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A comprehensive review of heuristic optimization algorithms for optimal combined heat and power dispatch from economic and environmental perspectives

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ABSTRACT

Combined heat and power economic dispatch (CHPED) aims to minimize the operational cost of heat and power units satisfying several equality and inequality operational and power network constraints. The CHPED should be handled considering valve-point loading impact of the conventional thermal plants, power transmission losses of the system, generation capacity limits of the production units, and heat-power dependency constraints of the cogeneration units. Several conventional optimization algorithms have been firstly presented for providing the optimal production scheduling of power and heat generation units. Recently, experience-based algorithms, which are called heuristic and meta-heuristic optimization procedures, are introduced for solving the CHPED optimization problem. In this paper, a comprehensive review on application of heuristic optimization algorithms for the solution of CHPED problem is provided. In addition, the most popular heuristic and meta-heuristic optimization algorithms are studied in this paper, and implementation of the optimization procedures for the solution of CHPED problem taking into account the objective functions and different constrains are discussed. The main contributions of the reviewed papers are studied and discussed in details. Additionally, main considerations of equality and inequality constraints handled by different research studies are reported in this paper. Five test systems are considered for evaluating the performance of different optimization techniques. Optimal solutions obtained by employment of multiple heuristic and meta-heuristic optimization methods for test instances are demonstrated and the introduced methods are compared in terms of convergence speed, attained optimal solutions, and constrains. The best optimal solutions for five test systems are provided in terms of operational cost by employment of different optimization methods.

1. Introduction

Combined heat and power (CHP) generation units are the most efficient concepts for simultaneous generation of thermal and electrical energy [1]. In fact, the whole thermal energy is not converted to electrical energy during power production by conventional thermal plants, and a significant amount of energy is wasted as heat during this process [2]. CHP units, which are also called cogeneration units, are capable to achieve an energy efficiency of 90% according to utilization of wasted heat in conversion process of fossil fuels to electrical energy [3]. Moreover, a typical 10–40% savings of the generation cost can be attained by utilizing CHP units comparing with conventional thermal units and heat-only boilers, which means that less fuel is required for generating an equal amount of useful energy [4]. Additionally, by introducing the CHP generation units, emissions of greenhouse gases are reduced almost 13–18% and such generation units are counted as environmental friendly systems [5]. Policy makers validate the advantages and high performance of the CHP units. G8 Summit Declaration offers expansion of CHP plants in providing electrical and heat demand by adopting instruments and measurements [6]. European Union can be introduced as an instance of the above mentioned policy, where a framework is proposed by CHP Directive (Directive 2004/8/EC, 2004) for increasing the share of CHP units in supplying the power and heat demand [7]. The examples of policies in the area of expansion of CHP units in the world are the target of the Integrated Energy and Climate Programme of the German Government [8] to supply 25% of the electrical energy demand by CHP units, and feed-in conditions outlines for CHP generation by the CHP Act (KWKG, 2009) [9].

Optimal generation scheduling of CHP systems is considered as interesting subjects taking into account several electrical and opera-

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tional constraints of the generation units [10,11]. CHP economic dispatch (CHPED) optimization problem is based on providing an optimal power and heat generation scheduling satisfying some equality and inequality constraints. In other words, the objective of CHEPD problem is minimizing cost of supplying heat and power demand, which considers constraints of demand and system. Coupling generation of power and heat by utilization of conventional thermal units, heat-only boilers, and CHP units with power and heat demand discovers the complexity of CHPED problem [12]. It should be noted that there is a dual dependency between heat and power generation of CHP units, which introduces another aspect of CHPED complexity [13]. Also, CHPED problem will be more complex considering the transmission losses between multiple areas of the power system.

The optimal solution of CHPED problem is studied in a wide range of research studies, which is solved by implementation of various conventional and mathematical methods including Lagrangian relaxation (LR) [14], Benders decomposition [15,16], mixed-integer nonlinear programming [17], and branch and bound algorithm [18]. Heuristic and meta-heuristic algorithms are experience-based optimization methods, which are widely implemented on different types of optimization problems [19]. Such optimization methods are capable to challenge complexities of CHPED problem including valve-point loading impact of conventional thermal plants, power transmission losses of the system and prohibited operation zones of power-only units. Several effective heuristic and meta-heuristic techniques are employed for obtaining the optimal generation scheduling of heat and power units.

A review on modeling, planning and energy management of combined cooling, heating and power systems (CCHP) is provided in [20], which studied the CCHP systems in terms of modeling aspects, methods implemented on planning of such systems, and energy management efforts in this area. In [21], analysis of CCHP systems from energy and energy point of views are prepared, which provided a comprehensive review of current trends in such systems and optimization methods employed to improve the performance of CCHP systems. A review on research and developments in the area of CHP production is performed in [22], which provided a review on exergoeconomics analysis and optimization of the cogeneration systems. A comprehensive review on definition and of benefits of CCHP systems, characteristics of such cogeneration system and various configurations of such systems is provided in [23]. The development aspects, advantages and analysis of CCHP systems are studied in [24]. In addition, the authors prepared a review on management, control, optimization process and sizing of such effective systems. An updated review study on solar energy based heat and power systems is proposed in [25], which concentrated on solar photovoltaic and solar thermal based generation units. Moreover, the authors studied the possibility of expansion of solar based power and heat generation units in Denmark. In [26], the authors reviewed current and future trends on the area of micro CHP systems as an effective solution for increasing system efficiencies and reducing pollutant gas emissions. In this reference, the residential applications of micro CHP systems, modeling such impactful systems and simulation of the micro CHP systems are studied.

