International Journal of Greenhouse Gas Control 63 (2017) 12–19

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

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

Carbon capture power plants: Decoupled emission and generation outputs for economic dispatch

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ARTICLE INFO

Keywords:
Carbon capture and storage
Economic dispatch
Low carbon power systems
Metaheuristic optimization algorithms
Power system operations
Carbon pricing

ABSTRACT

Integrating flexibly-operated carbon capture and storage (CCS) into the existing power plants has operational benefits for the future low carbon power systems. This paper proposes an improved formulation for flexible operation of carbon capture power plants (CCPPs) within the conventional economic dispatch (ED) problem. The main contribution of this work is the simplification and the practicality of the variables used for the flexible operation control of the facility. The optimal ED problem of thermal power generation portfolio with CCPPs within the mix are computed using a chaos-enhanced Cuckoo Search optimization algorithm. To test the proposed formulations, an IEEE 30 bus test system was used. The impact of varying carbon prices on the system dispatch was investigated. The results reveal the potentiality of decoupling the generation and emission outputs of the thermal power plants.

1. Introduction

Following the recent Paris Agreement on climate change, the global power systems, which account more than 42% (International Energy Agency, 2014) of the global CO_2 emissions, are subjected to shift to a low-carbon future. To put the low-carbon future in to perspective, for instance, in the European Union (EU) alone the power sector emission reductions "are projected to achieve reductions of 54%-68% by 2030 and 93%-99% by 2050 compared to 1990" (Brouwer et al., 2015). The transitions to these systems, in global scale, demands a shift to low-carbon technologies such as renewable technologies, nuclear power and fossil-fuel generators with carbon capture and storage (CCS) (Global CCS Institute, 2015). Carbon capture power plants (CCPPs) which result from retrofitting existing fossil-fired power plants with CCS technologies is at the forefront of emission mitigation measures.

Among the many benefits of the CCPP units over the other rival low carbon technologies is their ability for system dispatch. From the perspectives of power system operations and planning, the existing literature of flexible operation of CCPPs can be categorized into three major divisions. The first group of researchers emphasized the individual plant operation benefits within the competitive electricity markets e.g. the works of (Oates et al., 2014; Cohen et al., 2012). The second group of researchers concentrated the long term planning horizons e.g. Brouwer et al. (2015), van der Wijk et al. (2014). The last group of researchers investigated the operational formulations of the power systems such as (Lou et al., 2015; Ji et al., 2013). This work concentrates on the last category.

On this note, future power system operation routines need to be reconsidered under various contexts. Two important mitigation measures are concurrently considered. Firstly, adoption of the CCS technology is genuinely accelerated globally (with first practical facility coming online on 2014 (IEAGHG, 2015)). Secondly, the CO_2 emission pricing is highly promoted globally (Kossoy et al., 2015). Carbon pricing instruments will further affect the generation cost (hence the operating profits). Coupling these two aspects brings a new phase to the conventional economic and emission dispatch approaches.

Most of the current literature of economic dispatch within the field of thermal generators focused on enhancements of the methods while addressing various issues related to plant characteristics. These include the prohibited operating zones (Tao et al., 2015), valve-point loadings (Zhan et al., 2015) and multi-fuel (Barisal and Prusty, 2015) characteristics of the plants. Similarly, in terms of emission solution approach, the focus of the previous studies was concerned on the "short term mitigation" approaches. These included optimization-based approaches such as the use of multiobjective and the Pareto optimality (Secui, 2015) and the use of emission constraints (Fan and Zhang, 1998). Other research works also investigated the consideration of conventional low carbon technologies such as wind and solar within the dispatch

Abbreviations: CCPP, carbon capture power plants; CCS, carbon capture and storage; CP, carbon price; CS, cuckoo search; CT, carbon Tax; ED, Economic dispatch; EU, European Union; IEA, International Energy Agency; NP, non-capture plant

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http://dx.doi.org/10.1016/j.ijggc.2017.05.001
Received 11 January 2017; Received in revised form 19 April 2017; Accepted 7 May 2017
1750-5836/

Nomenclature and abbreviations

Carbon Capture Power Plant (CCPP) Formulation

P_N	Net power output
P_G	Gross power output (scheduled)
P_{CP}	Capacity penalty of the gross power output
P_{BP}	Basic penalty power
P_{OP}	Operating penalty power
w_{CC}	Amount of energy consumed by the CCS for every CO_2 treated
E_C	Captured emission
E_G	Gross emission
E_N	Net emission
e_E	Emission intensity
γ_C	Normalized rate of the treating ability of the stripper and the compressor
a_C	Capture rate of the scrubber

