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Power generation scheduling considering stochastic emission limits

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ABSTRACT

In some highly populated areas of the planet, air quality is an issue. Since power plants in those areas significantly contribute to air pollution due to SO_2 and NO_x emissions, it is appropriate to operate such power plants enforcing admissible emission limits. Since emissions directly impact the air quality index, which is highly uncertain 24 h in advance, admissible emission limits should be modeled as stochastic parameters.To represent the stochastic nature of such admissible emission limits, we propose a two-stage stochastic programming model for the commitment of power plants. The first stage represents the day-ahead scheduling, and the second stage represents the real-time power system operation under different weather and thus admissible emission limit conditions. We show the effect of stochastic emission limits on power system operations using a simple example and a 118-node case study.

1. Introduction

1.1. Motivation and aim

In some highly populated areas of the planet, air quality is an issue. In China, power plants contributed 35% of the SO_2 emissions and 38% of the NO_x emissions in 2014 [1]. Those air pollutants have severe negative impact on the environment and human health, and may shorten life expectancy by 5 years [2]. Thus, it is appropriate to operate such power plants enforcing suitable emission limits to reduce the risk to human life.

Different air quality indices (AQI) are used to measure air pollution. In some countries, such as US [3] and China [4], AQI is calculated using the concentration of several air pollutants (O_3, $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2). This is done as follows. First, the concentration of each pollutant is measured. Then, sub-indices are calculated for each pollutant according to the concentration and the national standard. Finally, the AQI equals the highest sub-index, and the corresponding pollutant is defined as the main air pollutant. In Europe, AQI is calculated similarly, while the national air quality standards generally differ among countries. The CITEAIR project was carried out to define a Common Air Quality Index (CAQI) to make the AQI among European cities comparable [5]. It is relevant to note that there is no perfect standard to measure air quality. The value of AQI generally varies with the selected measurement set and the calculation method [6]. For example, Ref. [7] compares alternative ozone metrics. In [8] an aggregate measure of air pollution is proposed. As a general rule, it should be noted that a smaller AQI means better air quality under a given AQI standard.

The main air pollutant in China is often $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm). $PM_{2.5}$ consists of two categories: primary $PM_{2.5}$ and secondary $PM_{2.5}$. Primary $PM_{2.5}$ comes directly from emission sources, while secondary $PM_{2.5}$ results from other gas or liquid pollutants in the air, such as SO_2 and NO_x. In heavily polluted cities in China (e.g. Beijing, Shanghai and Guangzhou), 51–77% of the $PM_{2.5}$ pollution is secondary [9]. The speed of secondary $PM_{2.5}$ formation depends on the concentration of pollutants and diffusion condition. In a steady atmosphere (bad diffusion condition), SO_2 and NO_x are more likely to convert to $PM_{2.5}$, which highly deteriorates air quality. Since a bad AQI usually results from bad diffusion condition, emissions during bad AQI periods will further degrade the air quality. To help ensure the air quality, many measures have been taken. Air pollution control devices have been widely installed in power plants, cars, and industries. Emissions are monitored and controlled by the government. If the forecasted AQI deteriorates in Beijing, an alert is issued by the government proportional to the level of air pollution. In turn, different measures are implemented to limit emissions, including reducing the number of cars during daytime, and reduction in the power output of local thermal power plants

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Nomenclature

Indices

i	index of thermal units
j	index of demands
k	index of segments in the piecewise model
n, r	index of nodes
p	index of air pollutants, such as SO_2 and NO_x
s	index of scenarios
t	index of time periods

Sets

T	set of time periods
Ω^{I}	set of thermal units
Ω^{I}_{n}	set of thermal units located at node n
Ω^{J}	set of demands
Ω^{J}_{n}	set of demands located at node n
Ω^{L}	set of transmission lines
Ω^{N}	set of nodes
Ω^{N}_{0}	set of emission-constrained nodes
Ω^{P}	set of air pollutants
Ω^{S}	set of scenarios
Ω_{n}	set of nodes adjacent to node n

Variables: Scheduling variables

z_{it}	on/off status of unit i at time t: 1 if on, 0 if off
y^{SU}_{it}	start-up status of unit i at time t: 1 if started-up at the beginning of period t, 0 otherwise
y^{SD}_{it}	shut-down status of unit i at time t: 1 if shut-down at the beginning of period t, 0 otherwise
P^{S}_{it}	scheduled power output of unit i at time t
E^{SU}_{itp}	start-up emission level of unit i at time t for pollutant p
θ^{S}_{nt}	voltage angle of node n at time t at the scheduling stage
λ^{S}_{nt}	dual variable of power balance constraint at the scheduling stage (locational marginal price) at node n and time t

