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Energy and reserve scheduling under ambiguity on renewable probability distribution

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ABSTRACT

This paper presents a novel methodology to devise a least-cost energy and reserve scheduling under uncertainty in renewable energy sources (RES) and equipment outages. The uncertainty in renewable production is accounted for by exogenously simulated scenarios, as customary in stochastic programming, whereas outages of generators and/or transmission lines are addressed via adjustable robust optimization. The precise characterization of the RES output by means of a unique probability distribution is a challenging task. Hence, we provide a general formulation that allows the consideration of a set of "credible" probability distributions. In this manner, the system operator's ambiguity aversion to uncertainty in renewable production is accounted for. Our proposed methodology determines the least-cost energy and reserve scheduling through a three-level model. Structurally, the upper level defines a least-cost scheduling and, under uncertainty in renewable production, the middle level identifies the worst contingency for the given operating point. The lower level then utilizes the scheduling provided by the upper-level to determine the best redispatch. In order to control the system equilibrium, we adapt risk constraint techniques to handle the system imbalance uncertainty and ensure a reliable operating level. To solve the multi-level problem, we propose an algorithm that combines Benders decomposition and column-and-constraint generation techniques to approximate the risk measure while scheduling power and reserves. The effectiveness of the proposed model and the importance of considering ambiguity are demonstrated through a case study with real data from the Great Britain power system network.

1. Introduction

Recently, most countries around the globe have experienced, and even fostered, a massive penetration of renewable energy into their power grids [1]. The European Union, whose renewable share has reached 16.7% in 2015 [2], has decided to address 20% of its energy demand through renewable sources by 2020 [3] and 27% by 2030 [4]. For instance, Sweden, Denmark, and Spain intend to cover 50%, 30%, and 20%, respectively, of their gross final consumption using renewable sources by 2020 [3]. The United Kingdom has supplied 8.9% of its total energy consumption by means of renewable energy in 2016 and aims at supplying 15% by 2020 [5]. China has committed to increase its renewable generation share to (at least) 17% by 2030 [6]. In the United States, the governments of California, Colorado, and Connecticut are pursuing an ambitious target to increase renewable sources in 33%, 30%, and 27% by 2020, respectively [7]. This global trend has as main goal the seek for a significant reduction on greenhouse gas emission and environmental impacts. In addition, from a commercial point-of-view, due to general short time for construction and cheap operating costs, most renewable plants are extremely competitive on energy market, helping to mitigate potential market inefficiencies. On the other hand, however, from a technical view-point, the uncertainty and non-controllability inherent to their energy production introduces several challenges of different natures for system operators.

Within this new environment, two of the most critical concerns in power system operations are (i) the variability of generation output, mainly associated with renewable production and (ii) equipment failures, which may occur either unintentionally [8] – often caused by weather and/or environment conditions, malfunction of protection mechanisms, and human error – or intentionally

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Nomenclature

Sets

$\mathcal{L}$: Set of transmission line indexes
N: Set of bus indexes
$\mathcal{I}$: Set of conventional generator indexes
$\mathcal{I}_b$: Set of indexes of generators connected to bus $b \in N$

Functions

$C_i(\cdot)$: Energy cost function offered by generator $i \in \mathcal{I}$

Constants

d_b: Demand at bus $b \in N$
$\overline{F}_l$: Power flow capacity of line $l \in \mathcal{L}$
$fr(l)$: Sending or origin bus of line $l \in \mathcal{L}$
$\hat{g}_b$: Expected or best estimation for renewable production at bus $b \in N$
$\overline{P}_i$: Capacity of conventional generator $i \in \mathcal{I}$
$\underline{P}_i$: Minimum power output of conventional generator $i \in \mathcal{I}$
$\overline{R}_i^D$: Upper bound for the down-spinning reserve contribution of conventional generator $i \in \mathcal{I}$
$\overline{R}_i^U$: Upper bound for the up-spinning reserve contribution of conventional generator $i \in \mathcal{I}$
$to(l)$: Receiving or destination bus of line $l \in \mathcal{L}$
x_l: Reactance of line $l \in \mathcal{L}$

Decision variables

θ_b: Phase angle at bus $b \in N$ in the pre-contingency state
f_l: Power flow of line $l \in \mathcal{L}$ in the pre-contingency state
p_i: Power output of generator $i \in \mathcal{I}$ in the pre-contingency state
r_i^D : Down-spinning reserve provided by generator $i \in \mathcal{I}$
r_i^U : Up-spinning reserve provided by generator $i \in \mathcal{I}$
v_i : Binary variable that represents the commitment status of conventional generator $i \in \mathcal{I}$

[9], fruit of deliberate attacks against the electric system. This paper is devoted to comprise both aforementioned concerns in a unified approach.

