - x_{r3,j}(t)) + x_{r1,j}(t) + F(x_{r1,j}(t) - x_{r4,j}(t)) \quad (12)$$

3.3 Crossover

To enhance the diversity of the altered vectors, crossover is applied. The initial vector is combined with mutated using (13).

$$u_{i,j}(t+1) = \begin{cases} v_{i,j}(t+1) & \text{if } rand < CR \\ x_{i,j}(t) & \text{otherwise} \end{cases} \quad (13)$$

3.4 Selection

To maintain a stable population size across successive generations, a selection procedure is implemented to ascertain which individual, either the offspring or the parent, will persist into the following generation using (14).

$$\vec{X}_i(t + 1) = \begin{cases} \vec{U}_i(t) & \text{if } f(\vec{U}_i(t)) \leq f(\vec{X}_i(t)) \\ \vec{X}_i(t) & \text{if } f(\vec{X}_i(t)) \leq f(\vec{U}_i(t)) \end{cases} \quad (14)$$

4 Result And Discussion

The proposed DE technique applied to solve CHPED issue, The population size, number of generations, mutation and crossover rates considered are 60, 200, 0.6 and 0.7 individually.

The simulation programs were executed on a personal computer equipped with i5 processor, 16GB of RAM, using the MATLAB 2013a software environment.

4.1 Case 1

Here a 24-unit CHP system is considered. The test results of case 1 are shown in Table 3. There are 13 POU, 6 CHP units, and 5 HOU in a 24-unit CHP system. It can be seen that the results attained with DE are better in comparison to other algorithms like WOA [12], IGA-NCM [13], and DRL-CSO [14]. It is understood that cost is minimized by 1.39%, 0.92%, and 1.04% compared to WOA [12], IGA-NCM [13], and DRL-CSO [14]. The adherence of the result to the power and heat inequality constraints is visibly verified in Fig. 1. The CHP unit generations also satisfied the constraint of the feasible operating region, and the same can be verified in Fig. 2. The convergence graph of the DE exhibits the better convergence and stable operation of the algorithm.

Table I. Test Results of Case 1

Output (MW or MWth)	WOA [12]	IGA- NCM [13]	DRL-CSO [14]	DE
P1	28.3185	628.3188	448.784	541.6564
P2	299.1993	299.0346	299.161	359.3292
P3	299.1993	298.7415	224.376	234.3834
P4	109.8665	109.8229	159.712	60
P5	109.8665	60	159.797	180
P6	109.8665	109.8636	159.703	61.50521
P7	109.8665	109.8482	159.814	179.6284
P8	60.0000	109.8429	109.832	180
P9	109.8665	109.8016	109.805	61.5351
P10	40.0000	77.3128	40.863	40
P11	76.9485	40	40	40
P12	55.0000	55.0057	91.66	55
P13	55.0000	55	55.356	55
PC1	81.0000	81.001	81.604	81.77052
PC2	40.0016	40.0048	40	110.1636
PC3	81.0000	81.0006	84.533	81.98455
PC4	40.0000	40.3997	40	40
PC5	10.0000	10.0013	10	10
PC6	35.0000	35	35	35
HC1	104.8000	104.7975	104.575	104.8737
HC2	75.0014	83.9529	75	135.5136
HC3	104.8000	107.7004	106.752	104.7084
HC4	75.0000	79.2794	75	75
HC5	40.0000	40.0006	40	40
HC6	20.0000	20.6318	20	20
H1	470.3986	445.2006	468.672	410.518
H2	59.9999	60	60	60
H3	59.9999	59.9988	60	60
H4	119.9999	120	120	119.6275
H5	119.9999	119.9999	120	119.6483
Minimum cost (\$/h)	57825.46	57831.3033	57902.3189	57298.97

