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Robust economic/emission dispatch considering wind power uncertainties and flexible operation of carbon capture and storage

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ABSTRACT

With increasing wind farm development, solutions of Economic/Emission Power Dispatch (EED) are becoming more difficult to meet the demand of both optimality and robustness because of wind power uncertainties. In this paper, a Robust Economic/Emission Dispatch (REED) model based on effective function is built to deal with wind power uncertainties and Latin hypercube sampling (LHS) method is employed to improve the calculation precision of effective function. As carbon capture and storage (CCS) plays an important role in reducing carbon emission, the impact of CCS, which operates in flexible mode, on EED problem is also investigated. Multi-objective bacterial colony chemotaxis (MOBCC) is adopted to solve the REED problem. Finally, tests of the proposed method are carried out in the IEEE 30-bus test system. Results demonstrate that the REED model can meet the demand of obtaining robust solutions in the presence of wind power uncertainties and flexible operation of CCS has the advantage of dealing with different carbon reduction index.

Introduction

According to preliminary estimates from the International Energy Agency (IEA), global carbon dioxide (CO_2) emissions from fossil-fuel combustion reached a record high of 31.6 Giga tons (Gt) in 2011. Coal accounted for 45% of total energy related CO_2 emissions. China made the largest contribution to the global increase, with its emissions rising by 720 million tons (Mt), or 9.3%, primarily due to higher coal consumption [1]. Greenhouse effect has received considerable attention in the 21st Century and carbon emission reduction is inevitable. China is in the phase of industrialization which determines the huge demand for electricity. The emission content of CO_2 from electric power system accounted for 38.76% of the total CO_2 emission in China [2]. So the pollution of the earth's atmosphere caused by the emissions from thermal power plants is of great concern to power utilities and communities in recent years. The increasing public awareness of the environmental protection and the Clean Air Act Amendments of 1990 have forced the power utilities to modify their operational strategies to reduce emissions [3,4]. The transformation from traditional Economic Dispatch (ED) to Economic/Emission Dispatch is becoming more and more important.

CCS is one family of technologies that could be used to reduce global carbon dioxide emissions significantly. Huaneng Beijing Power Plant, the first CO_2 capture industrial scale plant in China, shows the technology is a good option for capturing CO_2 from commercial thermal power plants [5]. In [6], performances in power peak-load shaving scheme and generation output limits of carbon capture power plant were revealed by studying the fundamental principle of CCS technology. Literature [7,8] studied how to scheduling CCS equipment to reduce energy consumption and network loss to meet the request of the emission reduction targets. Based on flexible operation, Chen et al. [9] presented CO_2 capture schedule, and bidding strategies in response of volatile power and carbon prices in a day-ahead energy market and a cap-and-trade carbon emission market. The importance of flexible-operation mechanism in enhancing economic returns and ensuring the secure operation of power system is also addressed by Chen et al. in [10]. Further studies show that flexible operation of CCS can also be of economic value in being able to provide ancillary services [11]. In practice, future large scale deployment of variable-output renewables such as wind power and/or inflexible nuclear power plants may make flexible operation of CCS obligatory [11,12]. So far, the characteristic of flexible operation of CCS is rarely studied in EED problem.

Besides CCS, Wind power also plays an important role in reducing CO_2 emission. In 2007, the Chinese government announced its

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medium- and long-term plan for renewable energy development, proposing that installed wind power capacity rise to 30 GW by 2020. That target was achieved by 2010, ten years ahead of schedule. Over the last decade, researchers have made significant effort to evaluate the impact of large scale wind generation on the operations, such as regulation and load following [13]. At the same time, lots of studies have also been carried out on EED problem incorporating wind energy [14–17]. Ref. [14] derives a closed-form in terms of the incomplete gamma function (IGF) to characterize the impact of wind power and the effects of wind power on emission control are investigated. In [15], Wind turbine power generation is considered to shave the power system load curves. In order to model the random nature of load demand and wind forecast errors, a scenario-based stochastic programming framework is presented in [16–18].

Traditional EED models [19–22] pursued minimum total emission and minimum total fuel cost by improving the performance of intelligent optimization algorithms. They ignored the robustness of the solution that caused by wind power uncertainty. What's more, conventional stochastic programming approach need probability density functions of the uncertain data which are hard-to-obtain. Considering the above factors, robust optimization (RO) obtains much attention. RO which only requires a deterministic uncertainty set, is another choice to take the uncertainties into account. Ben-Tal and Nemirovski [23–26] made great contributions to RO problem in the field of convex optimization and linear programs. Robust optimization of Unit Commitment (UC) [27] and Economic Dispatch (ED) [28] which are non-convex and non-linear problem have also obtained much attention. A two-stage adaptive robust unit commitment model is built in the presence of nodal net injection uncertainty [27]. The robust model of [28] considered both wind energy and plug-in electric vehicles (PEV). Two-stage strategy is used to solved the Robust optimization model presented in [27,28], where the second-stage problem is to model decision making after the first-stage decisions are made and the uncertainty is revealed. Market-clearing procedures for energy markets are also challenged by the growth of stochastic production capacity. Refs. [29–31] take adaptive robust optimization as an alternative approach to deal with the impact of wind energy on Electricity Markets.

