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Network-constrained unit commitment under significant wind penetration: A multistage robust approach with non-fixed recourse

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HIGHLIGHTS

- We examine the network-constrained unit commitment problem under wind uncertainty.
- A robust model considering the effect of dispatch nonanticipativity is proposed.
- Unlike existing approaches, the recourse model is non-scenario-based and non-fixed.
- Full immunization for significantly larger wind power penetration levels is provided.
- Optimality is attained in acceptable running times for a practical day-ahead setting.

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ABSTRACT

Generation scheduling in future smart grids will face significant uncertainty due to their considerable reliance on intermittent renewable-based generation such as wind power. Adaptive robust optimization provides a suitable framework to handle wind-related uncertainty in generation scheduling. However, available robust models feature relevant practical limitations including 1) the potential lack of physical implementability stemming from disregarding the nonanticipativity of the dispatch process, 2) the potential suboptimality or even infeasibility due to the use of fixed-recourse schemes, and 3) the intractable computational burden associated with a scenario-based counterpart. This paper presents a new multistage robust unit commitment approach with non-fixed recourse relying on the formulation of an alternative two-stage robust model. As a result, the least-cost generation schedule ensuring dispatch nonanticipativity is attained by solving a trilevel program of similar complexity as compared with available formulations neglecting this aspect. Moreover, an enhanced column-and-constraint generation algorithm is devised whereby lexicographic optimization is applied to accelerate the finite convergence to optimality. Numerical simulations including a practical out-of-sample validation procedure reveal that the proposed approach is 1) computationally effective even for a benchmark that is well beyond the capability of a recently published method, and 2) superior in terms of solution quality over existing two-stage robust models disregarding dispatch nonanticipativity.

1. Introduction

The unit commitment problem [1] plays a key role in the operation of current power systems. Using a day-ahead time span, system operators routinely solve this optimization problem to optimally schedule generation resources while complying with operational limits. Manifold works relying on the formulation of a unit commitment problem can be found in the literature such as [2], where consumer payment minimization was analyzed, [3], focused on the consideration of distributed power systems, [4], dealing with the incorporation of demand response, and [5], which addressed the impact of modeling inflexibilities.

Due to the growing reliance on significant penetration levels of intermittent renewable-based generation, in particular of wind energy, system operators face unprecedented uncertainty that is seriously challenging to cope with. As a consequence, the consideration of uncertainty in the unit commitment problem has been extensively examined [6]. The practical tradeoff between accuracy and tractability featured by adaptive robust optimization [7] has led researchers to

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recently place the focus on this framework. A comprehensive literature review on robust unit commitment can be found in [8]. Among others, relevant works are [9–24].

Pioneering research efforts [9,10] first modeled the reaction against uncertainty realizations by a trilevel program. In [9], the consideration of pumped-hydro storage units gave rise to a discrete lower optimization level. In [10], non-discrete corrective actions were accounted for. The set of uncertainty sources was extended in [11] to include demand response. Zhao and Guan [12] examined a multiobjective approach combining adaptive robust optimization and stochastic programming. Uncertainty correlation was first considered in [13]. Lorca et al. [14] raised awareness of the importance of considering dispatch nonanticipativity and suggested the use of affinely adjustable robust optimization, wherein recourse actions are fixed. In [15], a fixed-recourse scheme was also adopted to handle various generation resources including fast-acting generating units. The nonconvexity associated with the operation of such devices was addressed in [16] under a non-fixed-recourse framework. In [17], the impact of various optimization goals was examined whereas the effect of a bounding constraint on the recourse cost was analyzed in [18]. An alternative approach based on mixed-integer linear programming was described in [19] to effectively model the second-stage problem. In [20], the fixed-recourse scheme developed in [14] was extended to incorporate storage. Zhai et al. addressed the issue of dispatch nonanticipativity under a non-fixed-recourse framework [21]. In [22], a practical model was presented wherein new flexibility-related products were considered. In [23], the deliverability of reserve offers was examined while jointly considering system component outages and wind uncertainty. Recently, in [24], a robust model was presented to precisely account for bulk storage devices in the day-ahead operation of a co-optimized electricity market.

Under the worst-case setting featured by existing robust works [9–24], the day-ahead generation schedule is determined in the first stage, i.e., before the observation of the uncertain parameters within a pre-specified uncertainty set, whereas dispatch decisions are made in reaction to the corresponding worst-case materialization of uncertainty. In industry practice, sequential power system operation is implemented following the hourly unfolding of uncertainty. In other words, the generation dispatch at a given hour solely depends on the information on realized uncertain parameters that is available up to that hour. Thus, the decision-making process characterizing generation dispatch is multistage, which calls for multistage robust optimization approaches considering the nonanticipativity of dispatch decisions [25]. Unfortunately, multistage robust generation scheduling remains intractable in general [14,21].

