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Decision Support

Two-stage network constrained robust unit commitment problem ☆

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ABSTRACT

For a current deregulated power system, a large amount of operating reserve is often required to maintain the reliability of the power system using traditional approaches. In this paper, we propose a two-stage robust optimization model to address the network constrained unit commitment problem under uncertainty. In our approach, uncertain problem parameters are assumed to be within a given uncertainty set. We study cases with and without transmission capacity and ramp-rate limits (The latter case was described in Zhang and Guan (2009), for which the analysis part is included in Section 3 in this paper). We also analyze solution schemes to solve each problem that include an exact solution approach and an efficient heuristic approach that provides tight lower and upper bounds for the general network constrained robust unit commitment problem. The final computational experiments on an IEEE 118-bus system verify the effectiveness of our approaches, as compared to the nominal model without considering the uncertainty.

1. Introduction

For a current deregulated power system, the demands on a power system are highly uncertain (e.g., see Mazer, 2007) due to weather, demand response program, and other conditions. This brings great challenges in grid management and generation scheduling to power system operators. To address this uncertainty, most electric power markets in US execute reliability unit commitment runs after the closure of the day-ahead market, and ensure enough generation capacity for the next operating day (e.g., see Whittle et al., 2006). Stochastic programming approaches have been shown efficient to solve unit commitment problems under uncertainty. For instance, a multistage stochastic programming formulation and Lagrangian solution techniques were developed early in Takriti and Birge (2000). This approach was further studied considering incorporating fuel constraints and electricity spot prices (Takriti et al., 2000). Other relevant Lagrangian decomposition literature includes (Carpentier et al., 1996; Dentcheva and Römisch, 1997; Gollmer et al., 2000). Recently, the stochastic programming approach for unit commitment was applied to solve hydro-electric unit commitment subject to uncertain demand (Philpott et al., 2000), to generate supply curves in electric power markets (Philpott and Schultz, 2006), to serve as a decision aid for scheduling and hedging in the wholesale electric power markets (Sen et al., 2006), to help a power generation company take part in an electricity spot market (Cerisola et al., 2009), to help provide self-commitment of one generating unit under the deregulated market (Valenzuela and Mazumdar, 2003), and to estimate the potential contribution of demand flexibility in replacing operating reserves (Papavasiliou and Oren, 2010). Other recent related unit commitment studies include developing a real options approach to address short-term generation asset valuation (Tseng and Barz, 2002), evaluating the value of rolling-horizon policies for risk-averse hydro-thermal planning (Guigues and Sagastizábal, 2012), deriving an optimal scheduling policy for a hydro thermal power generation system (Oliveira et al., 1993), studying efficient algorithms for combined heat and power systems under the deregulated electricity market (Rong and Lahdelma, 2007; Rong et al., 2008), and deriving a floating-point genetic algorithm to solve the unit commitment problem (Dang and Li, 2007).

Besides the traditional two-stage and multi-stage stochastic programming approaches with the objective of minimizing the total expected cost, risk averse objectives, such as Conditional Value-at-Risk (CVaR) (Jabr, 2005), and chance constraints (Wang et al., 2012) are also introduced in power industry to control risk and ensure the feasibility. To solve the stochastic optimization problems, scenarios are usually generated based on the forecasted demand distributions. This usually leads to a large scale deterministic equivalent formulation and accordingly decomposition algorithms are developed to achieve tractable computation (Papavasiliou and Oren, 2010; Takriti and Birge, 2000). In this

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research, we emphasize risk rather than cost, because reliability has very high priority for system operators, which is also the reason to introduce reliability unit commitment runs. Thus, we propose a two-stage robust optimization approach (Ben-Tal and Nemirovski, 1998; El Ghaoui and Lebret, 1997; Bertsimas and Sim, 2003) to address uncertainty. Instead of providing a detailed description of the probability distributions, the uncertain parameters are assumed to be within a polyhedral uncertainty set (cf. Bertsimas and Sim, 2003; Bienstock and Özbay, 2008; Yao et al., 2009). Our proposed robust optimization approach can serve as a complement of the stochastic programming approaches, as well as the current reliability unit commitment run practice.

