Applied Energy 224 (2018) 357–370

Contents lists available at ScienceDirect

Applied Energy

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

Low-carbon economic dispatch for electricity and natural gas systems considering carbon capture systems and power-to-gas

Liangce He[a], Zhigang Lu[a,*], Jiangfeng Zhang[b], Lijun Geng[a], Hao Zhao[c], Xueping Li[a]

[a] Key Lab of Power Electronics for Energy Conservation and Motor Drive of Hebei Province, Yanshan University, Qinhuangdao, Hebei 066004, China
[b] School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia
[c] China Energy Engineering Group, Tianjin Electric Power Design Institute Co., Ltd., Tianjin 300400, China

HIGHLIGHTS

- A low-carbon economic dispatch model of electricity and natural gas systems is proposed.
- The post-combustion carbon capture system and PtG facility are considered simultaneously.
- A flexible operation mode for post-combustion carbon capture system and PtG facility are formulated.
- The sensitive analysis and cost-benefit analysis are presented in case studies.

ARTICLE INFO

Keywords:
Electricity and natural gas systems
Low-carbon economic dispatch
Flexible operation mode
Post-combustion carbon capture system
Power-to-gas

ABSTRACT

To mitigate the global warming threat, CO_2 emission reduction is an irreversible trend for the sustainable development of power systems. Among various low-carbon technologies, gas-fired power plants and power-to-gas facilities play an important role to reduce emissions, and they are increasing the interdependency between electricity and natural gas systems. Considering also the increasing penetration of wind power generation, this paper proposes a low-carbon economic dispatch model under both constraints of the electricity and natural gas systems. To reduce CO_2 emission and improve the wind power utilization, mathematical formulations of the post-combustion carbon capture system and power-to-gas facility are presented in the proposed model. Additionally, a flexible operation mode of post-combustion carbon capture system and power-to-gas facility is further analyzed. The objective function of the presented model is to minimize the total cost, which consists of the operation cost, the CO_2 processing cost and the penalty cost of wind power curtailment. Then the optimization model is converted into a mixed integer linear programming problem for efficient computation purpose. Numerical case studies are carried out to validate the effectiveness of the proposed model and the flexible operation mode.

1. Introduction

Global warming caused by greenhouse gas emission is a crucial issue in the world, and limiting global warming to 2.0 °C above pre-industrial levels and aspiring to 1.5 °C are the targets pursued in future sustainable development [1]. As a primary greenhouse gas, CO_2 accounts for more than 70% of greenhouse gas emission [2]. Therefore, CO_2 emission reduction has become an important problem in the study of power dispatch at fossil fuel-fired power plants, which emit significant portions of CO_2 into the atmosphere.

Nowadays, different measures can be taken to decrease the CO_2 emission in power plants. Within fossil fuel power plants, more natural gas-fired power plants should be encouraged to build due to their advantages of higher generation efficiency, faster ramp speed and lower CO_2 emission intensity against conventional coal-fired power plants [3]. Meanwhile, the carbon capture and storage (CCS) technology can contribute to form the carbon capture power plants (CCPPs) for reducing the CO_2 emission [4], since the replacement of existing coal-fired power plants takes quite a long time period. Moreover, renewable energy sources, such as wind energy, can be widely developed thanks to their increasing maturity of generation technology and nearly zero CO_2 emission. However, with the increasing penetration of wind power, more and more generation cannot be completely utilized and will have to be curtailed. Power-to-gas (PtG) is a promising technology to address this issue, which can convert excess power of wind power into hydrogen (H_2) by water electrolysis and further into methane (CH_4) via

* Corresponding author.
E-mail address: zhglu@ysu.edu.cn (Z. Lu).

https://doi.org/10.1016/j.apenergy.2018.04.119
Received 17 November 2017; Received in revised form 10 March 2018; Accepted 30 April 2018

Nomenclature

Indices and Sets:

c, d, i, k, p, w indices of carbon capture units, electrical loads, generating units, buses, PtG facilities and wind farms
l,s,ω indices of natural gas loads, gas storage facilities and gas wells
m, n indices of gas network nodes
t index of hours
$S(m)$ set of components connected to gas node m

