Energy xxx (2014) 1–18

Contents lists available at ScienceDirect

Energy

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

Coordination of combined heat and power-thermal-wind-photovoltaic units in economic load dispatch using chance-constrained and jointly distributed random variables methods

Rasoul Azizipanah-Abarghooee [a,*], Taher Niknam [a], Mohammad Amin Bina [b], Mohsen Zare [a]

[a] Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz, Iran
[b] Iran-Fars-Shiraz-Fars Electric Power Distributed Company, Iran

ARTICLE INFO

Article history:
Received 4 May 2013
Received in revised form
3 October 2014
Accepted 6 October 2014
Available online xxx

Keywords:
Combined heat and power economic dispatch
Chance constrained programming
Cuckoo search algorithm
Jointly distributed random variables method
Stochastic multi-objective optimization
Photovoltaic and wind power

ABSTRACT

CHP (Combined heat and power) generation or cogeneration has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation. Furthermore, the wind power generators and photovoltaic units have vastly speared over the power systems due to their free inputs. However, there are many challenges for power system operators because of uncertain characteristics of renewable units and load demands. Therefore, a new multi-objective stochastic framework based on chance constrained programming is developed to handle combined heat and power economic load dispatch considering the stochastic characteristics of wind and photovoltaic power outputs, customer's electrical and heat load demands. The proposed technique makes use of a jointly distributed random variables method to calculate chance of meeting the electrical and heat load requirement using the target decision variables while maintaining the electrical energy cost below a scheduled value. The framework benefits from a new method named hybrid modified cuckoo search algorithm and differential evolution to extract the Pareto optimal surface for minimum cost and maximum probability of meeting the target cost and applies them as the objective functions. Applying to 6 and 40 unit test systems, the ability of the suggested framework is confirmed.

1. Introduction

Nowadays, in some countries, the CHP (combined heat and power) systems are utilized in the power networks to generate both electricity and useful heat for the aim of decreasing the generation cost [1,2]. Because in TUs (thermal units), all of the thermal energy is not converted into electricity, a large amount of energy is squandered in the form of heat [3]. Using the heat, the CHP can potentially achieve an energy conversion efficiency of up to 80%. Furthermore, an increasing number of countries have tended towards using the RESs (renewable energy sources) such as WPGs (wind power generators) [4,5] and PVUs (photovoltaic units) [6] which are sustainable and have zero carbon emission. Increasing growth rate of these units has greatly challenged the way that the SO (system operator) should apply to serve both elastic heat and load demand under uncertainty of WPGs and PVUs [7]. The integration of WPGs and PVUs into the power systems leads to additional integration costs which are resulted from reserved capacity requirement and revenue loss due to wind and solar spillage. These costs need to be added to direct cost of wind and solar power. Hence, the integration of CHPs, WPGs and PVUs calls for advanced ED (economic dispatch) methods.

Electrical energy has been popular and challenging in electrical market, so the deregulated and vertically integrated electricity markets call for the robust ED tool that can decrease the electrical energy cost and overcome the power system constraints. The ED plays an important role for power system operators in both planning and operating stages. The main purpose of the ED problem is to determine optimal operating state of a power system for economic operation while at the same time, satisfying equality and inequality constraints. So far, several researchers have investigated different aspects of ED in two distinct scenarios i) considering CHPs

* Corresponding author. Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz 71555-313, Iran. Tel.: +98 913 2546011; fax: +98 711 7353502.
E-mail address: razizipanah@gmail.com (R. Azizipanah-Abarghooee).

http://dx.doi.org/10.1016/j.energy.2014.10.024
0360-5442/

Nomenclature

Indices

- *chp* CHP index
- *eq* equality constraints index
- *h* heat-only unit index
- *i, j* electrical generating unit indices
- *ieq* inequality constraints index
- *iter* iteration index of the proposed MCSA-DE
- *l* linear inequality constraint index of the CHP's FOR
- *m* cuckoo index
- *n* repository member index
- *obj* objective function index
- *pvu* PVU index
- *r* input random variable index
- *tu* TU index
- *wpg* WPG index

