Electric Power Systems Research 129 (2015) 32–43

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Multi-objective economic emission dispatch considering combined heat and power by normal boundary intersection method

Abdollah Ahmadi [a], Hadi Moghimi [b], Ali Esmaeel Nezhad [c], Vassilios G. Agelidis [a], Adel M. Sharaf [d,*]

[a] The Australian Energy Research Institute and the School of Electrical Engineering and Telecommunications, The University of New South Wales (UNSW Australia), Sydney 2052, NSW, Australia
[b] Department of Electrical and Electronic Engineering, Iran University of Science and Technology, Tehran, Iran
[c] Department of Electrical Engineering, Marvdasht Branch, Islamic Azad University, Marvdasht, Iran
[d] Sharaf Energy Systems, Inc., Fredericton, NB, Canada

ARTICLE INFO

Article history:
Received 15 January 2015
Received in revised form 16 June 2015
Accepted 19 July 2015

Keywords:
Combined heat-and-power
Greenhouse gas emission
Multi-objective optimization
Normal-boundary intersection
TOPSIS decision making approach

ABSTRACT

Pollutant gas emission concern is one of the most challenging issues in electric power systems putting excessive pressure on different participants of electricity markets. Integrating renewable energy sources and application of Combined Heat-and-Power to thermal power plants which are applied by system operators have many advantages, such as reducing green-house gas emission. This paper addresses a multi-objective electric model to integrate the generation of thermal units considering heat and power dispatch. The objective functions of the proposed multi-objective framework comprise simultaneous minimization of cost and thermal units' emission as well as maximizing heat generation. Normal-Boundary Intersection method is implemented to solve the proposed model and TOPSIS decision making approach has been employed to find the optimal Pareto solution as the best tradeoff between cost, green-house gas emission and heat generation. The results obtained in this paper are compared with the ones derived from other techniques recently used and verify the effectiveness and efficiency of the proposed multi-objective method. Besides, it is found that the solutions obtained by incorporating the lexicographic optimization and Normal Boundary Intersection method are exceptional in the case of fuel cost, emission and execution time.

1. Introduction

The increasing trend of fossil fuel price all around the world and environmental concern caused by pollutant gas emission in power industry have led to extreme pressure on power system operators to seek the application of distributed generations to the demand side of power system, integration of Distributed Energy Resources (DERs), e.g. wind power, solar energy, etc. as well as the optimal utilization of Combined Heat and Power (CHP) systems. CHP production which typically puts into action for thermal power plants means simultaneous production of useful heat and electric power. When steam or hot water is produced in an industrial plant or a residential area, electric power can also be produced as a by-product. Moreover, surplus heat from an electric power plant can be used for industrial/residential purposes or to heat space and water [1].

In some countries, CHP system has been integrated into power networks to generate both electricity and useful heat and also to offer a tremendous increase in revenue in order to decline fossil fuel emissions, while saving operation costs for power generation by capturing some or all of the by-product heat [2]. As mentioned in ref. [3], CHP integration uses heat and can potentially achieve an energy conversion efficiency of up to 80%, while the energy efficiency of a gas turbine is typically between 36% and 40% when used for electric power production only [1]. Energy efficiency of CHP utilization leads to significant savings in fuel and emissions compared to conventional condensing power plants that their efficiency is typically between 10% and 40% depending upon the technique used and the system replaced [4]. In the literature, most reported studies concentrated on the application of the environmentally beneficial and high energy-efficiency CHP systems [5–7].

The ever increasing interests toward CHP dispatch problem have become more worth developing research area to obtain accurate CHP dispatch results for practical CHP projects [8]. Incorporating co-generation units (CHP units) into the existing utility economic dispatch problem adds further complexity to the

* Corresponding author. Tel.: +1 506 999 2780.
E-mail address: profdramsharaf@yahoo.ca (A.M. Sharaf).

http://dx.doi.org/10.1016/j.epsr.2015.07.011
0378-7796/

Nomenclatures

Indices
h, i, j heat-only, thermal and CHP unit indices, respectively.
ii, jj electric power generating unit.
j' linear inequality constraint index of CHP feasible operation region.