In our approach, we provide unit commitment decisions in the first stage with the objective of minimizing the system-wide power generation costs including the unit commitment cost and dispatch cost under the worst-case scenarios. Our initial study on the two-stage robust unit commitment problem is described in Zhang and Guan (2009), for which the analysis part is included in Section 3 in this paper. Besides, for the single-stage robust optimization approach, the readers are referred to the initial studies on solving the contingency-constrained unit commitment with n–K security criterion described in Street et al. (2011) and on solving the optimal bidding strategy problem described in Baringo and Conejo (2011). Related two-stage robust optimization approaches include (Zhao and Zeng, 2012; Bertsimas et al., 2013; Jiang et al., 2012). In Zhao and Zeng (2012), a two-stage robust optimization model with one-dimensional demand uncertainty set (along time horizon) is proposed to solve an aggregated model without considering transmission constraints. In Bertsimas et al. (2013), a two-stage robust optimization model also with one-dimensional demand uncertainty set (along different buses for a given time unit) is introduced, and a heuristic separation approach is studied to test a real instance. In Jiang et al. (2012), a special case of this work is studied, in which a different one-dimensional cardinality uncertainty set is provided and a heuristic approach is developed to solve the problem with the consideration of pumped storage hydro. Besides the initial study for the two-stage robust unit commitment problem, as compared to the related two-stage robust optimization approaches (i.e., Zhao and Zeng, 2012; Bertsimas et al., 2013; Jiang et al., 2012), our additional contributions can be summarized as follows:

- We introduce a two-dimensional uncertainty set to describe the uncertain problem parameters. That is, we allow the uncertainty correlations among different buses and among different time periods, as compared to the one-dimensional uncertainty sets studied in related works.
- We develop an exact and a bilinear heuristic separation approaches to solve the robust unit commitment problem. Our bilinear separation approach can generate tight lower and upper bounds for the optimal objective value, and is computationally efficient as demonstrated in the computational experiments on an IEEE 118-bus system.
- We analyze the insights of the problem by studying a simplified version of the problem. The properties of the objective value functions are analyzed. In addition, the separation problem is shown NP-hard, which indicates the problem is hard to solve in general. Meanwhile, our computational results show that this simplified model provides a very tight lower bound for the problem.
- We introduce a Benders' decomposition framework that includes both feasibility and optimality cuts. The feasibility cuts in the Benders' decomposition framework help address important feasibility issues for the real-time market. Our computational results indicate that the proposed approach will generate significant cost savings, under the worst-case scenarios, as compared to the traditional nominal model.

The remaining part of this paper is organized as follows. Section 2 describes the mathematical formulation for the general network constrained robust unit commitment problem. In addition, we show that the spinning reserve constraints are not necessary for the robust optimization model. Section 3 develops a solution approach and explores insights for a simplified version of the network constrained robust unit commitment problem. In Section 4, we explore the solution schemes to solve the general network constrained robust unit commitment problem. Section 5 reports the extensive computational results. Finally, Section 6 concludes our study.

2. Notation and mathematical formulation

For a T-period network constrained unit commitment problem, we let $\mathbb{E} = \{1, 2, \ldots, M\}$ and $\mathbb{N} = \{1, n, \ldots, N\}$ represent the sets of buses and generators, and $\mathbb{A}$ represent the set of transmission lines linking two buses. For each bus $m \in \mathbb{E}$, we let $\mathbb{N}_m$ be the set of generators in this bus. Accordingly, for each generator $i \in \mathbb{N}_m$, we let $S_i^m(W_i^m)$ represent the start-up (shut-down) cost, $G_i^m(H_i^m)$ represent the minimum-up (minimum-down) time, $L_i^m(U_i^m)$ represent the minimum (maximum) output of electricity if the generator is on, $V_i^m(B_i^m)$ represent the ramp-up (ramp-down) rate limit, and $\overline{V}_i^m(\overline{B}_i^m)$ represent the start-up (shut-down) ramp rate limit. For each transmission line $(i,j) \in \mathbb{A}$, we let C_{ij} represent the capacity of the transmission line, and K_{ij}^m represent the line flow distribution factor for the transmission line, due to the net injection at bus m, $\forall m \in \mathbb{E}$. To describe the uncertainty set, we let $\overline{D}_{mt}, D_{mt}^{\ell}$, and D_{mt}^{u} represent the nominal demand, the lower and upper bounds of the demand at bus m in time period t. In addtion, we let $D_{mt}^{r} := D_{mt}^{u} - D_{mt}^{\ell}$.

