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Optimal Power Dispatch in Combined Heat and Power Systems with Solar and Wind Integration

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***Abstract*— Cogeneration, or combined heat and power (CHP) generation system delivers electrical energy and recovers dissipated heat, reducing costs, emissions, and enhancing renewable energy integration by smoothing intermittency. CHP economic dispatch problem (CHPED) is necessary for handling load dynamics and addressing the uncertainty of nonconventional energy sources. The primary focus of this proposed work is to minimize overall operational expenses while adhering to generator constraints and giving priority to solar, wind power output. For solving this CHPED problem, an arithmetic optimization algorithm (AOA) is utilized to obtain an optimal solution. In this study, a 10-unit framework is tested to establish the effectiveness of CHPED both including and excluding solar and wind power. Obtained results shows significant decrease of 18% in operational costs by incorporating considered renewable energy sources. This approach can enhance the integration of wind and solar source energy generated power as distributed sustainable energy into the CHPED process.**

Keywords*— *cogeneration; Arithmetic Optimization Algorithm; solar energy; wind energy; battery integration.

Nomenclature

P_{rtd}	*Rated power*
$\alpha_i, \beta_i, \gamma_i, \eta_i, \delta_i$	Fuel emission coefficients of the ith thermal unit
a_i, b_i, c_i, d_i, e_i	*Fuel cost coefficients of the ith thermal unit*
P_{SlZ} , P_{ucostl}	*Solar power generation and per unit cost of the lth solar plant*
P_{solar}	*Generated from solar plants*
P_{BTZ}	*Battery power at hour z*
N_T	Number of thermal generating units
WG, SG	Generated Wind power, Solar power

I. INTRODUCTION

Cogeneration units are becoming very important in modern power system networks as a result of their high energy performance, sustainable performance, and adaptability [1,2]. With the capability of shared energy conversion, there is plenty of opportunity to improve the energy efficiency of conventional CHP systems, despite available concerns regarding improving their economic feasibility [3]. Integrating CHP units into conventional economic dispatch (ED) problem has brought evident changes to the power sector. Economically and environmentally, cogeneration units represent favourable option within the electrical power industry [4]. Incorporating cogeneration (CHP) units into current power system networks can enhance the energy transfer efficiency of thermal power plants to approximately 80% to 90% and also reduce carbon emissions by approximately 13 to 18 percent. [5]. CHP generating units have the capability to generate electricity from different fuel sources while also seizing and recycling typically surplus heat produced during generation of electricity [6]. Monitoring operational output of energy networks with thermal power generation unit is extremely intricate, represented by nonlinear and non-convex behaviours. This intricateness introduces greater technical challenges when integrating renewable energy sources [7].

Over the recent years, different solution methods for the CHPED problem have been introduced by researchers. Such approaches are majorly categorized in two different categories: classic optimization approaches, such as Newton's approach [8], lagrange relaxation algorithm [9], lagrange relaxation algorithm sub-gradient method [10], branch bound algorithm [11] and Meta-heuristic optimization algorithms. For applying these algorithms in to the nonconvex nature and nonlinear property of the CHPED, defined by intricacies like valve point loading impact and operational constraints, presents crucial challenges. Classical optimization algorithms are esteemed for their robustness and computational performance. Nonetheless, their efficacy can be exceedingly influenced by the initial conditions and the specific characteristics of the objective function [12]. Consequently,

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these algorithms frequently face difficulty to ensure globally optimal or near-optimal solutions in feasible implementation.

However, metaheuristic techniques address the previously mentioned challenges and are capable of managing both single-criteria objective function and multi-criteria objective function optimization tasks. In the context of single-objective functions, the goal is to minimize operational costs. In reference [13], a hybrid method combining genetic algorithms and harmony searching technique was presented to resolve the CHPED problem. Reference [14] proposed the binary value technique as a strategy to mitigate the nonconvexity associated with the CHPED problem. Other different innovative and population-oriented optimization techniques have been introduced in research for the economic dispatch of both power and heat together consecutively in CHP generators. Some of the examples incorporate genetic algorithm (GA) [15], strength Pareto honey bee mating optimization (SPHBMO) [16], imperialist competitive algorithm (ICA) [17], and cuckoo search algorithm [18]. Additionally, various learning-based optimization algorithms are being implemented in the published research works, such as teaching learning-based optimization (TLBO) [19], gravitational search algorithm (GSA) [20], and exchange market algorithm (EMA) [21,22]. Above mentioned methods are excluded from derivatives and do not depend a precise initial value. However, they fail to assure the reaching of near global optimal outcome and may result trapping in local optimal solutions.

