Electrical Power and Energy Systems 102 (2018) 97–109

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Dynamic long-term expansion planning of generation resources and electric transmission network in multi-carrier energy systems

Hamed Fathtabar[a], Taghi Barforoushi[b,*], Majid Shahabi[a]

[a] Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran
[b] HV Substation Research Group, Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran

ARTICLE INFO

Keywords:
Combined heat and power (CHP)
Energy transmission network
Mixed integer linear programming (MILP)
Multi-carrier energy system (MCES)

ABSTRACT

In this paper, a new framework is proposed for long-term generation and transmission expansion planning in multi-carrier energy systems (MCES). The MCES considered here consists of combined heat and power (CHP), gas furnace, power generation unit and transmission lines associated to natural gas and electrical networks. In the proposed framework, by minimizing the total investment and operation costs, optimal capacity, location and time of installing of new heat and electrical generation resources and also electric transmission lines are determined in a multi-year horizon. A linearized AC load flow equations is used for modeling effects of electric transmission network and is compared with DC load flow model. Also, a linearized model of accurate gas flow equations in natural gas transmission pipelines is used and is compared with a simple model. By using linear models for energy transmission network, the expansion problem is converted to a mixed integer linear programming (MILP) problem. By solving the MILP model by GAMS in which mathematical algorithm is used, optimal operation and expansion strategies on heat and power generation resources as well as electric transmission lines are obtained over the planning horizon. Performance of the proposed model is evaluated through two system tests, where transmission losses, overall system efficiency, reliability of supply and emissions are considered as metrics. Simulation results show importance of energy transmission network modeling in investment and operation of MCES in the long-term.

1. Introduction

Today, on average, half of the world's population lives in urban areas, which accounts for more than 70 percent of urbanization in developed countries of Europe and North America [1]. The high urbanization rate has increased use of energy carriers, especially in the United States, the consumption of natural gas for electricity and heat has risen from 32% to 39% from 2007 to 2012 [2]. The steady growth in world energy demand requires the development of energy infrastructure, e.g. energy resources and transmission networks. In the traditional method, the required energy was provided separately and delivered to its customers. Today, however, due to the interaction and dependence among energy carriers, various types of energy are jointly managed and planned [3]. For example, in order to provide electricity and heat for consumers, it is possible to respond individually as well as using Combined Heat and Power (CHP) by linking electricity and natural gas. The sharing of energy carriers, such as the use of CHP, which has created a variety of energy sources, has affected the technical and economic characteristics of energy systems.

In previous researches, several models have been presented for operation and expansion planning of energy systems. In [4], in order to improve the performance of energy systems, coordination of electricity and natural gas networks has been studied in the optimal operation of gas-fired power plants. A model for assessing the security of energy systems and the effects of natural gas network on optimal operation of electrical and natural gas is presented in [5]. Various models of energy carrier are presented for optimal operation of MCES in [6–9]. In [6], using the concept of energy hub, a linear model is presented for the optimal dispatch of energy in electric and natural gas networks; by which the speed of solving the power flow problem in the power network has been improved. In [7], using of renewable energy sources, CHP units and electric vehicle in the provision of storage services, a model is presented for the optimal scheduling of MCES. A robust optimization method for optimal energy management in MCES is presented in [8] where, uncertainties of energy price and demand as well as the efficiency of components within the energy hub are included. In [9], by introducing the small scale CHP units in the home energy hub and considering the uncertainty of solar energy, a stochastic model is

---

* Corresponding author.
E-mail addresses: hamedfathtabar@gmail.com (H. Fathtabar), barforoshi@nit.ac.ir (T. Barforoushi), shahabi.m@nit.ac.ir (M. Shahabi).

https://doi.org/10.1016/j.ijepes.2018.04.014
Received 2 September 2017; Received in revised form 19 February 2018; Accepted 17 April 2018

Nomenclature

Sets

CC	set of candidates for CHP
CF	set of candidates for gas furnaces
CG	set of candidates for power generation units
CL	set of candidates for power transmission lines
EF	set of existing gas furnaces
EG	set of existing power generation units
EL	set of existing power transmission lines
GF	set of gas-fired power generation units

Indices

b	index for demand blocks
c	index for CHP
f	index for gas furnace
h	index for period
i	index for power generation units
l	index for power transmission line
m,*n*	Indices for bus
pip	index for natural gas pipelines
sup	index for natural gas suppliers
t	index for years

