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Solution of Combined Heat and Power Economic Dispatch Problem Using Direct Optimization Algorithm

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Abstract

This paper presents the solution to the combined heat and power economic dispatch problem using a direct solution algorithm for constrained optimization problems. With the potential of Combined Heat and Power (CHP) production to increase the efficiency of power and heat generation simultaneously having been researched and established, the increasing penetration of CHP systems, and determination of economic dispatch of power and heat assumes higher relevance. The Combined Heat and Power Economic Dispatch (CHPED) problem is a demanding optimization problem as both constraints and objective functions can be non-linear and non-convex. This paper presents an explicit formula developed for computing the system-wide incremental costs corresponding with optimal dispatch. The circumvention of the use of iterative search schemes for this crucial step is the innovation inherent in the proposed dispatch procedure. The feasible operating region of the CHP unit three is taken into account in the proposed CHPED problem model, whereas the optimal dispatch of power/heat outputs of CHP unit is determined using the direct Lagrange multiplier solution algorithm. The proposed algorithm is applied to a test system with four units and results are provided.

Keywords

Economic Dispatch, Lagrange Multiplier Algorithm, Combined Heat and Power, Constraints and Objective Functions, Optimal Dispatch

1. Introduction

Economic dispatch pertains to the problem of determining the outputs of the generating units in service. Its aim is to meet the total load demand while keeping the fuel cost at the barest minimum. It is common knowledge that at the optimum point, all units (excluding those at their limit) would be operating at equal incremental costs. Hence, current solution methods premise the finding of this particular value of the marginal cost ("lambda", λ), for a given load demand. Additional constraints to the power demand in systems have to be satisfied at the solution point with some co-generation units. Hence, the simple equal incremental cost-based economic dispatch schemes cannot be used for such systems. The main problem in economic dispatch lies with the distribution of generator load to produce the measure of electricity required. Examples of economic dispatch problems could be economic load dispatch in the operation of power systems, dynamic or static dispatch, hydrothermal scheduling problems and others [1]. A significant number of decision variables and non-linearity, ordinarily characterize Economic Load Dispatch (ELD) problems, including non-linear constraints due to the characteristics of modern units. Improvements in solving this class of optimization problems have led to significant savings in costs. The emergence of modern computational intelligence algorithms, genetic algorithms, differential evolution algorithms, artificial bee colony algorithms, whale optimization algorithms, Kho-Kho optimization algorithms, etc. has paved the way for solutions to complex optimization problems.

We begin with a brief review of related literature in Section 2. Subsequently in Section 3, we describe the mathematical model of the CHPED problem. In Section 4, we present the test system results and discuss our findings. Finally, the conclusions resulting from the research work are highlighted in Section 5.

2. Brief Literature Review

Integrating cogeneration units into the ED problem converts the ED problem into a Combined Heat and Power Economic Dispatch (CHPED) problem. The CHPED problem is a highly nonlinear and complex problem to solve since in addition to the linear and nonlinear constraints of the ED problem, the Feasible Operating Region (FOR) constraint of the cogeneration units must also be satisfied. Obtaining the solution to the CHPED problem is demanding due to the interdependence of heat and power generation of the cogeneration unit. It further requires extremely efficient algorithms to obtain the optimal solution [1]. Possible additional constraints in the economic dispatch problem of such systems depend on the type of co-generation units. Economic dispatch problem of systems with different co-generation unit types has been severally researched. The economic dispatch of systems having simple cycle co-generation units has been investigated in [2] [3] [4] [5]. In [6] [7], the ED problem with combined cycle co-generation units has been considered. The daily operation scheduling of co-generation units with heat storage tanks has been studied in [8]. Scheduling of back-pressure cogeneration plants has been considered in [9] [10]. In some of these investigations, additional issues like the time of use rate, wheeling, etc. have also been included. It is seen that the mathematical models for the combined heat and power dispatch of systems with cogeneration units turn out differently, depending on the type of the units as well as their operating environments. The multiplicity of the models has resulted in a variety of solution techniques such as quadratic programming [2], partial separable programming [2], two-layer Lagrangian relaxation [3], Newton's method [9], genetic algorithms [4] [5] [7] [8] [10], etc. being proposed in these investigations. The focus of the present paper is limited to one class of the problem—the ED of systems having simple cycle co-generation units. This class of problems has been considered in [2] [3] [4] [5]. In this ED problem, meeting the heat demand of each area, in addition to the system power demand in the most economical way is necessary. Combined Heat and Power (CHP) dispatch problem is formulated in [11] as an optimization problem with quadratic objective function and liner constraints. It is shown in [12] that, though this problem can be solved by standard quadratic programming, it can be solved more efficiently based on Dual, Partial-separable Programming (DPS) method. Guo *et al.* have proposed an alternate solution approach to this problem. The problem in [13] is decomposed into heat and power dispatch sub-problems. The two sub-problems are connected by the heat-power feasible region constraints of the co-generation units.

