Energy Conversion and Management 148 (2017) 974–992

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Optimal integrated sizing and planning of hubs with midsize/large CHP units considering reliability of supply

Saeed Moradi [a,*], Reza Ghaffarpour [b], Ali Mohammad Ranjbar [c], Babak Mozaffari [b]

[a] Faculty of Electrical & Computer Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[c] Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 25 November 2016
Received in revised form 29 May 2017
Accepted 3 June 2017

Keywords:
Midsize/large CHP
Energy hub
Integrated sizing and planning
Feasible operating region
Linearization of two-variable CHP fuel function
Reliability of supply

ABSTRACT

Use of multi-carrier energy systems and the energy hub concept has recently been a widespread trend worldwide. However, most of the related researches specialize in CHP systems with constant electricity/heat ratios and linear operating characteristics. In this paper, integrated energy hub planning and sizing is developed for the energy systems with mid-scale and large-scale CHP units, by taking their wide operating range into consideration. The proposed formulation is aimed at taking the best use of the beneficial degrees of freedom associated with these units for decreasing total costs and increasing reliability. High-accuracy piecewise linearization techniques with approximation errors of about 1% are introduced for the nonlinear two-dimensional CHP input-output function, making it possible to successfully integrate the CHP sizing. Efficient operation of CHP and the hub at contingencies is extracted via a new formulation, which is developed to be incorporated to the planning and sizing problem. Optimal operation, planning, sizing and contingency operation of hub components are integrated and formulated as a single comprehensive MILP problem. Results on a case study with midsize CHPs reveal a 33% reduction in total costs, and it is demonstrated that the proposed formulation ceases the need for additional components/capacities for increasing reliability of supply.

1. Introduction

Nowadays, the traditional centralized power generation is giving its place to decentralized power generation using different energy resources. One of the main reasons to this evolution is the development of new generation power plants, which are commercialized at a wide capacity range of a few KWs to hundreds of MWs, all providing considerably high efficiencies [1]. The other substantial change in energy systems involves the utilization of the abundant heat, which is produced during electricity generation, and was usually disposed before. Extended use of the so-called combined heat and power (CHP) systems, and incorporated operation of multiple energy carriers has drawn focus on the newly introduced "energy hub" concept for supplying required powers.

1.1. Literature review

In the past decade, plenty of research has been done on multi-carrier energy systems, and on planning and operation of the integrated infrastructures which involve different energy carrier technologies. "Energy hub" as the main conceptual model in this regard was introduced generally in [2]. In this reference, besides the comprehensive modeling of an individual hub, multi-carrier optimal power flow has also been studied theoretically, which was further developed later in different researches, such as [3–5]. In [6], some modifications have been made to the energy hub model for addressing operational constraints of some hub components. In [7], a general model is proposed for energy hub economic dispatch.

CHP units, as the inseparable part of multi-carrier systems, have attracted a great deal of attention, recently. Refs. [8–10] have presented detailed investigations on CHP technology and modeling. The optimization of an individual CCHP system is studied in [11], where energy conversion and flow from the system input to the output is modeled by a conversion matrix. Coupled operation of CHP units with electrical and thermal storage systems has been investigated in [12–14]. Cogeneration planning under uncertainty is addressed in [15] in which the most appropriate solutions are

* Corresponding author.
E-mail addresses: saeed.moradie@gmail.com (S. Moradi), rghaffarpour@srbiau.ac.ir (R. Ghaffarpour), amranjbar@sharif.edu (A.M. Ranjbar), mozafari.babak@yahoo.com (B. Mozaffari).

http://dx.doi.org/10.1016/j.enconman.2017.06.008
0196-8904/

Nomenclature

Indices

j/k	index for vertical/horizontal divisions of approximation domain in Cartesian approach
l	index for domain divisions in gradient-oriented approximation approach
t	index for time blocks
α	index for input energy type, including e (electricity) and g (natural gas)
β	index for output energy type, including e (electrical) and h (heat)
γ	index for candidate hub components
δ	index for contingency type

Sets

CHP	combined heat and power units
EES	electrical energy storage system
Fur	gas furnaces
TES	thermal energy storage system
Tra	transformers