Parameters

A	bus-line incidence matrix
$\acute{A}$	modified bus-line incidence matrix
B	node-natural gas supplier load incidence matrix
C^e	coupling matrix for transformer
C_{pip}	pipeline constant (MMBtu/PSIG)
d	discount rate
DT	duration time (hour)
ENS^{lim}	energy not supply limit (MWh)
FIC	investment cost of gas furnace ($/MMBtu)
fl^{Max}	natural gas pipeline capacity (MMBtu)
GIC	investment cost of power generation unit ($/MW)
g_l,be_l	real and imaginary part of power transmission line admittance (pu)
HIC	investment cost of CHP ($/MW)
H^{Max}	thermal generation capacity, (MMBtu)
k	dispatch factor
OC	operation cost of CHP in $/MWh and $/MMBtuh
PD	forecasted electricity peak demand (MW)
P^{Max}	capacity of power generation unit (MW)
P^D	active power demand (MW)
q^D	reactive power demand (MVar)
R	system spinning reserve requirement (MW)
r_{el},x_{el}	resistance and reactance of power transmission line (pu)
S_e	bus-electricity branch connectivity matrix
S_g	node-natural gas pipeline connectivity matrix
SL^{Max}	power transmission line capacity (MVA)
T	number of year in the planning horizon
T^{Com}	commissioning year
TIC	investment cost of power transmission line ($/MVA)
V^{Min},V^{Max}	minimum and maximum voltage at each bus (pu)
$VOLL$	value of lost load ($/KWh)
v^{Min},v^{Max}	minimum and maximum natural gas supply volume (MMBtu)
Γ_1,Γ_2	coefficients for fuel consumption of power generation units
γ	salvage factor
τ	coefficient for present worth calculation
η	energy conversion efficiency
π^{Min},π^{Max}	minimum and maximum natural gas pressure at each node (PSIG)
π'_m	initial natural gas pressure at each node *m* (PSIG)

Variables

DL	electricity load curtailment (MW)
E	input energy of a hub (MW-MMBtu)
E^{g2e}	input energy to gas-fired units (MMBtu)
$ENSC$	cost of energy not supplied ($)
em	emission of pollutants (lb)
FC	investment and operation cost of gas furnace ($)
$flow$	natural gas pipeline flow (MMBtu)
GC	investment and operation cost of power generation unit ($)
H	thermal generation (MMBtu)
HC	investment and operation cost of CHP ($)
P	active power (MW)
PL	electricity branch flow (MVA)
P^{loss}	active power loss in transmission line (MW)
P^s,q^s	active and reactive power flows at sending end (MW-MVar)
P^r,q^r	active and reactive power flows at receiving end (MW-MVar)
q	reactive power generation (MVar)
q^{loss}	reactive power loss in transmission line (MVar)
Q_{Fuel}	total fuel input (MMBtu)
Q_{Th}	total thermal power generation (MMBtu)
TC	investment cost of power transmission line ($)
u	investment state of CHP
σ_{pip}	status of natural gas pipelines
V_m	the voltage magnitude of each bus (pu)
W^{out}	total electric power generation (MW)
x	investment state of gas furnace
y	investment state of power transmission line
z	investment state of power generation unit
ν	gas delivery quantity of supplier (MMBtu)
π_m	pressure of natural gas at node *m* (PSIG)
δ_m	voltage angle for each bus, (pu)

presented for managing energy consumption. In [10,11], Time Varying Acceleration Coefficients Particle Swarm Optimization (TVAC-PSO) algorithm is presented to solve the Energy Hub Economic Dispatch (EHED) problem taking into account the exact model of electrical and natural gas transmission networks in the operation of MCES. In [12], using the multidimensional piecewise linear approximation method for nonlinear equations of a natural gas transmission network, a MILP model is proposed to solve the optimal power flow problem in energy hubs.

Resource expansion planning models of MCES have been introduced in [13,14]. In [13], in the absence of CHP, a dynamic model is presented for long-term planning of MCES taking into account the interactions of the power network and the natural gas. In [14], considering the uncertainty of wind power, the energy price and demand, a stochastic model is presented for the planning of energy sources of MCES where, impacts of the electricity and natural gas network has been neglected. In [15], a dynamic model is presented for the expansion of distributed resources (DR) in the MCES, taking into account the uncertainty of the energy price. In [16], a static model is presented to design the structure and optimal size of an energy system consisting of