Constants
a_i, b_i, c_i, d_i, e_i cost coefficients of thermal unit i.
$B_{ii,jj,t}$ loss coefficient relating to the productions of electric power generating units ii and jj (1 MW^{-1}).
$B_{0,ii,t}$ loss coefficient associated with the production of electric power generating unit ii.
$B_{00,t}$ loss coefficient parameter (MW).
DR_i^{TU}, DR_j^{CHP} ramp-down rate of thermal unit i and CHP unit j, respectively (MW/h).
$P_{D,t}$ electric load demands (MWt).
$H_{h,\max}^{H}, H_{j,\max}^{CHP}$ heat capacity of heat-only unit h and CHP unit j, respectively (MWt).
$H_{h,\min}^{H}, H_{j,\min}^{CHP}$ minimum heat output of heat-only unit h and CHP unit j, respectively (MWt).
N_{CHP}, N_{TU}, N_H number of CHP, thermal and heat-only units, respectively.
N_{lin} number of linear inequality constraints of CHP feasible operation region.
NG Number of electric power generating units.
NT number of time intervals.
$P_{j,\max}^{CHP}, P_{i,\max}^{TU}$ power capacity of CHP unit j and thermal unit i, respectively (MW).
$P_{j,\min}^{CHP}, P_{i,\min}^{TU}$ minimum power output of CHP unit j and thermal unit i, respectively (MW).
$P_{ii,\max}$, UR_{ii} power capacity and ramp-up rate of electric power generating unit ii, respectively (MW).
UR_j^{CHP}, UR_i^{TU} ramp-up rate of CHP unit j and thermal unit i, respectively (MW/h).
$x_{j',j,t}, y_{j',j,t}, z_{j',j,t}$ coefficients of power-heat feasible operation region of linear inequality equation j' for CHP unit j.
$a_j, b_j, c_j, d_j, e_j, f_j$ cost coefficients of CHP unit j.
a_h, b_h, c_h cost coefficients of heat-only unit h.
$\alpha_i, \beta_i, \gamma_i, \xi_i, \lambda_i$ emission coefficients of thermal unit i.
α_j, β_j emission coefficients of CHP unit j.
α_h, β_h emission coefficients of heat-only unit h.

Variables
F_1, F_2, F_3 total operation costs ($), emissions (lbs) and heat (MWt), respectively.
$\underline{H}_{j,t}^{CHP}, \bar{H}_{j,t}^{CHP}$ lower and upper limits of the jth CHP unit output heat, respectively (MWt).
$P_{\text{Loss},t}$ real power losses (MW).
PH_G generating unit vector.
$P_{ii,t}$ power generation output of electric power generating unit ii (MW).
$P_{i,t}^{TU}, P_{j,t}^{CHP}$ power generation output of thermal unit i and CHP unit j, respectively (MW).
$\bar{P}_{i,t}^{TU}, \bar{P}_{j,t}^{CHP}$ upper limit of the output power of the ith thermal unit and the jth CHP unit, respectively (MW).
$\underline{P}_{i,t}^{TU}, \underline{P}_{j,t}^{CHP}$ lower limit of the output power of the ith thermal unit and jth CHP unit, respectively (MW).

solution methodology. Several classical optimization techniques, such as Lagrangian relaxation, dual and quadratic programming can be used to solve the CHP dispatch problem [9,10].

Nevertheless, these traditional optimization techniques cannot be directly applied to a CHP dispatch problem when the fuel cost functions of units are much more complicated due to the physical operation limitations influencing the shape of fuel cost functions and the non-linearity of other technical constraints. In order to obtain precise dispatch results, several optimization algorithms based on stochastic searching techniques including Artificial Neural Network (ANN) [11], Genetic Algorithm (GA) [12,13], Ant Colony Search Algorithm (ACSA) [14], Evolutionary Programming (EP) [15], Harmony Search Algorithm (HSA) [16,17] and Particle Swarm Optimization (PSO) [18] can be developed to solve the highly nonlinear CHP dispatch problem without restrictions on the shape of fuel cost functions. Multi-objective Mathematical Programming (MMP) models in the deterministic framework [19–22] proposed for electricity market are cleared in previous works. The objective functions of the MMP model in refs. [19–22] include generation offer cost, and emission in addition to several technical considerations.

In this paper, a multi-objective electricity market operation framework is addressed for integration of thermal power plants taking into consideration the CHP options. The problem is formulated as a deterministic Non-Linear programming (NLP) and Normal Boundary Intersection (NBI) method is employed to find the optimal Pareto front of the solutions (best tradeoff between minimum cost, minimum emission and maximum heat).

The main contributions of this work with respect to the earlier ones can be briefly summarized as follows:

(a) The model gives optimal power generation of thermal units, CHP units as well as heat-only units.
(b) Generating the evenly distributed Pareto optimal solutions by NBI method.
(c) Reduced fuel cost, emission and solution time compared to recently published papers using the proposed method.

The remainder of the paper is organized as follows: Section 2 includes the brief description and formulation of multi-objective electricity market framework consisting of the objective functions of market framework considering CHP options while the problem's constraints are mathematically presented. Section 3 addresses the proposed solution methodology of multi-objective operation model. Case study and simulation results are discussed in Section 4. Some concluding remarks on the proposed solution methodology are drawn in Section 5.

2. Multi-objective problem description and formulation

In the following subsections, the multi-objective problem is introduced in the form of NLP formulation. The main objectives of the problem are cost of production, emission concerns of generation units and heat generation considering three different options of generation units; power-only units, combined heat and power units and heat-only units.

2.1. Objective functions

The objective functions of multi-objective operation problem in the present survey are formulated as:

$$F_1 = \text{Cost}(\text{PH}_G) = \sum_{t=1}^{NT} (G_1(P_t^{TU}) + G_2(P_t^{CHP}, H_t^{CHP}) + G_3(H_t^H)) \qquad (1)$$