In this article, we aim to solve the CHP dispatch problem directly. By CHP dispatch, we mean a simple cycle cogeneration unit with quadratic cost functions. We develop a formula for the system lambdas corresponding to the power and heat demands in term of the coefficients of the generator cost functions for the most common form of this problem formulated in [14]. This operation is based on the assumption that the cost functions are quadratic. The unit outputs corresponding to these system lambda values constitute the required heat and power dispatch, provided none of the unit outputs hit their limits. To account for situations where some of the outputs corresponding to the computed system λ values happen to violate their limits, we propose a simple scheme for setting the outputs of such units at appropriate limits. Setting some units at their limits could result in mismatches between the demand and the generation. We therefore resort to recalculating the system λ, for the units not set at their limits to eliminate these mismatches.

3. Combined Heat and Power Economic Dispatch Problem Formulation

The CHPED problems are constrained optimization problems, which consists of decision variables *i.e.* (heat, power dispatch values) and objective function. The objective function indicates how much each decision variables contributes to the value of the function (cost) to be optimized in the problem statement and its duty is to minimize the total generation cost in a system that consists of the conventional thermal power and heat units plus the cogeneration unit with feasible operation region. The two power units, a cogeneration unit and a heat-only unit in the research have quadratic cost functions. The limit on the outputs of the co-generation unit is specified by listing the co-ordinates of the corners of the feasible operating region of the unit as shown in **Table 4**. The objective function also represents the input fuel cost while the constraints are inequality, equality and other operational constraints that matches load and heat demands with power generation. In this research, the system transmission losses were neglected leaving power and heat loads plus the machine operation bound as the only available constraints. The research first shows that it is possible to solve CHPED problem using direct method [1]. Furthermore, artificial bee colony, genetic, particle swarm optimization and differential evolution algorithms can also be employed to this class of optimization problem and results from the various algorithms were compared to determine the algorithm with optimal result and best operational costs. Firstly, we developed a formula for the system lambdas which correspond to the power and heat demands in terms of the coefficients of the generator cost functions for the most common form of this problem formulated assuming that the cost functions are quadratic. The unit output corresponding to these system lambda values constitute the required heat and power dispatch, provided none of the unit outputs hit their limits. In order to handle situations where some of the output corresponding to the computed system Lagrange multiplier λ-values happens to violate their limits, we developed a simple scheme for setting the outputs of such units at appropriate limits. Setting some units at their limits could result in mismatches between the demand and the generation. We recalculate the system λ, for the units not set at their limits in order to eliminate mismatch. To calculate combined heat and power economic dispatch decision variables directly, the problem statement was modelled such as to determine combined heat and power economic dispatch decision variables.

