On the Robust Solution to SCUC With Load and Wind Uncertainty Correlations

Bingqian Hu, *Student Member, IEEE*, Lei Wu, *Senior Member, IEEE*, and Muhammad Marwali, *Senior Member, IEEE*

***Abstract*—With the increasing penetration of variable renewable generations, independent system operators (ISOs)/regional transmission organizations (RTOs) are faced with new challenges for the secure and economic operation of power systems. This paper proposes an effective approach for deriving robust solutions to the security-constrained unit commitment (SCUC) problem, which considers load and wind uncertainties via interval numbers. Different from most robust optimization-based SCUC approaches in literature which explore robust unit commitment (UC) solutions for immunizing against the worst economic scenario in terms of the highest minimum dispatch cost, the proposed robust SCUC model minimizes operation cost for the base case while guaranteeing that the robust UC and dispatch solutions could be adaptively and securely adjusted in response to uncertain intervals. Thus, the proposed model achieves smaller unit commitment costs while maintaining the solution robustness as compared with literature. In addition, the proposed model describes base case dispatches and corrective actions in uncertain intervals, which is more consistent with the current day-ahead and real-time markets. Furthermore, besides budget constraints used in literature, this paper also considers load and wind variability correlations in constructing uncertain intervals, which would eliminate unlike-to-happen scenarios and further limit the level of conservatism of the robust solution. The proposed robust SCUC model is solved by Benders decomposition, which decomposes the original problem into a master UC problem for the base case and subproblems for the base case network evaluation and the security checking for uncertain intervals. Feasibility cuts are generated and fed back to the master problem for further iterations when violations are identified in subproblems. Numerical case studies on the modified IEEE 118-bus system illustrate the effectiveness of the proposed robust SCUC model for the secure and economic operation of power systems under various uncertainties.**

***Index Terms*—Benders decomposition, interval number, load and wind correlation, robust security-constrained unit commitment (SCUC).**

NOMENCLATURE

Variables:

d, i, k, l	Indices of load demands, thermal units, and curve segments, and lines.
m, s, t, w	Indices of buses, samples, hours, and wind farms.
I_{it}^{b}	Commitment of unit i at time t in the base case.
P_{ikt}^{b}	Dispatch of unit i at time t at segment k in the base case.
P_{it}^{b}, P_{wt}^{b}	Dispatch of unit i/wind farm w at time t in the base case.
P_{it}^{u}, P_{wt}^{u}	Adaptive dispatch adjustment of unit i/wind farm w at time t in response to uncertain intervals.
P_{dt}^{u}	Uncertain load demand of load d at time t.
$P_{f,wt}^{u}$	Uncertain wind generation of wind farm w at time t.
SU_{it}^{b}, SD_{it}^{b}	Startup/ shutdown cost of unit i at time t.
v	Slack variable.
$X_{\text{on},it}, X_{\text{off},it}$	ON/OFF time counter of unit i at time t.
λ, μ, η	Dual variables.

Constants:

a_{wdt}, b_{wdt}	Parameters to represent the correlation of wind farm w and load d at time t.
c_{ik}	Incremental cost of segment k of unit i.
$m(i)$	Index of the bus where unit i is located.
$m(w)$	Index of the bus where wind farm w is located.
N_{i}	No-load cost of unit i.
NI, NW	Number of thermal units/wind farms.
NS, NT	Number of samples/hours.
P_{dt}^{b}	Forecast value of load d at time t.
$\tilde{P}_{dt}$	Load deviation of load d from the forecast value at time t.
$\overline{P}_{dt}$	Average value of historical load samples for load d at time t.
$P_{dt,s}$	sth historical load sample of load d at time t.
$P_{f,wt}^{b}$	Wind energy forecast for wind farm w at time t.

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B. Hu and L. Wu are with the Electrical and Computer Engineering Department, Clarkson University, Potsdam, NY 13699 USA. (e-mail: hub@clarkson.edu; lwu@clarkson.edu).