The literature review cited above does not adequately cover the integration of solar, wind and battery the CHPED problem, specifically addressing constraints associated with CHP units. Therefore, this research work introduces the adoption of an arithmetic optimization algorithm (AOA) for CHPED, with and without solar, wind and battery incorporated in hybrid energy framework. The effectiveness of the proposed algorithm is authenticated using a standard ten generating unit test system power generation network. The results illustrate that integrating solar, wind, and battery systems with a CHPED structure results in a significant reduction in overall operational fuel costs.

This article follows the structured as mentioned here. Section II explains mathematical modelling of cost function. AOA is discussed in Section III. In Section IV, contrasts the findings from the ten-generation unit test case platform under review. Lastly, in Section V conclusions are drawn from the results and findings.

II. Mathematical Modelling of Cost Function

The objective cost functions for different generators are incorporated into the mathematical formulation of the solar, wind, battery integrated CHPED problem.

A. Cost Function of Thermal Power Generation Unit

The thermal power generation unit's fuel cost mathematical function is configured by Equation (1) [23].

$$\sum_{i=1}^{N_T} C_i(P_i^T) = \sum_{i=1}^{N_T} [a_i P_i^{T^2} + b_i P_i^T + c_i](\$/h) \tag{1}$$

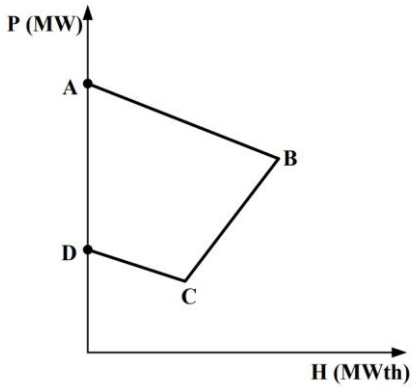


Fig.1. possible operating zone of CHP generating unit

In the Equation (1), $C_i(P^T_i)$ denotes the fuel charges for the i^{th} thermal generator unit, where P^T_i is the generated power output. N_T represents the count of thermal power generating units, and a_i, b_i, and c_i are represents cost coefficients. Considering valve point irregularity impact a sine function component is taken into the cost function to improve the real world modelling.

$$\sum_{i=1}^{N_T} C_i(P_i^T) = \sum_{i=1}^{N_T} [a_i P_i^{T^2} + b_i P_i^T + c_i + |e_i sin\{f_i\left(P_i^{T^{min}} - P_i^T\right)\}|](\$/h) \tag{2}$$

B. Cogeneration Unit Cost Function

Equation (3) provides the cost model for the cogeneration unit

$$\sum_{j=1}^{N_C} C_j\left(P_j^C, h_j^C\right) = \sum_{j=1}^{N_C} [a_j P_j^{C^2} + b_j P_j^C + c_j + d_j h_j^{C^2} + e_j h_j^C + f_j P_j^C h_j^C](\$/h) \tag{3}$$

Where the j^{th} cogeneration unit's cost function is $C_j(P^c_j\, h^c_j)$. aj, bj, cj, dj, ej, fj is cost coefficients. P^c_j(MW) and h^c_j (MWth) represents the real power and heat output, respectively. The number of cogeneration unit is N_c . As shown in the Figure 1 ABCDA is the possible operational zone of CHP unit [3,4].

C. Heat Unit Cost Function

Equation (4) represents the heat unit cost function. Here kth is the heat only unit. Here a_k, b_k and c_k are cost coefficients.

$$\sum_{k=1}^{N_H} C_k\left(h_k^H\right) = \sum_{k=1}^{N_H} a_k h_k^{H^2} + b_k h_k^H + c_k(\$/h) \tag{4}$$

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D. Solar Unit Cost Function

Solar-based power ($P_{_solar}$) is generated by transforming the solar incident radiation either explicitly or scattered, into electrical energy traversing the atmosphere. The generated power by solar power unit is derived using the equation (5)

$$P_{solar} = \frac{S_i P_{rtd}}{1000}\left[1 + \alpha\left(T_{ref} - T_{amb}\right)\right] \tag{5}$$

Where P_{rtd} and Si are denoted as rated capacity of power and solar radiation incident, respectively and α, T_{amb}, T_{ref} are temperature coefficient, ambient temperature and reference temperature, in order.