Combined Heat and Power Dispatch Problem

Given respectively, the quadratic fuel cost function of power-only, cogeneration and heat-only units in Naira (₦), we have:

$$c_{e,i}\left(p_i\right)=\alpha_i+\beta_i p_i+\gamma_i p_i^2 \tag{1}$$

$$c_{c,i}\left(p_i,q_i\right)=\alpha_i+\beta_i p_i+\gamma_i p_i^2+\delta_i q_i+\varepsilon_i q_i^2+\zeta_i p_i q_i \tag{2}$$

$$c_{h,i}\left(q_i\right)=\alpha_i+\delta_i q_i+\varepsilon_i q_i^2 \tag{3}$$

where, α_i,β_i and γ_i are the cost coefficient of i^{th} power-only unit, $\alpha_j,\beta_j,\gamma_j,\delta_j,\varepsilon_j$ and ζ_j are the cost coefficients for the j^{th} cogeneration unit, α_k,δ_k and ε_k represent the coefficient of k^{th} heat-only unit. The objective function of the combined heat and power economic dispatch problem is to minimize the cost function, subject to equality, inequality and other operational constraints.

The objective function of the combined heat and power economic dispatch problem can be stated thus:

$$\text{Min } C = \sum_{i\in e} c_{e,i}\left(p_i\right) + \sum_{i\in c} c_{c,i}\left(p_i, q_i\right) + \sum_{i\in h} c_{h,i}\left(q_i\right) \tag{4}$$

Q and P are the heat and electrical power output decision variables of the units respectively. $c_{e,i}\left(p_i\right)$, $c_{c,j}\left(p_j, q_j\right)$ and $c_{h,k}\left(q_k\right)$ constitute the fuel cost function of i^{th} power-only unit, fuel cost function of j^{th} cogeneration unit and fuel cost function of k^{th} heat-only unit. We wish to minimize the total cost function given by Equation (4) subject to the following constraints.

- Real power created by power unit plus the real power created by cogeneration unit is equal to the real power demand of power systems abandoning power loss, and this is stated mathematically in Equation (5) below:

$$\sum_{i\in e} p_i + \sum_{i\in c} p_i = p^{demand} \tag{5}$$

- Comparably, the total heat created by boilers plus the active heat created by cogeneration units is equal to the heat demand, abandoning heat loss, and can be stated thus:

$$\sum_{i\in e} q_i + \sum_{i\in h} q_i = q^{demand} \tag{6}$$

where, p^{demand} and q^{demand} are the total heat and power demand of system, respectively. In the heat equality constraint, heat losses are postulated to be zero because no research work about heat losses during process of transmitting heat to heat loads has been carried out. For clarity, that postulation was employed in this research. Therefore heat losses are negligible.

- Furthermore, if heat losses are a function of heat outputs similar to power loss function or a constant, heat balance constraint will be solved simply and successfully.

$$p_i^{\min} \le p_i \le p_i^{\max} \tag{7}$$

$$q_i^{\min} \le q_i \le q_i^{\max} \tag{8}$$

Thus formally, the optimization problem to be solved is:

$$\begin{cases} \text{Min } C = \sum_{i\in e} c_{e,i}\left(p_i\right) + \sum_{i\in c} c_{c,i}\left(p_i, q_i\right) + \sum_{i\in h} c_{h,i}\left(q_i\right) \\ \text{subject to} \\ \sum_{i\in e} p_i + \sum_{i\in c} p_i = p^{demand} \\ \sum_{i\in e} q_i + \sum_{i\in h} q_i = q^{demand} \\ p_i^{\min} \le p_i \le p_i^{\max} \\ q_i^{\min} \le q_i \le q_i^{\max} \end{cases} \tag{9}$$

We also impose extra constraints on the output of the cogeneration unit as:

$$a_{ij} p_i + b_{ij} q_i \ge c_{ji} \quad j = 1, \cdots, n_i \tag{10}$$

The output of the cogeneration unit is presumed to lie in a region in the P_i-Q_i plane bounded by n_i lines. These lines are illustrated in Figure 1.