Operation variables

P_{its}	power output of unit i at time t in scenario s
e^{U}_{its}	up-reserve deployment of unit i at time t in scenario s to comply with emission limit uncertainty
e^{D}_{its}	down-reserve deployment of unit i at time t in scenario s to comply with emission limit uncertainty
D^{SHED}_{jts}	load shedding of demand j at time t in scenario s
E_{itsp}	operation emission level of unit i at time t and scenario s for pollutant p
θ_{nts}	voltage angle of node n at time t in scenario s
λ_{nts}	dual variable of power balance constraint at the operational stage at node n and time t in scenario s
μ_{ntsp}	dual variable of emission limit constraint of pollutant p at node n and time t in scenario s

Variables: Parameters

C_{i}	marginal cost for unit i, \$/MW h
D_{jt}	load of demand j at time t, MW
F^{max}_{nr}	transmission capacity of line $n-r$, MW
K^{M}_{ntsp}	emission limit of pollutant p at node n and time t in scenario s, kg/h
$L^{U,max}_{i}$	ramp up limit for unit i, MW/h
$L^{D,max}_{i}$	ramp down limit for unit i, MW/h
P^{max}_{i}	capacity of unit i, MW
P^{min}_{i}	minimum power output of unit i, MW
$R^{U,max}_{i}$	maximum up reserve for unit i, MW
$R^{D,max}_{i}$	maximum down reserve for unit i, MW
V^{LOL}_{j}	value of loss of load for demand j, \$/MW h
x_{nr}	per-unit reactance of line $n-r$
π^{SU}_{i}	start-up cost for unit i, \$
σ^{SU}_{ip}	start-up emission of pollutant p for unit i, kg
ρ_{s}	probability of scenario s
θ^{min}_{n}	minimum voltage angle of node n
θ^{max}_{n}	maximum voltage angle of node n

[10]. Therefore, emission limits based on AQI are appropriate to regulate power system emissions [11].

Real-time air quality forecasting (RT-AQF), a discipline of the atmosphere sciences, was started in 1970s [12]. Major RT-AQF techniques can be grouped into two categories: statistical approaches and physically-based approaches [12,13]. Statistical approaches are based on the fact that weather and air quality variables are statistically correlated. They usually require a large amount of historical measured data under various atmospheric conditions. Statistical approaches are computationally fast, but generally entail comparatively lower accuracy, since they neglect the changes in emissions and do not embody a description of chemical and physical processes. Physically-based approaches refer to those using chemical transport models (CTMs). The CTM model describes meteorological fields, emissions, and initial and boundary conditions. Physically-based models generally have better performance than statistical approaches, but a higher computational cost.

Although hourly AQI can be forecasted 8 days in advance [14], RT-AQF is still a very challenging task. Due to the uncertainty in weather and emissions forecast, and to the inaccuracy of the atmosphere model, significant errors in RT-AQF are inevitable [15–18]. For example, for the daily 72-h $PM_{2.5}$ forecast in the Eastern part of China, more than 3/4 of all cities have normalized mean biases within ±25% [17]. Moreover, the accuracy tends to go down in highly polluted areas. Forecasting accuracy for six pollutants and different models is compared in [18], which may vary among cities and cases. Probabilistic forecast can be used to overcome the limitations [12].

At the time of scheduling power plants for next-day operation, air quality and thus admissible emission limits are not accurately known. Therefore, to make efficient commitment decisions while ensuring low-enough pollution levels, the uncertainty in air quality needs to be carefully represented. Using a simplistic deterministic model [11] that disregards such uncertainty generally results in either a highly costly operation or pollution levels overpassing health safety limits.

To address this scheduling problem under weather uncertainty, we propose a two-stage stochastic unit commitment model. The first stage of this model represents the scheduling task that takes place one day in advance, and the second stage represents the many operating conditions that may occur the next day under different AQI scenarios. We denote this model Stochastic Emission-Constrained Unit Commitment (SECUC).

1.2. Literature review

Relevant works related to environmental generation scheduling are reviewed below. Delson [19] proposes an emission controlled dispatch model, where the goal is to meet a given emission limit