M. Marwali is with New York Independent System Operator, Rensselaer, NY 13699 USA. (e-mail: MMarwali@nyiso.com).

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$\tilde{P}_{wt}$	Wind energy generation deviation of wind farm w from the forecast value at time t.
$\overline{P}_{wt}$	Average value of historical wind generation samples of wind farm w at time t.
$P_{wt,s}$	sth historical wind generation sample of wind farm w at time t
$P_i^{\min}, P_i^{\max}$	Minimum/maximum capacity of unit i.
$P_{ik}^{\max}$	Power capacity of segment k of unit i.
$PL_l^{\max}$	Upper limit for power flow of line l.
$R_i^{\mathrm{up}}, R_i^{\mathrm{down}}$	Up/down corrective action limit of unit i.
$SF_{l,m}$	Shift factor of line l and bus m.
su_i, sd_i	Startup/ shutdown cost of unit i.
$t_{NS-1}^{0.975}$	t-distribution with degrees of freedom $NS-1$ and 95% confidence level.
$T_{\mathrm{on},i}, T_{\mathrm{off},i}$	Minimum ON/OFF time limit of unit i.
UR_i, DR_i	Ramp up/down rate limit of unit i.
σ_{wdt}	Variance of the deviation of historical wind and load data from the approximated linear correlation representation.
Δ_d, Δ_w	Budget level of system load/wind energy generation uncertainty.

Sets:

$\mathbf{D}(m)$	Set of load demands located at bus m.
$\mathbf{U}(m)$	Set of thermal units located at bus m.
$\mathbf{W}(m)$	Set of wind farms located at bus m.

I. INTRODUCTION

As environmental impacts of the electricity section become more significant, renewable generations such as wind and solar are rapidly deployed, which are plentiful, environmentally friendly, and widely distributed. However, they introduce multiple uncertain factors and, in turn, bring new challenges for managing the operational security of power systems.

Two distinct solution approaches have been studied in literature for addressing the impacts of uncertainties on the operational security of power systems: the scenario-based approach and the interval-based approach. The works in [1] and [2] are among the first that apply the scenario-based approach and the interval-based approach to unit commitment (UC) problems with the consideration of various uncertainties. The scenario-based approach generates scenarios via presumed probability distribution functions for simulating uncertainties. Scenario generation methods include Monte Carlo (MC) sampling, moment matching principles, and methods motivated by stability analysis [3]. The work in [4] presented a scenario-based security-constrained unit commitment (SCUC) model which considered intermittency and volatility of wind generations. The work in [5] studied the impacts of random generator outages and load forecast errors on SCUC via scenario trees. The authors of [6] used the N-K contingency criterion to study the impacts of random generator outages on power system security while assuming that load forecast errors follow normal distributions. The scenario-based approach acknowledges given probability distributions, and it is usually difficult to justify if they could truly represent actual uncertainty factors. In addition, a large number of scenarios are needed for achieving an acceptable solution accuracy, which increases the scale of the models, expand the computational burden, and in turn limits the application to large-scale power systems.

The second model for addressing the impacts of uncertainties is the interval-based approach. Rather than sampling scenarios, the interval optimization uses uncertain intervals in terms of upper and lower bounds for representing uncertainties of certain parameters, and finds the best and the worst optimum solutions for satisfying system security requirements. The work in [7] used a boundary analysis for reliability and economic assessment of power distribution systems. The authors of [8] proposed an interval based UC model for accommodating volatile nodal injections, such as wind power, electric vehicles, and demand response loads. The work in [9] compared applications of scenario-based and interval-based approaches to SCUC. The interval-based approach does not require presumed probability distributions. However, uncertain intervals need to be carefully designed. A narrow uncertain interval may not cover the entire uncertainty spectrum and result in SCUC solutions that may not correspond to all uncertain situations. On the other hand, wide intervals may lead to pessimistic solutions that would not dispatch system resources efficiently. Uncertain intervals of load and wind can be derived by load and wind interval predictions [10], [11].

Recently, the robust approach has received significant attention. The robust optimization seeks for commitment and dispatch of generation resources for immunizing against all possible uncertain situations. The authors of [12] proposed a two-stage adaptive robust SCUC model in which the first-stage determines the robust UC solution with respect to all possible net injections and the second-stage handles the worst case dispatch. [13] applied the robust UC model to the wind and pumped-storage coordination for handling wind generation uncertainties. [14] studied the robust UC model for handling uncertainties of wind energy and demand response. [15] extended the two-stage robust formulation to a multistage model for handling uncertainties of wind energy and demand response. In [16] and [17], the authors proposed a unified stochastic/robust optimization UC model, which combines the features of both stochastic optimization and robust optimization approaches for addressing various uncertainties. The model in [16] and [17] is designed to minimize the commitment cost plus the weighted expected generation cost and worst case violation cost.

Most robust optimization-based SCUC models in literature explore robust UC solutions for immunizing against the worst economic situation in terms of the highest minimum dispatch cost, while neglecting the base case robust dispatch solution and corrective actions of generators in response to uncertainties. Based on the “Standard BAL-002-0” of the New