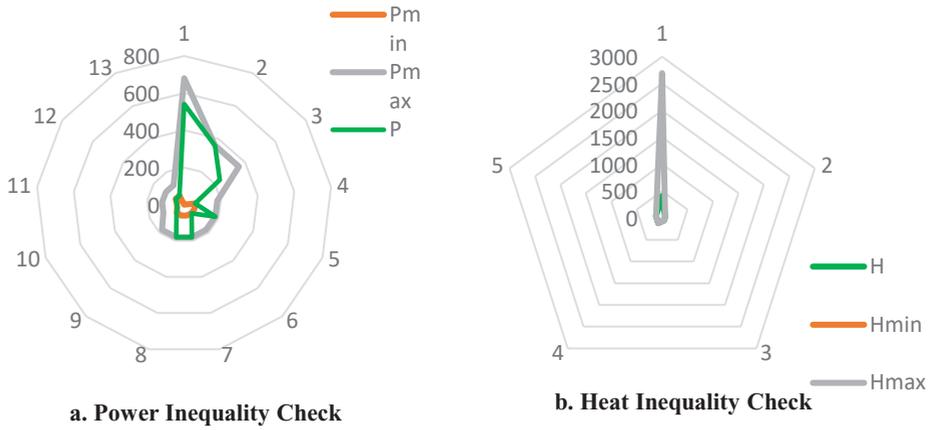


Fig. 1. Inequality constraints check for POU and HOU

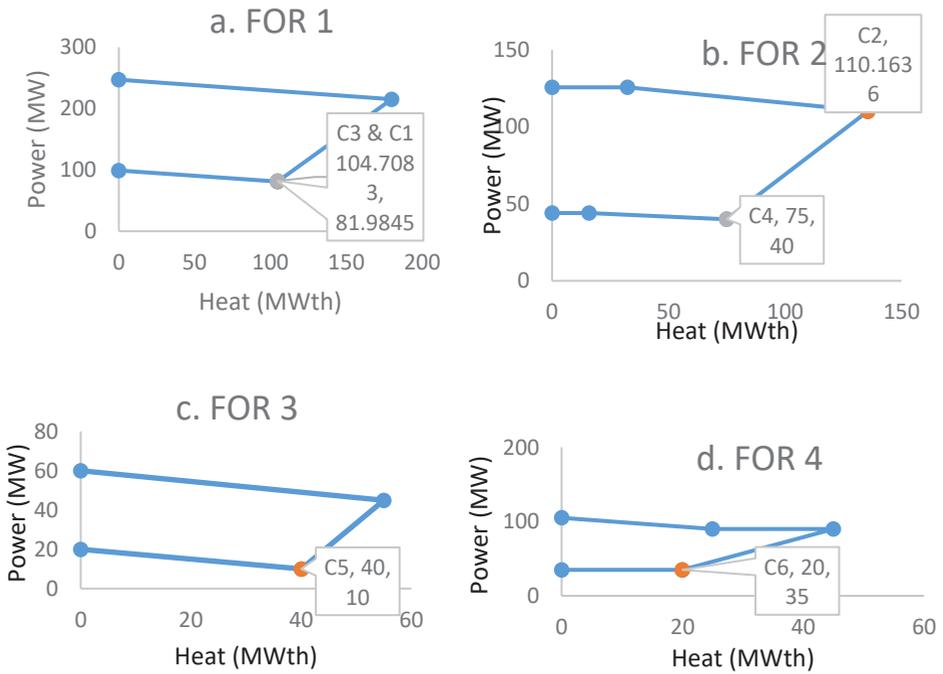


Fig. 2. Inequality constraints check for CHP systems

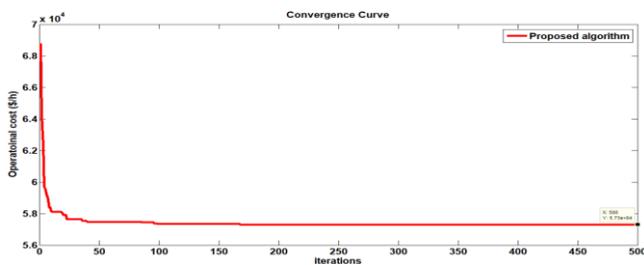


Fig. 3. Convergence characteristics of proposed algorithm

4.2 Case 2

48-unit CHP system with 26 POU, 10 HOU, and 12 CHP systems are included in Case 2. The results are compared to other algorithms and observed that the cost is reduced by 12.7%, 13%, 12.4%, and 12.37% compared to DEGM [15], SaDE [15], JADE [15], and SDEGCM [15] respectively.

Table II. Comparison of Case 2 Results

Method	Cost(\$/h)
DEGM [15]	116074.4967
SaDE [15]	116493.6203
JADE [15]	115687.8406
SDEGCM [15]	115626.3697
DE	101315.2537

Table III. Output of All units for Case 2

Output	DE	Output	DE
P1	628.9438	PC5	45
P2	15.05562	PC6	42.77249
P3	324.9378	PC7	98.8
P4	172.0773	PC8	54.1668
P5	96.97508	PC9	93.44661
P6	62.42791	PC10	78.45994
P7	129.9208	PC11	45
P8	107.3281	PC12	35
P9	147.4456	HC1	65.84414
P10	47.86219	HC2	73.34293
P11	87.7641	HC3	94.73729
P12	55	HC4	75
P13	78.22089	HC5	55
P14	280.8809	HC6	10.91535
P15	347.8522	HC7	0
P16	343.6928	HC8	64.55085
P17	141.7808	HC9	79.61939
P18	123.4712	HC10	82.60655
P19	154.3369	HC11	55
P20	69.39975	HC12	20
P21	91.10248	H1	100.8723
P22	158.087	H2	60
P23	40	H3	51.40967
P24	94.70463	H4	76.00984
P25	103.4307	H5	112.6969
P26	100.1155	H6	1116.438
PC1	103.4523	H7	60
PC2	83.63594	H8	54.32972
PC3	158.5071	H9	120
PC4	40	H10	119.7763
		Minimum	101315.3

5 CONCLUSION

This research examined the issue of CHPED utilizing the proposed DE algorithm. Upon conducting numerical analyses and evaluating the findings, it was determined that the results derived from the DE method demonstrate its efficiency and capability to find better optimal

solution. The proposed method effectively accounts for the FoR of cogeneration units, which is challenging. Upon resolving the problem, it was determined that the suggested solution possesses both a minimal and an optimal value. The proposed method serves as a suitable solution for addressing the CHPED issue, as it can get an optimal solution and incorporate relevant constraints.

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