Figure 1 is a typical polyhedron of a feasible region (search space) of a cogeneration unit bounded by four hyper-plane lines in the P_i-Q_i plane. In such a plane, there are three kinds of operating points of a cogeneration unit. At point O (feasible region or solution space), the unit is not bounded by any constraints. At points N and M, the unit is bounded by only one constraint and at point K; the unit is bounded by two constraints. For a point in Figure 1 to be feasible, it should be above line AB, below line CD, right of AD and left of BC and anything contrary to these is infeasible region. To determine if a point is feasible or not, we substitute the value of [p, q] inside equation of a line formed between two vertices connected by a line segment. For any value of [p, q], substituting the value of the function maybe zero, positive or negative. The operating point is positive when the value is in the region O, zero when the value is on the line of the quadrilateral (ABCD) and negative when it is either at positions M, N and K or infeasible region. The problem described by the system (9) and (10), is an optimization problem, which contains both equality and inequality constraints needs the deployment of the Karush-Kuhn-Tucker (KKT) optimality conditions.

The Karush-Kuhn-Tucker (KKT) Lagrange multiplier for the dispatch problem given is:

$$\begin{aligned} L = {} & \sum_{i\in e} c_{e,i}\left(p_i\right) + \sum_{i\in c} c_{c,i}\left(p_i, q_i\right) + \sum_{i\in h} c_{h,i}\left(q_i\right) \\ & -\lambda_p\left(\sum_{i\in e} p_i + \sum_{i\in c} p_i - p^{demand}\right) - \lambda_q\left(\sum_{i\in e} q_i + \sum_{i\in h} q_i - q^{demand}\right) \end{aligned} \quad (11)$$

where, λ_p and λ_q are the so called Lagrange multipliers associated with the constraints.

The Karush-Kuhn-Tucker (KKT) necessary optimality conditions for the above problem are:

$$\frac{\partial L}{\partial p_i} = \frac{\partial L}{\partial q_i} = \frac{\partial L}{\partial \lambda_p} = \frac{\partial L}{\partial \lambda_q} = 0 \quad (12)$$

Hence, the equations to be solved are as follows:

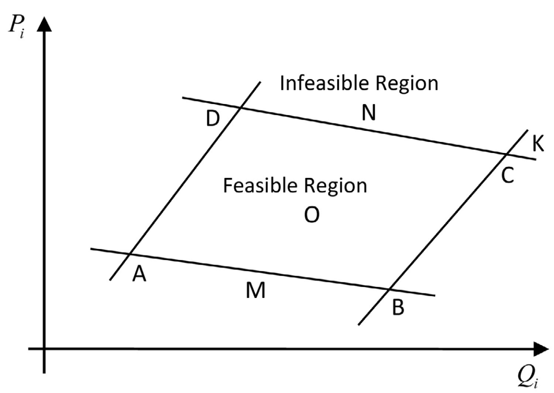

Figure 1. Feasible operating region of a cogeneration unit.

$$\begin{cases} \dfrac{\partial}{\partial p_i} c_{e,i}\left(p_i\right) - \lambda_p = 0 \quad \forall i \in e, & \dfrac{\partial}{\partial p_i} c_{c,i}\left(p_i, q_i\right) - \lambda_p = 0 \quad \forall i \in c \\ \dfrac{\partial}{\partial q_i} c_{c,i}\left(p_i, q_i\right) - \lambda_q = 0 \quad \forall i \in c, & \dfrac{\partial}{\partial q_i} c_{h,i}\left(q_i\right) - \lambda_q = 0 \quad \forall i \in h \\ \sum_{i \in e} p_i + \sum_{i \in c} p_i = p^{demand}, & \sum_{i \in c} q_i + \sum_{i \in h} q_i = q^{demand} \end{cases} \tag{13}$$

With $c_{e,i}\left(p_i\right) = \alpha_i + \beta_i p_i + \gamma_i p_i^2$, we have:

$$\frac{\partial}{\partial p_i} c_{e,i}\left(p_i\right) - \lambda_p = 0 \quad \Rightarrow \quad \beta_i + 2\gamma_i p_i - \lambda_p = 0 \quad \forall i \in e \tag{14}$$

