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Stochastic low-carbon scheduling with carbon capture power plants and coupon-based demand response

Xue Li[a], Rufeng Zhang[a], Linquan Bai[b], Guoqing Li[a], Tao Jiang[a,*], Houhe Chen[a,*]

[a] Department of Electrical Engineering, Northeast Electric Power University, Jilin, JL 132012, China
[b] ABB Power Consulting, Raleigh, NC 27606, USA

HIGHLIGHTS

- A stochastic day-ahead scheduling model with CCPPs and CDR is proposed.
- Operation models of CCPPs and CDR are presented.
- Flexible operation mechanism of CCPPs and CDR is analyzed.
- The random forecasting errors of hourly wind power output and loads are considered.

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ABSTRACT

Global warming caused by excessive CO_2 emissions has make it urgent to develop low-carbon economy. The carbon capture system is effective to reduce the carbon footprint of coal-fired power plants. Meanwhile, using more renewable energies such as wind power will require less generations from traditional power plants and hence limit the overall carbon emission. However, the wind power is intermittent by nature and hence may fluctuate and present a stochastic feature. In order to effectively reduce the overall carbon emission, a stochastic day-ahead scheduling optimization model with wind power integration incorporating carbon capture power plant (CCPP) and coupon-based demand response (CDR) is proposed in this work. Firstly, the formulation of CDR and the operating mechanism of CCPPs are clarified. Then the flexible operation mechanism aiming at reducing wind power curtailment and CO_2 emissions is analyzed. The random forecasting errors of the day-ahead hourly wind power output and loads are considered. Monte Carlo method is applied to simulate stochastic scenarios and a scenario reduction method is applied to ease the computational burden. Simulation results with on the PJM 5-bus system and the IEEE 118-bus system demonstrate the effectiveness of the proposed method in carbon emission reduction and wind curtailments decrease.

1. Introduction

Global warming caused by carbon dioxide (CO_2) has become a worldwide concern. As one of the major sources of CO_2 emissions, efforts have been made to adjust the operational strategies of conventional fossil fuel fired power plants to reduce their emissions and hence to develop a low-carbon economy [1,2]. Carbon capture and storage (CCS) technology has been regarded as one of the most promising means to reduce anthropogenic CO_2 emissions [3–6]. To ensure carbon emissions within the targeted range, an effective way is to vigorously develop renewable energy. At the same time CCS technology should be applied in conventional power plants [7,8]. CCS technology equipped in a conventional thermal power plant can capture CO_2 and transport it to a storage location. The captured CO_2 is permanently isolated from the atmosphere and the entire CO_2 emissions are reduced. At present, several pilot carbon capture power plants (CCPPs) have been planned, established or operated in different countries [9]. In China, three CCPPs have been built in Beijing, Shanghai, and Chongqing, respectively [10]. In UK, all new-built coal-fired power plants have been suggested to equip CCS facilities in about 10–15 years [11].

The application of CCS technology introduces great complexities to carbon capture power plants. CCS system consumes energy to separate CO_2, and increases the operation cost of a CCPP. At the same time, the flexibility and constraints brought by CCS should also be considered in the operation of CCPPs. Some studies on the operation of CCPP have been conducted. A techno-economic comparison between coal

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* Corresponding authors.
E-mail addresses: tjiang@neepu.edu.cn (T. Jiang), chenhouhe@neepu.edu.cn (H. Chen).

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Nomenclature

Abbreviation

CCS	carbon capture and storage
MILP	mixed integer linear programming
CDR	coupon-based demand response
MC	Monte Carlo
TOU	time-of-use
GAMS	General Algebraic Modeling System
CCPP	carbon capture power plants
DR	demand response
CDR	coupon-based demand response
ISO	Independent System Operator
LP	linear programming