Power output threshold for constrained solar power generating unit is considered. Generally, 30% of total power demand power can be generated from solar power units [25]. Power generation constraint of solar power generation unit is shown in (6) as

$$\sum_{l=1}^{G_S} P_{S_l} \times Ds_l \leq 0.3 \times P_D \tag{6}$$

Where D_{s_l} is denoted for indicating the operational effectiveness of solar plant at active state or idle state. Generation cost of solar power (7) [25] is calculated using (7) as

$$C(P_S olar) = \sum_{l=1}^{G_S} P_{ucostl} \times P_{S_l} \times Ds_l \tag{7}$$

E. Wind Power Generation Unit Cost Model

The Weibull statistical function for calculating the wind speed v in meters per second is expressed by Equation (8), here k denotes the shape factor and x is the scale factor parameter [26].

$$f_v(v) = (k/x) * \left(\frac{v}{x}\right)^{(k-1)} * e^{-\left(\frac{v}{x}\right)^k} for\ 0 < v < \infty \tag{8}$$

P_w denotes wind power generated which is a dependent of wind speed v, given by Equation (9)

$$p_w(v) = \begin{cases} 0 & for v < v_{in}\ and\ v > v_o \\ p_{wt}\left\{\frac{(v - v_{in})}{(v_r - v_{in})}\right\} & for\ v_{in} \leq v \leq v_r \\ p_{wt} & for\ v_r < v \leq v_o \end{cases} \tag{9}$$

In Equation (9), V_{in} represents the cut-in wind speed, V_r is the rated wind speed, and V_{out} implies the cut-out speed of the wind turbine. The rated output power is expressed as P_{wt}. The cost function of the n^{th} wind turbine include the direct cost $C_{w,n}(P_{ws,n})$, reserve cost $C_{rw,n}(P_{ws,n} - P_{wav,n})$, and penalty cost $C_{pw,n}(P_{wav,n} - P_{ws,n})$. Equation (10) provides the constant direct cost of the nth wind power turbine unit [26].

$$C_{w,n}(P_{ws,n}) = g_n * P_{ws,n} \tag{10}$$

Since wind speed varies, the power produced from the wind turbine shows high unpredictability. In these cases, if the generated wind turbine power output of the turbine is lower than the forecasted wind power, an overestimation cost is obtained. On the other hand, if the wind power production exceeds predicted value, the underestimation cost is used. Equation (11) expresses the reserve cost for the n^{th} wind turbine [26].

$$\begin{aligned} C_{pw,n}(p_{wav,n} - p_{ws,n}) &= k_{pw,n}(p_{wav,n} - p_{ws,n}) \\ &= k_{pw,n}\int_{p_{ws,n}}^{p_{wr,n}} (p_{w,n} - p_{ws,n}) f_w(p_{w,n}) dp_{w,n} \end{aligned} \tag{11}$$

F. Objective Function

The core objective of the proposed work is to decrease operational costs and deliver near optimal heat demand and load power requirement while satisfying to all constraints. To perfectly estimate real-world conditions, the solar-wind integrated CHPED the unpredictability of wind energy source and solar power sources are taken in to consideration. Additionally, the configured model of the wind determines the optimal wind power output. Two scenarios are presented: first, the objective function is modeled without any renewable power unit; second, the objective function includes solar and wind power unit.

$$\begin{aligned} MinC &= \sum_{i=1}^{N_T} C_i(P_i^T) + \sum_{j=1}^{N_C} C_j\left(P_j^C, h_j^C\right) + \sum_{k=1}^{N_H} C_k(P_k^H) \\ &+ \sum_{n=1}^{N_{wt}} \left[C_{w,n}(p_{ws,n}) + C_{rw,n}(p_{ws,n} - p_{wav,n}) + C_{pw,n}(p_{wav,n} - p_{ws,n})\right] \\ &+ \sum_{l=1}^{G_S} C(P_S olar) \end{aligned} \tag{12}$$

The overall operational cost is C as given in Equation (11).

G. Constraints

The following balancing criteria and inequality criteria required to resolve CHPED are described below.