Constants

a_i,b_i,c_i cost coefficients of unit i (MBtu, MBtu/MWh, MBtu/MW^{2}h)
C_{mn} characteristics constant of gas pipeline mn (kcf/Psig)
G_{ij-k} power transfer distribution factor of transmission line ij of node k
N_{CCU}, N_{CS}, N_{FU}, N_{GU} numbers of carbon capture units, CO_2 storage facilities, fossil fuel-fired units, gas-fired units
N_B, N_D, N_T numbers of buses, electrical loads and hours
N_{GW}, N_{GS}, N_P, N_W numbers of gas wells, natural gas storage facilities, PtG facilities and wind farms
$p_{m,\min}$,$p_{m,\max}$ min/max pressure of natural gas node m (Psig)
P_d,P_w^{f},Q_l forecasted values of electrical load d (MW), wind generation of wind farm w (MW) and gas load l (kcf)
$P_{ij,\min}$,$P_{ij,\max}$ Min/Max power flow of transmission line ij (MW)
$P_{p,\min}^{\mathrm{in}}$,$P_{p,\max}^{\mathrm{in}}$ Min/Max power input of PtG facility p (MW)
$P_{p,\min}^{\mathrm{out}}$,$P_{p,\max}^{\mathrm{out}}$ Min/Max power output of PtG facility p (MW)
$Q_{\omega,\min}$,$Q_{\omega,\max}$ Min/Max production of gas well ω (kcf/h)
$Q_{s,\max}^{\mathrm{NG,in}}$,$Q_{s,\max}^{\mathrm{CO_2,in}}$,$Q_{s,\max}^{\mathrm{H_2,in}}$ maximum injection rate of natural gas/CO_2/H_2 storage facility s (kcf/h)
$Q_{s,\max}^{\mathrm{NG,out}}$,$Q_{s,\max}^{\mathrm{CO_2,out}}$,$Q_{s,\max}^{\mathrm{H_2,out}}$ maximum withdrawal rate of natural gas/CO_2/H_2 storage facility s (kcf/h)
R_i^{UP},R_i^{DN} ramp up/down rate of unit i (MW)
su_i,sd_i start up/shut down fuel of generating unit i (MBtu)
SR^{up},SR^{down} up/down system spinning reverse (MW)
$T_{i,\min}^{\mathrm{on}}$,$T_{i,\min}^{\mathrm{off}}$ minimum on/off time of unit i (h)
β_c,γ_c CO_2 capturing rate/energy consumption for dealing with per unit CO_2 of carbon capture unit c (MWh/kcf)
μ_i CO_2 emission intensity of unit i (kcf/MWh)
Γ_{ka},Γ_{kc},Γ_{kw},Γ_{kp},Γ_{kd} node incidence matrix at row k of non-carbon capture unit a, carbon capture unit c, wind farm w, PtG facility p and electrical load d
$\eta_p^{\mathrm{H_2}}$ power to H_2 efficiency of PtG facility p
$\phi_{\mathrm{H_2-CO_2}}$,$\phi_{\mathrm{H_2-CH_4}}$ reaction coefficients of H_2 to CO_2/CH_4
ϕ_{heat} heat release factor of the Sabatier reaction (MWh/kcf)
λ_c compressing factor of compressor c
ρ_i,ρ_ω,ρ_s,ρ_w fuel price of coal-fired unit i ($/MBtu), production price of gas well ω ($/kcf), storage price of natural gas storage facility s ($/kcf) and penalty price of wind power curtailment for wind farm w ($/MWh)
ρ^{ct},ρ^{ts},ρ^{cc} carbon tax price ($/ton), CO_2 transmission & storage price ($/ton), and CO_2 capture price from atmosphere ($/ton)