With $c_{c,i}\left(p_i, q_i\right) = \alpha_i + \beta_i p_i + \gamma_i p_i^2 + \delta_i q_i + \varepsilon_i q_i^2 + \zeta_i p_i q_i$, we have:

$$\frac{\partial}{\partial p_i} c_{c,i}\left(p_i, q_i\right) - \lambda_p = 0 \quad \Rightarrow \quad 2\gamma_i p_i + \zeta_i q_i + \beta_i - \lambda_p = 0 \quad \forall i \in c \tag{15}$$

$$\frac{\partial}{\partial q_i} c_{c,i}\left(p_i, q_i\right) - \lambda_q = 0 \quad \Rightarrow \quad 2\varepsilon_i q_i + \zeta_i p_i + \delta_i - \lambda_q = 0 \quad \forall i \in c \tag{16}$$

With $c_{h,i}\left(q_i\right) = \alpha_i + \delta_i q_i + \varepsilon_i q_i^2$, we have:

$$\frac{\partial}{\partial q_i} c_{h,i}\left(q_i\right) - \lambda_q = 0 \quad \Rightarrow \quad 2\varepsilon_i q_i + \delta_i - \lambda_q = 0 \quad \forall i \in h \tag{17}$$

Hence, the resulting equations to be solved for p_i, q_i, λ_p and λ_q are:

$$\beta_i + 2\gamma_i p_i - \lambda_p = 0 \quad \forall i \in e \tag{18}$$

$$2\gamma_i p_i + \zeta_i q_i + \beta_i - \lambda_p = 0 \quad \forall i \in c \tag{19}$$

$$2\varepsilon_i q_i + \zeta_i p_i + \delta_i - \lambda_q = 0 \quad \forall i \in c \tag{20}$$

$$2\varepsilon_i q_i + \delta_i - \lambda_q = 0 \quad \forall i \in h \tag{21}$$

After some algebra, the above equations yield

$$[A]\begin{bmatrix} \lambda_p \\ \lambda_q \end{bmatrix} = \begin{bmatrix} p^{demand} \\ q^{demand} \end{bmatrix} + \sum_{i \in e} \begin{bmatrix} \beta_i / 2\gamma_i \\ 0 \end{bmatrix} + \sum_{i \in h} \begin{bmatrix} 0 \\ \delta_i / 2\varepsilon_i \end{bmatrix} + \sum_{i \in c} \begin{bmatrix} 2\gamma_i & \zeta_i \\ \zeta_i & 2\varepsilon_i \end{bmatrix}^{-1} \begin{bmatrix} \beta_i \\ \delta_i \end{bmatrix} \tag{22}$$

$$\Rightarrow \begin{bmatrix} \lambda_p \\ \lambda_q \end{bmatrix} = [A]^{-1} \left\{ \begin{bmatrix} p^{demand} \\ q^{demand} \end{bmatrix} + \sum_{i \in e} \begin{bmatrix} \beta_i / 2\gamma_i \\ 0 \end{bmatrix} + \sum_{i \in h} \begin{bmatrix} 0 \\ \delta_i / 2\varepsilon_i \end{bmatrix} + \sum_{i \in c} \begin{bmatrix} 2\gamma_i & \zeta_i \\ \zeta_i & 2\varepsilon_i \end{bmatrix}^{-1} \begin{bmatrix} \beta_i \\ \delta_i \end{bmatrix} \right\} \tag{23}$$

where

$$[A] = \sum_{i \in e} \begin{bmatrix} 1/2\gamma_i & 0 \\ 0 & 0 \end{bmatrix} + \sum_{i \in h} \begin{bmatrix} 0 & 0 \\ 0 & 1/2\varepsilon_i \end{bmatrix} + \sum_{i \in c} \begin{bmatrix} 2\gamma_i & \zeta_i \\ \zeta_i & 2\varepsilon_i \end{bmatrix}^{-1} \tag{24}$$

The data set for the CHPED problem is given in Tables 1-3.