Constants

- a_{tu}, b_{tu}, c_{tu}, d_{tu}, e_{tu} electrical energy cost coefficients of the *tu*th TU
- a_{chp}, b_{chp}, c_{chp}, d_{chp}, e_{chp}, f_{chp} electrical energy cost coefficients of the *chp*th CHP
- a_h, b_h, c_h electrical energy cost coefficients of the *h*th heat-only unit
- B_{ij} loss coefficient relating the productions of generating units *i* and *j* (MW^{-1})
- B_{0i} loss coefficient associated with the production of generating unit *i*
- B_{00} loss coefficient parameter (MW)
- C_{wpg}, $C_{OE,wpg}$, $C_{UE,wpg}$ direst, OE and UE electrical energy cost coefficients of the *wpg*th WPG, respectively
- C_{pvu}, $C_{OE,pvu}$, $C_{UE,pvu}$ direst, OE and UE electrical energy cost coefficients of the *pvu*th PVU, respectively
- *CR* crossover rate for DE algorithm
- $F_{obj}^{\max}$, $F_{obj}^{\min}$ maximum and minimum acceptable level of objective function *obj*, respectively
- $F_m^{(iter)}$ mutation scaling factor for cuckoo *m* in iteration *iter*
- $G_{std,pvu}$ reference solar irradiance for the *pvu*th PVU (W/m^2)
- $\widehat{G}_{pvu}$, $\widehat{v}_{wpg}$ forecasted solar irradiance and wind speed for the *pvu*th PVU and *wpg*th WPG, respectively
- $H_{h,\max}^{H}$, $H_{chp,\max}^{CHP}$ heat capacity of heat-only unit *h* and CHP unit *chp*, respectively (MWth)
- $H_{h,\min}^{H}$, $H_{chp,\min}^{CHP}$ minimum heat output of heat-only unit *h* and CHP unit *chp*, respectively (MWth)
- $iter_{\max}$ maximum number of iteration for the proposed MCSA-DE
- *Nchp*, *Nh*, *Npvu*, *Ntu*, *Nwpg*, number of CHP, heat-only, PVU, TU and WPG, respectively
- N_{eq}, N_{ieq} number of equality and inequality constraints, respectively
- *NG* number of generating units
- *Nirv* number of input random variables
- *Nl* number of linear inequality constraints of CHP's FOR
- *Nobj* number of objective function
- *NPOP* number of particles in the population of MCSA-DE
- *Nrep* number of non-dominated solutions
- *NVAR* number of variables in decision vector
- $P_{tu,\min}^{TU}$, $P_{chp,\min}^{CHP}$ minimum power output of the *tu*th TU and *chp*th CHP, respectively (MW)
- $P_{tu,\max}^{TU}$, $P_{chp,\max}^{CHP}$ power capacity of the *tu*th TU and *chp*th CHP, respectively (MW)
- $\widehat{P}_{wpg}^{WPG}$, $\widehat{P}_{pvu}^{PVU}$ actual available power for the *wpg*th WPG and *pvu*th PVU, respectively (MW)
- $P_{wpg,rate}^{WPG}$, $P_{pvu,rate}^{PVU}$ rated power of the *wpg*th WPG and *pvu*th PVU, respectively (MW)
- $\widehat{P}_{D\_electrical}$, $\widehat{P}_{D\_thermal}$ forecasted electrical and heat load demand, respectively
- *rand*(.) random function generator in the range [0,1]
- $rand_m^{(iter)}$ random function generator in the range [0,1] for cuckoo *m* in iteration *iter*
- $r_{up,max,chp}$, $r_{dn,max,chp}$ maximum sustained up and down spinning reserve of the *chp*th CHP within the specific time period 10 min, respectively (MW)
- $r_{up,max,tu}$, $r_{dn,max,tu}$ maximum sustained up and down spinning reserve of the *tu*th TU within the specific time period 10 min, respectively (MW)
- $s_{1,wpg}$, $s_{2,wpg}$, $s_{3,wpg}$ slope of the first, second and third segment of the *wpg*th WPG, respectively
- $T_{r,pvu}$ temperature for standard testing conditions reference for the *pvu*th PVU
- $T_{c,pvu}$ temperature for the surface of the *pvu*th PVU
- $v_{ci,wpg}$ cut-in wind speed of the *wpg*th WPG
- $v_{co,wpg}$ cut-out wind speed of the *wpg*th WPG
- $v_{1,wpg}$, $v_{2,wpg}$ breakpoint of the first and second segments of the *wpg*th WPG, respectively
- $v_{r,wpg}$ rated wind speed of the *wpg*th WPG
- $x_{l,chp}$, $y_{l,chp}$, $z_{l,chp}$ coefficients of power-heat FOR of linear inequality equation *l* for the *chp*th CHP
- W_{obj} weight factor for the *obj*th objective function
- α prescribed probability level for meeting inequality constraints
- α_{up}, α_{dn} prescribed probability levels for having sufficient up and down spinning reserve, Respectively
- δ parameter of Gumbel-Copula function
- γ maximum power correction for temperature of PVU
- μ_{obj}^{ref} reference membership value for the *obj*th objective function
- ξ input random variables vector

Variables

- $C_1(\mathbf{P}^{TU})$, $C_2(\mathbf{P}^{CHP},\mathbf{H}^{CHP})$, $C_3(\mathbf{H}^{H})$, $C_4(\mathbf{P}^{WPG})$, $C_5(\mathbf{P}^{PVU})$ TU, CHP, heat-only, WPG and PVU generation cost ($), respectively
- $c_{OE,wpg}$, $c_{UE,wpg}$ OE and UE electrical energy cost function of the *wpg*th WPG, respectively
- $c_{OE,pvu}$, $c_{UE,pvu}$ OE and UE electrical energy cost function of the *pvu*th PVU, respectively
- $\mathbf{Best}^{(iter)}$, $\mathbf{Worst}^{(iter)}$ best and worst solutions in iteration *iter*, respectively
- F_1 electrical energy cost objective function as the output random variable ($)
- $\overline{F}_1$ scheduled electrical energy cost function ($)
- $f_{F_1}(F_1)$ output random variable's PDF of the electrical energy cost
- $f(\xi_1,\xi_2,...,\xi_{Nirv})$ JDF between the *Nirv* input random variables
- $f_{\xi_r}(\xi_r)$ PDF of the *r*th input random variable
- $F(\xi_1,\xi_2,...,\xi_{Nirv})$ joint distribution function between the *Nirv* input random variables

Please cite this article in press as: Azizipanah-Abarghooee R, et al., Coordination of combined heat and power-thermal-wind-photovoltaic units in economic load dispatch using chance-constrained and jointly distributed random variables methods, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.10.024