The generating constraints of the operating generators must be satisfied, like, linear and nonlinear constraints considered during generation of power. All the working generators must generate power within their generation limits along with fulfilling the Demand power (P_D) for each hour z. Demand power balance equation expressed by Equation (13).

$$\sum_{i=1}^{G_T} P_{TiZ} + \sum_{j=1}^{G_W} P_{WjZ} + \sum_{l=1}^{G_S} P_{SlZ} + \sum_{z=1}^{h} P_{BTZ} - P_{DZ} = 0 \tag{13}$$

The generating limits of i^{th} thermal power generator [27] are at any period z are shown in Equation (14).

$$P_{Ti}^{min} \leq P_{TiZ} \leq P_{Ti}^{max} \tag{14}$$

The overall power generated by the power, CHP generator, solar and wind turbine units must align with the overall power demand indicated in Equation (15). The total heat output by

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the combined cycle and heat generation must be equivalent to the overall heat required as represented in Equation (16).

$$\sum_{i=1}^{N_T} P_i^T + \sum_{i=1}^{N_C} P_j^C + \sum_{n=1}^{N_{wt}} p_{ws,n} = P_d \tag{15}$$

$$\sum_{j=1}^{N_C} h_j^C + \sum_{k=1}^{N_H} h_k^H = h_d \tag{16}$$

III. AOA

In this section, a novel algorithm AOA proposed by Abualigah et al. [28] has been discussed which is further improvised by considering chaotic map (i.e., Gauss map). The four main basic math operators as multiplication, division, subtraction, and addition are traditionally used to study the operation on numbers [28]. AOA is a new meta-heuristic algorithm that employs the distribution behaviour of these main arithmetic operators in mathematics. AOA is a innovative meta-heuristic approach that implements the distribution nature arithmetic operators of mathematics. There are mainly two main phases: exploration (diversification) and exploitation (intensification) processes [28] of the AOA. The major advantage of the AOA is that it is a population-driven meta-heuristic algorithm which is efficient in solving various modern optimization scenarios without calculating derivatives of the objective functions. Fig.2 represents the hierarchy of arithmetic operators and its distribution from the outside to the inside [28].

The AOA has established superior forecasting qualities for unpredictable nonlinear, nonconvex models like CHPED problems due to its capability to balance exploration and exploitation perfectly. Its mathematical implementation allows it to navigate very complex search spaces, skipping local optima, and adaption of high-dimensional data handling capability, non-linear nature of CHPED models. Apart from this the robustness and fast convergence capability of the AOA also allows to tackle the complex issues of the CHPED problem [28].

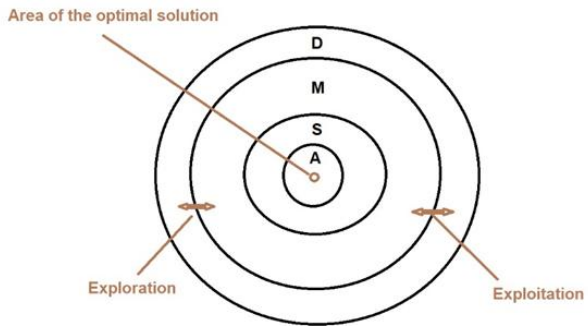


Fig.2. Hierarchy of Arithmetic operators

IV. Results and Discussion

In the current section Table1 shows the optimal thermal power in MW and heat in MWth generation without Solar Wind Power units using AOA where total cost is achieved as 19319.00 $. However by using solar & wind power generating units we can bring that cost down to 15838.00 $ as shown in Table 2. Thus it shows a significant 18% reduction in total cost by using renewable sources. Fig.3 and Fig.4 shows the convergence curves of the optimal generation without solar and wind consideration and with solar and wind power respectively. After the 100th iteration, the total cost shows very minimal changes, which shows that the algorithm AOA has successfully reached the near optimal minimum cost. This stability reflects the efficiency of the proposed method in converging to an accurate solution while addressing the complexities of the CHPED problem.

Table 3 shows the supremacy of AOA over other studied algorithms such as squirrel search algorithm (SSA), particle swarm optimization (PSO) and backtracking search algorithm (BSA).