The solution of optimal power and heat generation scheduling of CHP systems is obtained by implementation of various optimization techniques, which can be classified to mathematical programming methods and heuristic optimization procedures. Heuristic optimization producers, which are introduced as experience-based optimization methods, are quick techniques to obtain optimal solutions of optimization problems, for which mathematical methods are not capable to provide optimal solutions in finite time. The CHPED problem is a non-convex and non-linear optimization problem with a series of intense equality and inequality constraints. This paper aims to study the most effective heuristic optimization methods applied for solving the non-convex non-smooth CHPED optimization problem. To the best knowledge of the authors, the most papers implemented heuristic optimization methods to obtain optimal solution of CHPED problem are reviewed in this review paper. A brief definition on the employed heuristic methods is provided in order to familiarize the readers to the applied heuristic techniques and the most contributions of each research papers are introduced. Additionally, the obtained optimal solutions in the reviewed papers are tabulated for preparing a useful survey on the application of heuristic methods for the solution of CHPED problem. Comparisons between reviewed papers in terms of objective function, constraints, minimum operational cost and computational time are provided. This paper can considerably help the researchers in the area of optimal generation planning of CHP systems.

The remainder of the paper is organized as follows: Section 2 provides the formulation of CHPED problem. A comprehensive review on employment of heuristic and meta-heuristic optimization methods for generation scheduling of CHP units are presented in Section 3. Section 4 is compared the utilized optimization algorithms in different studies considering different point of views. Future research trends in the area of CHPED are studied in Section 5. Finally, the conclusion of this paper is provided in Section 6.

2. Problem formulation

CHPED aims to minimize total fuel cost of CHP units to meet heat and power demands. The objective function of the CHPED problem taking into account power-only units, CHP units and heat-only units can be written as:

$$\min \sum_{i=1}^{N_p} C_i(P_i^p) + \sum_{j=1}^{N_c} C_j(P_j^c, H_j^c) + \sum_{k=1}^{N_h} C_k(H_k^h) \ \ (\$/\mathrm{h}) \tag{1}$$

In which, C_i, C_j, and C_k are the respective indicators for total production cost of power-only units, CHP units, and heat-only units. N_p, N_c, and N_h are utilized to define the number of power-only units, CHP units, and heat-only units, respectively. The respective generated power and heat by the generation units are demonstrated by P and H. Subscripts i, j, and k are utilized in the formulation for determining the power-only units, CHP units, and heat-only units, respectively. The cost function of power-only generation plant is modeled as a quadratic function, which can be stated as:

$$C_i(P_i^p) = a_i(P_i^p)^2 + b_i\, P_i^p + c_i \ \ (\$/h) \tag{2}$$

where $C_i(P_i^p)$ is the fuel cost of i th power-only generation unit. a_i, b_i, and c_i are the cost coefficients of power-only unit i.

Valve point impact consideration

Considering several steam admitting valves in conventional thermal units, the effect of valve-point is required to be modeled in the objective function of cost function of power-only generation plants. For modeling valve-point impact, a sinusoidal term is added to the quadratic cost function of conventional thermal units. Consideration of valve-point effect results to a non-convex optimization problem. The cost function of power-only units with the consideration of valve-point impact can be formulated as:

$$C_i(P_i^p) = a_i(P_i^p)^2 + b_i\, P_i^p + c_i + |d_i \ \sin(e_i(P_i^{p\min} - P_i^p))| \ \ (\$/h) \tag{3}$$

In which, d_i and e_i are cost coefficients of valve-point impacts. Moreover, the cost function of CHP unit is formulated as follows:

$$C_j(P_j^c, H_j^c) = a_j(P_j^c)^2 + b_j\, P_j^c + c_j + d_j(H_j^c)^2 + e_j\, H_j^c + f_j\, H_j^c\, P_j^c \ \ (\$/\mathrm{h}) \tag{4}$$

In which, $C_j(P_j^c, H_j^c)$ is the cost function of j th CHP unit, and a_j, b_j, c_j, d_j, e_j and f_j are the cost coefficients of this unit. Additionally, the cost function of heat-only units is modeled as a quadratic function, which is formulated as follows:

$$C_k(H_k^h) = a_k\,(H_k^h)^2 + b_k\, H_k^h + c_k \ \ (\$/\mathrm{h}) \tag{5}$$

where, $C_k(H_k^h)$ is the cost of kth heat-only unit, and H_k^h is the generated heat by this unit. a_k, b_k, and c_k are the cost coefficients of heat-only unit