For our two-stage network constrained robust unit commitment problem, in the first stage we provide the unit commitment decisions $(y_{it}^m, u_{it}^m, v_{it}^m)$ for each generator that include: 1) if generator i at bus m is on or not in time period t (i.e., $y_{it}^m = 1$ if yes; $y_{it}^m = 0$ o.w.), 2) if generator i at bus m is started up or not in time period t (i.e., $u_{it}^m = 1$ if yes; $u_{it}^m = 0$ o.w.), and 3) if generator i at bus m is shut down or not in time period t (i.e., $v_{it}^m = 1$ if yes; $v_{it}^m = 0$ o.w.). In the second stage, we let random parameter d_{mt} represent the demand at bus m in time period t, and decision variable x_{it}^m represent the amount of electricity generated by generator i at bus m in time period t. In addition, we approximate the non-decreasing convex fuel cost $f_{it}^m(x_{it}^m) = c_{it}^m (x_{it}^m)^2 + b_{it}^m x_{it}^m + a_{it}^m$ by a P-piece piecewise linear function $f_{it}^m(x_{it}^m) \geqslant \alpha_{it}^{mp} y_{it}^m + \beta_{it}^{mp} x_{it}^m$, $\forall m \in \mathbb{E}, \forall i \in \mathbb{N}_m, 1 \leqslant p \leqslant P$. Then the two-stage network constrained robust unit commitment problem can be described as follows:

$$z^{\mathrm{R}} = \min_{y,u,v} \quad \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i \in \mathbb{N}_m} (S_i^m u_{it}^m + W_i^m v_{it}^m) + \max_{d \in \mathcal{D}} \min_{(x,\vartheta) \in \mathcal{X}(y,d)} \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{i \in \mathbb{N}_m} \vartheta_{it}^m$$

$$\text{s.t.} \quad -y_{i(t-1)}^m + y_{it}^m - y_{ik}^m \leqslant 0, 1 \leqslant k - (t-1) \leqslant G_i^m, \ \forall m \in \mathbb{E}, \ \forall i \in \mathbb{N}_m, \ \forall t \in \mathcal{T} \quad (1)$$

$$y_{i(t-1)}^m - y_{it}^m + y_{ik}^m \leqslant 1, 1 \leqslant k - (t-1) \leqslant H_i^m, \ \forall m \in \mathbb{E}, \ \forall i \in \mathbb{N}_m, \ \forall t \in \mathcal{T} \quad (2)$$

$$(\mathrm{NC-RUC}) \quad -y_{i(t-1)}^m + y_{it}^m - u_{it}^m \leqslant 0, \ \forall m \in \mathbb{E}, \ \forall i \in \mathbb{N}_m, \ \forall t \in \mathcal{T} \quad (3)$$

$$y_{i(t-1)}^m - y_{it}^m - v_{it}^m \leqslant 0, \ \forall m \in \mathbb{E}, \ \forall i \in \mathbb{N}_m, \ \forall t \in \mathcal{T} \quad (4)$$

$$\sum_{m=1}^{M} \sum_{i \in \mathbb{N}_m} U_i^m y_{it}^m \geqslant (1 + R\%) \sum_{m=1}^{M} \overline{D}_{mt}, \quad \forall t \in \mathcal{T} \quad (5)$$

$$y_{it}^m, u_{it}^m, v_{it}^m \in \{0, 1\}, \ \forall m \in \mathbb{E}, \ \forall i \in \mathbb{N}_m, \ \forall t \in \mathcal{T},$$