Varaibles and indices

α_C	capture rate of CO_2
c_{co2}	CO_2 price
$c_{c,ccpp}$	CO_2 transportation cost coefficient
c_i	bidding prices of conventional units
c_{wind}	Bidding price of wind power
$\Delta d_{b,i,t}$	demand in the *i*th block
$\Delta D_{b,t}$	total exchanged load
$\Delta D_{b,\max}$	allowable exchange of load at bus *b*
D_t^s	power demand in scenario *s* at time *t*
$E_{P,i,t}$	amount of CO_2
$E_{N,i,t}$	net carbon emission
$E_{G,i,t}$	CO_2 emission from the plant
$E_{ccpp,i,t}$	captured carbon
e_G	emission intensity of gross power output
$F_{IDR,b,t}$	CDR compensation cost at bus *b*
$GSF_{l\text{-}i}$	generation shift factor
$Limit_l$	transmission capacity of line *l*
N_i	stepwise number
N_s	scenarios number
N	conventional units number
N_c	CCPPs number
$PD_{b,i,t}$	price demand in the *i*th block
$P_{C,i,t}^N$	net power generation
$P_{C,i,t}^G$	total power output
$P_{C,i,t}^{EP}$	energy consumed by CCS in the *i*th block of the stepwise at time *t*
$P_{C,i,t}^N$	net power generation in the *i*th block of the stepwise at time *t*
$P_{C,i,t}^G$	total power output in the *i*th block of the stepwise at time *t*
$P_{C,i,t}^{EP}$	energy consumed by CCS in the *i*th block of the stepwise at time *t*
$P_{C,i,t}^{EP,B}$	basic power consumption of CCPP
$P_{C,i,t}^{EP,OP}$	operation power consumption of CCPP
$P_{\mathrm{imin}}/P_{\mathrm{imax}}$	minimum/maximum power output of conventional units
$P_{wind,t}^{forecast}$	wind power forecast output
$Ramp_I^u/Ramp_I^d$	up/down ramping limits of conventional units
R_{up}/R_{down}	up/down reserve requirements
R_d	reserve requirements
$S_{0,i,t}$	volumes of solvent in the tanks initially
$S_{ccpp,i,t}$	volumes of solvent in the tanks at time *t*
S_I^{max}	maximum capacity of the tanks
T	scheduling periods
ΔT	time interval
$\mu_{b,t}$	auxiliary variable
η_{ccpp}	operating energy penalty rate
$\delta_{i,b,t}$	*i*th block of the piecewise linear demand bid at bus *b* at time *t*

combustion and gasification technologies is conducted in [12]. Flexible operation potential of CCPP has been analyzed in [13], and the flexible operation mechanism is modeled in [14]. In [15], a mixed integer linear programming (MILP) model was developed for a pulverized coal plant with post-combustion carbon capture. The ability of CCPPs contributing to load following by changing operating mode was also demonstrated. Chen et al. [16] developed a mathematical model of the flexible operation of CCPPs in day-ahead power market, which could bring significantly improvement on the overall economics of a CCPP. Economic dispatch incorporating CCPPs were studied in [2,17–20]. Lou et al. [21] proposed a multi-period optimization model for spinning reserve requirement considering CCPPs, in which the contribution of CCPP to spinning reserve requirement was analyzed.

The integration of large-scale renewable energy, such as wind power, could reduce fuel consumptions and CO_2 emissions of the traditional power systems. However, volatility and uncertainty of wind power require more flexibility to maintain the power supply and demand balance. Several studies have been conducted on the flexible operation of wind power and CCPPs. Modeling and optimal operation of carbon capture from the atmosphere driven by wind power were studied in [22]. Li et al. [23] proposed a low-carbon unit commitment model for CCPPs and wind power, in which CCS technique was demonstrated to help wind power accommodation. But the flexibility of CCPPs is limited due to the number and capacity of CCS.

The emerging demand response (DR) technology is effective to improve the flexibility of power system operation and enhance system reliability to address wind power and load uncertainties [24–27]. Stochastic day-ahead scheduling with demand response and uncertain wind power is studied in [27–29]. A day-ahead decentralized energy trading algorithm with generation uncertainty that jointly optimizes the cost of load aggregators and profit of the generators is proposed in [30]. However, to the authors' best knowledge, few published literatures have studied the coordination of CCPP and DR to reduce wind power curtailment and CO_2 emission.

For this purpose, this paper proposes a multi-period stochastic day-ahead scheduling optimization model of wind power integrated power systems incorporating carbon capture power plant and demand response considering uncertainties of wind power and load. Coupon-based demand response (CDR) model is employed to perform load shifting. Formulations of CDR and CCPPs in day-ahead scheduling are investigated and the flexible operation mechanism is analyzed. The hourly forecasting errors of wind power and load are considered. Monte Carlo (MC) simulation is applied to generate uncertain scenarios and the scenario reduction method is introduced to lower the computational burden of Monte Carlo method. The proposed stochastic day-ahead scheduling optimization model is tested on a PJM 5-bus system and IEEE 118-bus system. The benefit of the integration of CDR and CCPPs on wind power curtailment and CO_2 emission reduction is discussed. The major contributions of the paper can be summarized as follows:

- Operation models of CCPP and DR are presented and uncertainties of wind power and load are considered.
- The flexible operation mechanism of CCPP and DR to reduce wind power curtailments is analyzed.
- A stochastic day-ahead scheduling optimization model of wind power integrated power systems incorporating CCPP and DR is proposed under low-carbon economy.
- The results show that the integration of CCPP and DR is effective on