Variables

E_s^{NG},$E_s^{\mathrm{CO_2}}$,$E_s^{\mathrm{H_2}}$ storage volume of natural gas/CO_2/H_2 storage facility s (kcf)
I_i,I_p^{in},I_p^{out} commitment statuses of unit i, electrolysis facility and H_2 gas turbine in PtG facility p
p_m pressure of natural gas node m (Psig)
P_p^{heat} recycled heat energy of PtG facility p (MW)
P_i,P_w generation dispatch of unit i and wind farm w (MW)
P_p^{in},P_p^{out} input/output power of PtG facility p (MW)
P_c,P_c^{net} total/net power output of carbon capture unit c (MW)
P_c^{ccs},P_c^{m},P_c^{o} total/fixed/operation energy consumptions of carbon capture system equipped in carbon capture unit c (MW)
Q_c,Q_c^{tre},Q_c^{cc} Volumes of CO_2 being emitted, treated and captured in carbon capture unit c (kcf/h)
Q_ω production of gas well ω (kcf/h)
Q_{mn} gas flow of pipeline mn (kcf/h)
$Q_p^{\mathrm{H_2}}$ produced H_2 in the PtG facility p (kcf/h)
Q_i consumed natural gas of unit i (kcf/h)
$Q_s^{\mathrm{H_2,out,G}}$,$Q_s^{\mathrm{H_2,out,M}}$ the amount of gas withdrawn from H_2 storage facility s for generating electricity/synthesizing CH_4 (kcf/h)
$Q_p^{\mathrm{CO_2}}$,$Q_p^{\mathrm{CH_4}}$ required amount of CO_2 for synthesizing CH_4 and produced CH_4 in PtG facility (kcf/h)
$Q_s^{\mathrm{NG,in}}$,$Q_s^{\mathrm{CO_2,in}}$,$Q_s^{\mathrm{H_2,in}}$ inflow of natural gas/CO_2/H_2 storage facilities s (kcf/h)
$Q_s^{\mathrm{NG,out}}$,$Q_s^{\mathrm{CO_2,out}}$,$Q_s^{\mathrm{H_2,out}}$ Outflow of natural gas/CO_2/H_2 storage facilities s (kcf/h)
$Q_s^{\mathrm{CO_2,in,cc}}$,$Q_s^{\mathrm{CO_2,in,a}}$ inflow of carbon storage facility s from carbon capture system and atmosphere (kcf/h)
SU_i,SD_i start up and shut down fuel of unit i (MBtu)
T_i^{on},T_i^{off} on/off time counter of unit i (h)

Sabatier reaction [5].

Different from obtaining coal on site in many coal-fired power plants, the fuel of gas-fired power plants is mainly provided by natural gas pipelines. A large amount of synthesizing CH_4 from PtG facilities can be injected into the natural gas pipelines directly to serve other gas users [6]. Thus, a bidirectional energy conversion between the power system and natural gas system is achieved by gas-fired power plants and PtG facilities [7]. With the significant growth of the installed capacity of natural gas-fired power plants and PtG facilities, the interdependence of electricity and natural gas systems becomes more significant [8]. Therefore, the operation conditions of natural gas system need to be considered in the low-carbon economic dispatch of power systems.

Due to the above reasons, the unit commitment (UC) problem of power systems has been studied in [9–13] by considering the gas supply contracts and network security constraints of natural gas system. The hourly UC and dispatch of power system in [9] are determined by considering the constraints of electricity and natural gas networks, and Newton-Raphson method is adopted to solve the nonlinear natural gas flow equations. Uncertainty factors including load forecast errors, random outages of generating units and transmission lines are considered in [10] to the security-constrained unit commitment (SCUC) model, and hourly electricity demand response model is added in [11] to maximize the expected social welfare of power systems. The impacts of natural gas price fluctuation and wind power forecast uncertainty on the SCUC are discussed in [12]. A two stage stochastic mixed-integer linear program (MILP) model is proposed in [13] under natural gas pipeline congestion and gas price variability. However, the electrical power system is optimized singly in these studies, which may result in compromised operation of the natural gas system.

Therefore, it is necessary to study power dispatch by optimizing both the electric system and the natural gas system. In [14], a MILP security-constrained optimal power and gas flow model is formulated, and contingency analysis of natural gas system is introduced using linear sensitivity factors. A short-term dispatch of electricity and natural gas systems is developed in [15] considering the dynamic process involving gas travel velocity and line pack of natural gas system. Reference [16] proposes a robust dispatch model to address the wind power uncertainty issue considering the power system contingency and