Table 1
Optimal thermal power (MW) and heat (MWth) generation without Solar Wind Power Units

Unit Type	Optimum Points	power (MW)	Optimum Points	Heat (MWth)
Power Only	P1	156.5529	------	------
Power Only	P2	205.9319	------	------
Cogeneration	P3	148.3787	H3	148.0391
Cogeneration	P4	235.9241	H4	54.41843
Cogeneration	P5	144.9457	H5	203.4598
Cogeneration	P6	154.9408	H6	171.5341
Cogeneration	P7	261.3931	H7	194.6093
Cogeneration	P8	191.933	H8	98.9888
Heat Only	------	------	H9	124.4386
Heat Only	------	------	H10	187.9157
Total Power Demand (MW)		1500		
Total Heat Demand (MWth)		1183		
Total cost ($)		**19319.00**		

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Table 2
Optimal power (MW) and heat (MWth) generation with Solar Wind Power Units

Unit Type	Optimum Points	power (MW)	Optimum Points	Heat (MWth)
Power Only	P1	131.2403	------	------
Power Only	P2	197.6842	------	------
Cogeneration	P3	119.5052	H3	160.0390
Cogeneration	P4	131.8846	H4	131.4184
Cogeneration	P5	195.5614	H5	107.4597
Cogeneration	P6	173.2203	H6	159.8091
Cogeneration	P7	193.5362	H7	177.3883
Cogeneration	P8	149.5052	H8	149.2098
Heat Only	------	------	H9	136.1435
Heat Only	------	------	H10	161.9156
Solar Power (MW)	128.7126			
Wind Power (MW)	79.15			
Total Power Demand	1500			
Total Heat Demand	1183			
Total cost ($)	**15838.00**			

Table 3
Optimal generation costs for CHPED with and without Solar Wind

Method	CHPED without Solar Wind	CHPED with Solar Wind	Simulation
	Generation cost ($)	Generation cost ($)	time(s)
AOA[Proposed]	19319.00	15838.00	16
SSA[3][Studied]	21110.00	16791.00	19
PSO[5][Studied]	20023.00	17019.00	21
BSA[4][Studied]	21420.00	17118.00	19

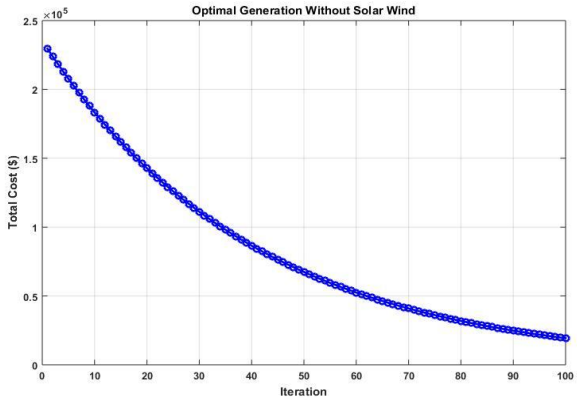


Fig.3. Convergence plot of optimal generation without solar and wind power

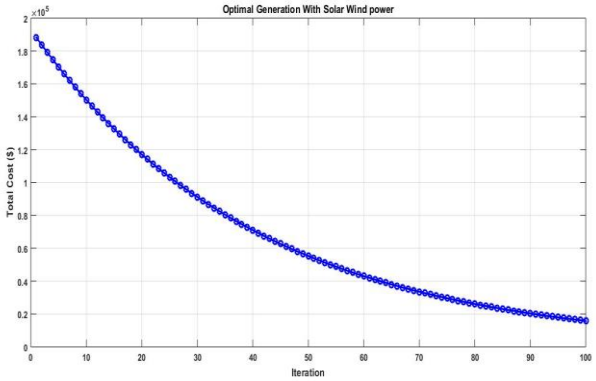


Fig.4. Convergence behavior of optimal generation with solar and wind power

V. CONCLUSION

This study has illustrated the effectiveness of integrating solar and wind energy resources into the CHPED problem. By using AOA, the overall cost of operation is minimized along with complying with generator constraints and emphasizing solar and wind power outputs, resulting in an 18% reduction in operational costs in a 10-unit framework. This approach not only reduces costs and emissions but also enhances the stability and reliability of renewable energy integration by smoothing intermittency. The findings suggests that the introduced approach in this paper can effectively execute the incorporation of solar and wind sources with conventional thermal power generating units in CHPED problem, thereby adding to a more sustainable and efficient energy system.

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