As a consequence, most existing robust models [9–13,16–19,23,24] are instances of two-stage robust optimization neglecting the aforementioned nonanticipativity. Such relaxed versions of the actual multistage problem provide a lower bound on the true optimal cost. Moreover, first-stage decisions may be optimistically biased regarding the system capability to comply with inter-temporal constraints [14,21]. Hence, insufficient ramping capability may arise if uncertainty realizations, even though lying within the pre-specified uncertainty set, do not materialize as anticipated. Thus, the resulting solutions may not be implementable in practice. In other words, despite accounting for all possible vectors of uncertainty realizations within the uncertainty set, the robustness of most available two-stage robust models for multi-period generation scheduling [9–13,16–19,23,24] is questionable since dispatch nonanticipativity is disregarded. The significance of this information-related inconsistency is particularly stressed in the current context where recent issues involving wind power ramp events [26] reveal the need for multistage generation scheduling approaches accounting for dispatch nonanticipativity. The multistage robust models presented in [14,15,20–22] are relevant examples albeit featuring practical limitations.

In [14,15,20,22], an approximate fixed-recourse framework is adopted for the sake of tractability. In those works, dispatch nonanticipativity is explicitly enforced in the recourse problem by approximating generation dispatch decisions through affine functions of uncertain parameters. Such models thus provide an upper bound for the true optimal cost and may even lead to infeasibility [25]. The non-fixed-recourse framework recently proposed in [21] is a relevant alternative to multistage robust models with fixed recourse. However, such an approach relies on a scenario-based robust counterpart wherein the operation of the system is explicitly modeled for every scenario representing a vertex of the polyhedron characterizing the uncertainty set. Thus, scalability issues are featured as the dimension of the resulting model exponentially grows with the number of uncertainty sources. This shortcoming is evidenced by the impractical computing times reported in [21] for the IEEE 118-bus system with as few as 3 wind farms. Moreover, the nonanticipativity of the dispatch process involving start ups and shut downs is neglected.

In this paper, we address the multistage robust unit commitment with non-fixed recourse under significant penetration levels of wind power generation. This work is built on [24], where the nonanticipativity of the time-coupled operation of bulk storage devices was precisely accounted for under a robust framework with non-fixed recourse. Here, we propose extending the application scope of the storage-related findings of [24]. Thus, a different operational aspect is addressed, namely the ramping-related effect of the nonanticipativity of the dispatch of generating units. To that end, we depart from the conventional approach relying on the incorporation of computationally expensive dispatch nonanticipativity constraints in the form of time-dependent uncertainty sets [14]. Rather, we propose attaining the optimal generation schedule by solving an alternative two-stage robust counterpart with non-fixed recourse wherein enough room for dispatch adjustment is provided between consecutive periods. As a result, the scalability and modeling issues of [21] are overcome without resorting to the approximations characterizing [9–20,22–24]. In contrast to [21], the system operation is implicitly modeled under all uncertainty realizations within the pre-specified uncertainty set. Thus, as compared with [21], a larger and more practical number of wind farms can be handled within acceptable time frames. Moreover, in the proposed counterpart, inter-period ramping limitations, including those considered in [21] as well as start-up and shut-down ramp rates, are met for all plausible pairs of consecutive generation levels observing dispatch nonanticipativity. In addition, unlike [9–20,22–24], the consideration of dispatch nonanticipativity under a non-fixed-recourse scheme guarantees least-cost immunization against all possible uncertainty realizations within the prescribed uncertainty set.

A summary of the above distinctive modeling features is provided in Table 1, where "✓" and "–" respectively indicate whether a particular

Table 1
Proposed approach versus the related literature.

Approach	Nonanticipativity	Non-fixed recourse	Non-scenario-based
[9]	–	✓	✓
[10]	–	✓	✓
[11]	–	✓	✓
[12]	–	✓	✓
[13]	–	✓	✓
[14]	✓	–	✓
[15]	✓	–	✓
[16]	–	✓	✓
[17]	–	✓	✓
[18]	–	✓	✓
[19]	–	✓	✓
[20]	✓	–	✓
[21]	✓	✓	–
[22]	✓	–	✓
[23]	–	✓	✓
[24]	–	✓	✓
Proposed approach	✓	✓	✓