Over the last decade, the generation scheduling problem under both energy production and system outage uncertainties has been extensively addressed in technical literature [10]. Within the set of techniques found in recent works, Stochastic (SO) [11] and Robust Optimization (RO) [12], particularly Adjustable Robust Optimization (ARO) [13], appear as the most efficient methods. Within a SO framework, in [14], a stochastic model for security-constrained unit commitment is proposed to minimize the expected value of the system cost over scenarios of energy production and transmission asset outages as well as demand level using Monte-Carlo techniques. Moreover, [15] provides a comparison between stochastic and deterministic optimization for unit commitment under significant wind penetration and studies the impact of different frequency planning on system costs. Additionally, in [16], each single contingency state is explicitly considered in the presented formulation associated with a given probability of occurrence. The main goal in [16] is to find the best transmission switching scheme in order to minimize the expected dispatch cost. Similarly, [17] discusses a stochastic security-constrained unit commitment with transmission switching to accommodate wind uncertainty in day-ahead scheduling. In [18], a mixed integer linear program (MILP) formulation is proposed for stochastic unit commitment in isolated regions, such as islands, with renewable penetration. From a probabilistic optimization perspective, [19] combines chance constraints and stochastic optimization methods to ensure that a significant part of the wind production output is likely to be consumed. Also, in [20], a probabilistic reserve level determination approach is incorporated into the stochastic optimization framework to reduce the number of scenarios required to achieve stable solutions and therefore increase computational efficiency. In [21], an efficient methodology for solving the stochastic unit commitment problem is proposed and a comparison between different topologies of scenario trees and methods of scenario generation is provided. In [22], the work of [21] is further extended to account for system inertia while scheduling primary frequency response. On the other hand, from a RO perspective, in [23,24], an ARO-based dispatch model is discussed to deal with nodal injection undesired variability. The primary objective of [23,24] is to find the unit commitment that minimizes generation costs under worst-case realization of nodal injection uncertainty. In [25], robust optimization techniques are adapted to develop a min-max regret unit commitment model under uncertain wind output. In [26], a network-constrained three-level formulation is presented to define a least-cost unit commitment and scheduling of power and reserves that ensures an $n-K$ security criterion. Also, in [27], a similar multi-level formulation is devised to address $n-1$ security criterion and correlated nodal demand uncertainty while scheduling power and reserves in electricity markets.

From a methodological point-of-view, both stochastic and robust approaches individually present strengths and weaknesses. If in one hand, stochastic optimization takes advantage of a full knowledge about the underlying process behind the uncertainty factors, on the other hand they may be computationally intractable. In addition, the very definition of an accurate probability distribution is usually a big challenge in several practical applications. In contrast, (adjustable) robust optimization is often computationally less expensive and does not require full information regarding the probability distribution. However, RO-based models typically provide over conservative solutions.

In this paper, we aim to address the problem of scheduling energy and reserves so that the system is able to comply with a predefined security criterion while circumventing the difficulties associated with modeling renewable energy sources. To do so, we combine the features of stochastic and adjustable robust optimization to propose an unified methodology. This unified methodology is capable to comprise the uncertainty related to Renewable Energy Sources (RES) while considering deterministic security criterion to protect the system against outages of generators and/or transmission lines. Due to its close relation to physical variables, RES variability is addressed within a scenario-based approach, as customary in stochastic programming. Nevertheless, we recognize that the probabilistic behavior of equipment failures is difficult to characterize. Hence, we adapt the adjustable robust optimization technique to tackle outages of system elements. Within this context, along with a standard generation scheduling problem formulation, we impose risk constraints over the (uncertain) power imbalance to ensure demand-supply balance. In this work, we resort to a widely used α-percentile risk functional, the α-Conditional Value-at-Risk (CVaR_α) [28].

Structurally, the scheduling model derived in this paper is a (hierarchical) three-level system of optimization problems. To solve this multi-level problem, we exploit the fundamental properties of the CVaR_α risk measure and combine an outer-approximation technique with a column-and-constraint generation approach to derive a solution methodology with ε-global convergence guarantee.

A critical point regarding practical implementation of the proposed energy and reserve scheduling methodology is related to how the RES output state is inferred. The standard stochastic