Indices

N_{CP}	Number of CCPPs
N_{NP}	Number of non-capture plants
N_D	Number of population
N_x	Number of decision variables
d	Index counter for non-capture plants
k	Index counter for CCPPs
i	Index counter for individuals within the population
j	Index counter for number of dimensions of the problem
t	Index counter for iterations of the algorithm

Formulation of Economic Dispatch (ED)

P_d	Scheduled power of the non-capture plant

A – Costs

C_F	Fuel cost of the non-capture plants
C_E	Emission cost of the non-capture plants
C_{FC}	Fuel cost of the CCPPs
C_{EC}	Emission cost of the CCPPs

B – Fuel Cost Coefficients

a_i, b_i, c_i	Fuel cost characteristic of the plants
e_i, f_i	Valve point loading coefficients

C – Emission Cost Coefficients

CP	Carbon price
ef	Emission factor
f_i, g_i, h_i	Fuel consumption coefficients (emission coefficients)

D – System Variables

P_D	Total system demand
P_L	Power loss
λ	Penalty factor multiplier
$P^{\max}$	Maximum stable generation
$P^{\min}$	Minimum stable generation

Optimization (CS) Algorithm

$y(t)$	Value of the chaotic map at each iteration t
y_0	Initial value of the chebyshev chaotic map
$x_{i,j}$	Population of nests
x_i^{new}	New solution candidates
β	Levy flight exponent
$Levy(\beta)$	Levy flight function
x_m and x_n	Two different solutions selected randomly by permutation
$H(u)$	Heaviside function controlled by a switching parameter P_a
P_a	Switching parameter
ε	Uniformly distributed random number

formulations (e.g. the work in Hetzer et al., 2008).

The consideration of the operational flexibility of CCPPs within dispatch formulation has been, so far, addressed in few literatures (Ji et al., 2013; Chen et al., 2010; Chen et al., 2012; Lu et al., 2013). First, an innovative work from Chen et al. (2010) and their follow-up work (Chen et al., 2012) have provided initial grounds for formulations of the flexible operation of the CCPPs. However, their works incorporate the generation efficiency "thread" within the formulations. However, existing ED formulations are based on output power "thread". Second, the approach presented in (Lu et al., 2013), which was used in other studies (Lou et al., 2015; Jiaming et al., 2015), does not formulate emission as an independent controllable variable. Instead, the presented formulation is a multi-decision-oriented procedure that is aimed to determine the captured emission and net power output of the CCPP.

Thirdly, while the work of Ji et al. (2013) formulates emission as a dispatchable resource, the work has two inherent mathematical complexity. First, the four auxiliary decision variables, employed to help the optimization routine to select an operating point, significantly increase the problem complexity by multiplying four extra decision variables for each considered CCPP unit within the system. From the mathematical optimization point of view, this is called the "curse of dimensionality" problem i.e. the exponential rise in the time and space required to compute an approximate solution to a problem as the dimension (i.e. the number of control variables) increases. Second, the work also developed two additional equality constraints; one for the auxiliary decision variables and one for the coordination between net emission, net power output and the gross power output. For large-scale systems in particular, this approach presents a considerable complexity when using advanced metaheuristic optimization techniques.

Capitalising the existing formulations and aiming to address the existing weaknesses, the main objective of this work is to develop a modified model formulation of the flexible operation of CCPP units suitable for the conventional static ED problem. Based on the proposed CCPP model, the conventional ED is reformulated taking into account the generation mix diversity. Then the impact of CCPP within the generation mix on different aspects of the power system such as generation mix, generation cost, CO_2 cost, emission intensity and others are studied.

As far as our current literature is concerned, this paper presents the first attempt to integrate the CCPP within a set of thermal generators for the static ED problem. This is important to provide understanding of the optimal operating characteristic of the facility while using snapshots of plant operation. The presented model may be useful in incorporating within the future releases of the professional power system operations software available to system planners and operators. For example, authors in van der Wijk et al. (2014) unavoidably developed a separate Excel-based module for CCS operation and then integrated it with PLEXOS, a professional power system operations tool.

The work presented is organized as follows. The existing model formulations are firstly improved within the Section 1. It is then