Parameters

$a_\gamma, b_\gamma, c_\gamma, d_\gamma, e_\gamma, f_\gamma$	CHP fuel function coefficients
$A_{0_\gamma}, B_{0_\gamma}$	minimum fuel consumption in the approximation domain
CCP_γ	capital cost per power for γ
CCV_γ	capital cost per storage volume for γ
Eb^j_γ/Hb^k_γ	electrical/heat upper bound value of jth vertical/kth horizontal segment
F_γ	forced outage rate of γ
FC_γ	fixed capital cost of γ
Gb^l_γ	upper bound value of lth division in gradient-oriented approach
IR	interest rate
$J/K/L$	number of divisions of the approximation domain in linearization techniques
m^j_γ/n^k_γ	fuel-per-power ratio for electrical/heat power in jth vertical/kth horizontal segment
MRU_γ	maximum ramp up of γ (including transformers and furnaces)
$MRU^\beta_\gamma/MRD^\beta_\gamma$	maximum ramp up/down of CHP units concerning output power of type β
L^e_t/L^h_t	electrical/heat load demand at t
o^l_γ	fuel-per-power ratio for lth division in gradient-oriented approach
$VOLL^\beta$	value of lost load of type β
Y	planning horizon in years
η_γ	efficiency of energy converter γ (for transformers and gas furnaces)
$\eta^{ch}_\gamma/\eta^{dis}_\gamma$	charge/discharge efficiency of energy storage system γ
μ_γ	hourly retention coefficient of γ for stored energy
λ^α_t	hourly price of energy carrier α at t
θ	polar angle of the approximation direction in gradient-oriented approximation
Ψ	set of test points evenly distributed in FOR

Variables

$\overline{()}/\underline{()}$	upper and lower bound values for variables
$e^j_{\gamma,t}/h^k_{\gamma,t}$	segment electrical/heat generation of γ in jth vertical/kth horizontal division at t
$E_{\gamma,t}/H_{\gamma,t}$	electrical/heat power generation of CHP at t (equivalent to $P^{out,e}_{\gamma,t}/P^{out,h}_{\gamma,t}$ for $\gamma \in \gamma_{CHP}$)
$g^l_{\gamma,t}$	segment power generation of γ in lth division at t
$LL^\beta_{\gamma,t}$	lost load of type β at t due to unavailability of γ
$P^{in}_{\gamma,t}/P^{out}_{\gamma,t}$	input/output power of γ at t (including transformers and furnaces)
$P^{in,\min}_\gamma$	minimum input power of γ (including transformers and furnaces)
$P^{out,\min}_\gamma/P^{out,\max}_\gamma$	minimum/maximum output power of γ (including transformers and furnaces)
$R^\beta_{\gamma,t}$	power reserve of γ concerning type β at t (for transformers and gas furnaces)
$R^{\beta,\delta}_{\gamma,t}$	CHP power reserve of type β at t, in case of contingency of type δ
$Reserve^{\beta,\delta}_t$	hub reserve of type β at t, in case of contingency of type δ
$S^{ch}_{\gamma,t}/S^{dis}_{\gamma,t}$	charge/discharge power of energy storage unit γ at t
$S^{ch,\max}_\gamma/S^{dis,\max}_\gamma$	maximum charge/discharge power of energy storage unit γ
TIP^α_t	total hub input power of type α at t
$type(\gamma)$	type of the unavailable component γ
u_γ	investment state of component γ
$\upsilon^{ch}_{\gamma,t}/\upsilon^{dis}_{\gamma,t}$	binary variables used to determine the charge/discharge states of the energy storage unit γ at t (when charging: $\upsilon^{ch}_{\gamma,t}=1, \upsilon^{dis}_{\gamma,t}=0$, and when discharging: $\upsilon^{ch}_{\gamma,t}=0, \upsilon^{dis}_{\gamma,t}=1$)
$V_{\gamma,t}$	energy stored in storage unit γ at t
$V^{\max}_\gamma$	Storage capacity of energy storage unit γ
$V^{\min}_\gamma$	minimum allowable energy stored in γ
$x^j/y^k/r^l$	binary variables used for correct allocation of CHP output values to different approximation segments
$z^\beta_{\gamma,t}$	hub's load loss status concerning loss of β load at t due to unavailability of γ

identified among a pre-defined set of planning alternatives based on decision theory-based criteria. Ref. [16] has presented an economic evaluation of financial incentives for CHP systems for various U.S. states, signifying the role of different factors such as CHP capacities in their economic viability.

General reliability models of a typical multi-carrier energy system are introduced in [17,18]. In these papers, the Markov model is used for analyzing and evaluating the expected reliability of supply. Other comprehensive models are proposed in [19,20] for CHP reliability and availability based on interactions between subsystem of CHP systems. Ref. [21] has presented a method to make the right choice about a tri-generation and district heating energy system, based on integrated evaluation of energy savings and reliability for a residential sector near Rome. Reliability constraints are integrated to the planning of hub infrastructures in [22] in which a planning model is proposed based on CHP units with constant efficiencies. Besides the reliability modeling, the dynamic behavior of thermal loads is also considered in [23].

Modeling and optimization of a network of energy hubs has been studied in many researches such as [24,25]. Optimal expansion planning of a set of energy hubs is studied in [26] in which generating units, transmission lines, gas furnaces, and CHP units are used as candidate devices for renewing a traditional power system. Ref. [27] introduces another modeling in this regard in which