So far, few researchers emphasized the importance of robust multi-objective optimization in EED problem. Deb and Gupta presented two different robust multi-objective optimization procedures in [32] and extended the concepts for finding robust solutions in the presence of active constraints in [33]. So this paper mainly focuses on the application of robust multi-objective optimization based on intelligent optimization algorithms (IOA) in EED problem.

The paper is organized as follows: Section 'Economic/emission dispatch model' describes the deterministic EED model; Section 'Robust economic/emission dispatch model' shows the process of converting the deterministic EED problem into REED problem; Section 'Simulation results' gives a case study and Section 'Conclusions' states the conclusion.

Economic/emission dispatch model

Economic objective function

The economic objective function is given in this section. The proposed function, based on original EED model, consists of two parts, namely fuel cost considering the effect of flexible operation of CCS and penalty cost of the wind generation uncertainties which is represented by the wind forecast errors.

Fuel cost function

A liner function is used to describe the power consumption of CCS that operating in flexible mode; it can be expressed as (1):

$$p_{ccsi} = p_{mi} + p^*_{ccsi} \tag{1}$$

where p_{ccsi} denotes the ith CCS total consumption of real power, p_{mi} is the maintain power which is a constant value, p^*_{ccsi} is the variable power when operating in flexible mode.

When the net output power of ith generator is p_i, the total output power p_{gi} can be expressed as (2):

$$p_{gi} = p_i + p_{ccsi} \tag{2}$$

where p_{ccsi} is zero when the ith generator is not equipped with CCS.

A quadratic function of the generator's real output power is used to describe the fuel cost function, considering a power system with N generators. The total fuel cost $C(p_{gi})$ (\$/h) can be expressed as (3):

$$C(p_{gi}) = \sum_{i=1}^{N} (a_i p_{gi}^2 + b_i p_{gi} + c_i) \tag{3}$$

where p_{gi} denotes the ith generator's total real power output, a_i, b_i and c_i are the coefficients of the ith generator's fuel cost.

According to formulas (2) and (3), the fuel cost function can be expressed as (4)

$$C(p_i, p_{ccsi}) = \sum_{i=1}^{N} (a_i (p_i + p_{ccsi})^2 + b_i (p_i + p_{ccsi}) + c_i) \tag{4}$$

Penalty cost for wind forecast errors

In order to encourage the development of renewable energy, The State Grid is asked to accept wind energy as much as possible. Coal-fired power plants should decrease the output when the wind energy is underestimated, which leads to the reduction of coal consumption and CO_2 emission, so the penalty cost should be lower. But when the wind energy is overestimated, Coal-fired power plants should compensate the lack of power, resulting in more coal consumption and more emission, so the penalty cost should be higher. It can be expressed as (5):

$$C_w = \sum_{i=1}^{N_w} Ce^{\frac{\Delta P_{wi}}{\Delta P_{wi}-\alpha}} |\Delta p_{wi}| \tag{5}$$

where $Ce^{\frac{\Delta P_{wi}}{\Delta P_{wi}-\alpha}}$ denotes the variable penalty coefficient and C is a constant value, Fig. 1 shows the characteristic of Penalty Coefficient

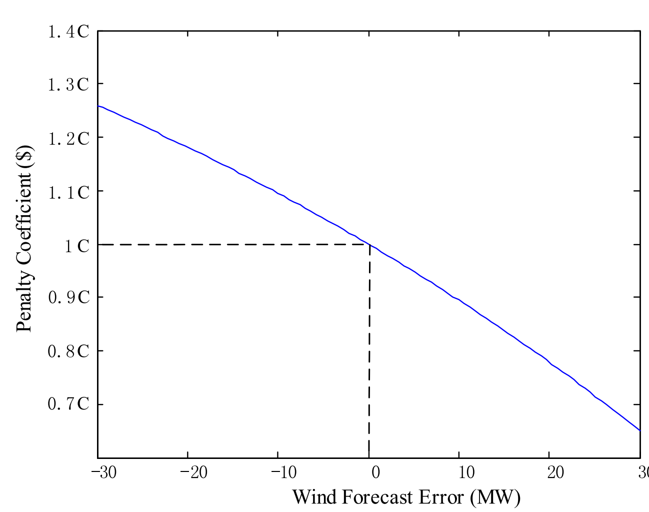

Fig. 1. Characteristic of penalty coefficient curve.