Table 1. Power units-cost coefficients.

Units	PGmax	PGmin	$a = \alpha$	$b = \beta$	$c = \gamma$
1	250	10	1000	13.5	0.0345
2	200	20	1245	13.1	0.033

Table 2. (Unit 3) cogeneration unit-cost coefficients.

Unit	$a=\alpha$	$b=\beta$	$c=\gamma$	$d=\delta$	$e=\varepsilon$	$f=\zeta$
1	2650	14.5	0.0345	4.2	0.03	0.011

Table 3. (Unit 4) heat unit cost coefficients.

Unit	$a=\alpha$	$b=\delta$	$c=\varepsilon$	q^{max}	q^{min}
1	1200	4.2	0.02	250	20

4. Numerical Result from Direct Solution (Lagrange Multiplier) Technique

The above mathematical algorithm illustrates the solution of combined heat and power economic dispatch problem by Lagrange multiplier method or direct solution algorithm. The test system consists of two conventional power units, one cogeneration unit and a heat-only unit. The heat-power feasible operation region of the cogeneration unit 3 is illustrated in Figure 1. As demonstrated by the above algorithm, combined heat and power economic dispatch has been formulated with the objective of minimizing fuel cost. Hence, data set for the combined heat and power dispatch problem were given in Tables 1-3 along with feasible region coordinates of combined heat and power unit in Table 4 respectively. Table 5 shows result of output decision variables from the four-unit test system with power demand = 500 MW and heat demand = 300 MW respectively. Combined heat and power economic dispatch decision variables were obtained by applying formula derived during modelling of the problem statement. According to Table 5, this algorithm has objective function value (N18933.8) and all the output decision variables (P1, P2, P3, Q3 and Q4) were found to satisfy the given constraints of Equations (7), (8) and (10) respectively. Result shows that this technique can provide the combined heat and power dispatch solution in few steps when the load levels are such that all units can operate at the same incremental cost. However, one of the demerits of this technique is that it requires a few additional steps to identify all violating units if the load levels are such that some of the units are to be set at their limits, that is, when the unit has heat limit. It becomes vital to mention that the intention of the above algorithm is to prove that combined heat and power economic dispatch problem can be solved directly in spite of artificial bee colony, whale, genetic algorithms, etc. [15], being automated and fast in determining the output decision variables. It attained optimal result even in large system like the one in this research compared with automated methods. The Lagrangian multiplier algorithm framework is indeed a powerful paradigm and there is no reason why it should fail to provide solutions for this class of optimization problems [16] to a certain degree.

Table 4. Coordinate of the corners of the feasible region of the co-generation unit.

Corners	(p_1, q_1)	(p_2, q_2)	(p_3, q_3)	(p_4, q_4)
Unit 3	(20, 0.1)	(200, 0.5)	(195, 120)	(15, 110)

Table 5. Results by direct solution.

	Lagrange Multiplier Algorithm
P_1 (MWth)	155.9
P_2 (MWth)	169.1
P_3 (MWth)	195
Q_3 (MWth)	120
Q_4 (MWth)	180
Cost (₦)	18933.8

5. Conclusion

In proposing a new algorithm for the solution of the CHP dispatch problem, this research has explored a novel formula derived for calculating the optimum marginal costs (λ-s) corresponding with a specified heat and power demand. The optimum λ-s obtained using the formula gives the final dispatch if none of the units violates their limits. On the other hand, in case of violations, this step facilitates the identification of the violating units. The final dispatch is obtained by recalculating the λ-s, considering only the non-violating units when all the violating units are identified and set at their limits. The effectiveness of the proposed algorithm has been demonstrated by considering a 4-unit test system. The performance of the new algorithm has been critically assessed in comparison with the artificial bee colony algorithm in order to highlight its merits. The formulation of the CHP dispatch problem considered here conforms to the prevailing practice of using quadratic cost functions for the units. The possibility of extending the proposed solution scheme for cases where the cost functions are not quadratic is currently being explored.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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