An Assessment of the Impact of Stochastic Day-Ahead SCUC on Economic and Reliability Metrics at Multiple Timescales

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An Assessment of the Impact of Stochastic Day-Ahead SCUC on Economic and Reliability Metrics at Multiple Timescales

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***Abstract*—This paper incorporates the stochastic day-ahead security-constrained unit commitment (DASCUC) within a multi-timescale, multi-scheduling application with commitment, dispatch, and automatic generation control. The stochastic DASCUC is solved using a progressive hedging algorithm with constrained ordinal optimization to accelerate the individual scenario solution. Sensitivity studies are performed in the RTS-96 system, and the results show how this new scheduling application would impact costs and reliability with a closer representation of timescales of system operations in practice.**

***Index Terms*—Area control error, multiple timescales, stochastic optimization, progressive hedging, security-constrained unit commitment.**

Parameters:

N_T	Number of time periods
N_I	Number of generating units
N_S	Number of scenarios
N_G	Number of segments in production cost curve
t	Index for time periods, $t = 1, 2, \cdots, N_T$
i	Index for generating units, $i = 1, 2, \cdots, N_I$
s	Index for scenarios $s = 1, 2, \cdots, N_S$
d	Index for cost curve segments $d = 1, 2, \cdots, N_G$
NQ	Set of non-quick-start generating units
Pr^s	Probability of scenario s
NL_i	No-load cost of thermal unit i, in \$/h
$c_{d,i}$	Incremental cost of generating unit i at segment d, in \$/MWh

Variables:

$I_{i,t}^s$	State of generating unit i at time t in scenario s; 1 for ON and 0 for OFF
$p_{d,i,t}^s$	Dispatch of generating unit i at segment d at time t in scenario s, in MWh
$SU_{i,t}^s$	Startup cost of generating unit i at time t, in \$
$C_{i,t}$	Implementable state of generating unit i at time t
$\lambda_{i,t}^s$	Multipliers for generating unit i at time t in scenario s
w^s	Penalty factor in scenario s

I. Introduction

Variable generation (VG), especially wind and photovoltaic solar generation, represent important components of the future energy portfolio. In the United States, wind energy has the potential to provide 20% of the U.S. energy production portfolio by 2030 [1]. The introduction of greater amounts of VG and the increase in distributed resources and demand participation are increasing the system uncertainty and leading to various challenges for bulk power system operations [2]-[4].

Power system operators and planners have recently made considerable efforts to address the impacts of uncertainties on the solution of security-constrained unit commitment (SCUC). A common solution method presented in the literature is the scenario-based method, in which multiple scenarios are modeled to represent the possible realization of uncertainties [5]. The solution of stochastic unit commitment (UC) with a high penetration of wind was examined under rolling planning with scenario trees [6]. A multi-scenario long-term SCUC model for calculating the cost of power system reliability is proposed in [7] in which the loss of load expectation is considered as a constraint for calculating the cost of supplying system reserves. A chance-constrained stochastic UC problem is solved by a sample average approximation algorithm in which a large portion of the hourly wind energy is guaranteed to be utilized [8]. A UC model is presented for balancing the required spinning reserves with a high penetration level of wind energy in [9]. In general, the scenario-based approach is capable of dealing with the uncertainties that are inherent in SCUC, but it may result in an intractable optimization problem with exponentially expanding size [10], [11].

Each of the models discussed above use various methods to show the improvements of scenario-based methods on decreasing costs, to improve reliability compared to traditional scheduling methods, or to show improvements in computational speed from previous algorithms. Generally, these models focus on hourly resolution: stochastic UC in the day-ahead, with hourly dispatch correction in real time. Although hourly loss of load can be an output of these models, it is rare and highly dependent on the model parameters (e.g., value of loss load input). This paper will evaluate the impacts of stochastic day-ahead SCUC (DASCUC) with the subsequent real-time commitments and dispatch occurring at finer timescales to better represent the full scheduling procedures typically utilized at independent system operators (ISOs) and regional transmission organizations (RTOs). In the short term, area control error (ACE) occurs when there is an imbalance within a balancing area. This can result in interchange scheduling error and/or frequency error. Significant ACE or frequency deviations can lead to potential reliability events, such as triggering underfrequency load shedding. Also, significant deviations may lead not to actual reliability events but to higher costs because of relying on expensive resources to correct the imbalances at very short timescales. In this paper, we incorporate the stochastic DASCUC within a multi-timescale, multi-scheduling application with commitment, dispatch, and automatic generation control (AGC) to better understand how this new scheduling application may impact costs and ACE at detailed timescales that represent those of the current state-of-the-art ISO operations. We also perform sensitivity studies to show why including the full multi-timescale scheduling representation may be important when looking at how these new modeling applications can influence the results.

The rest of the paper is organized as follows. The proposed stochastic DASCUC model is discussed in Section II. Numerical results are presented and analyzed in Section III. Conclusions are drawn in Section IV.

II. Model Description

A. Stochastic DASCUC Formulation

The two-stage stochastic SCUC, expressed in (1), is formulated as a mixed-integer linear programming (MILP) problem. The objective function includes the costs of the first-stage unit commitment (here-and-now decisions) and second-stage hourly schedules for generating resources (wait-and-see decisions) to minimize the expected production cost across all scenarios.

$$\begin{aligned}
&\min \sum_{s=1}^{N_S} \Pr^s \sum_{t=1}^{N_T}\sum_{i=1}^{N_I}(NL_i \cdot I_{i,t}^s + SU_{i,t}^s + \sum_{d=1}^{N_G} c_{d,i}\cdot p_{d,i,t}^s)\\
&s.t.\\
&(1)\text{ Prevailing SCUC constraints w.r.t individual scenario}\\
&(2) Non-anticipativity: I_{i,t}^s = I_{i,t}^{s'} = C_{i,t} = \sum_{s=1}^{NS}\Pr^s\cdot \hat{I}_{i,t}^s,\\
&\qquad \forall i \in NQ, \forall t, \forall s, \forall s' \neq s
\end{aligned} \tag{1}$$

where the second constraint is the non-anticipativity constraint linking all scenarios; $C_{i,t}$ is the implementable state of generator *i* at time *t*, which indicates the unit commitment for all pair of Scenarios *s* and *s'* that are indistinguishable up to time *t*. $C_{i,t}$ is obtained by averaging over all scenarios at a scenario tree node. The multiplier $\lambda_{i,t}^s$ and penalty factor w^s are introduced to relax and to penalize the non-anticipativity constraints. The objective in (1) is transformed into the following two-level optimization structure:

$$\begin{aligned}
L(\mathbf{P},\mathbf{I},\boldsymbol{\lambda},\mathbf{w}) &= \sum_{s=1}^{N_S}\Pr^s\sum_{t=1}^{N_T}\sum_{i=1}^{N_I}(NL_i\cdot I_{i,t}^s + SU_{i,t}^s + \sum_{d=1}^{N_G}c_{d,i}\cdot p_{d,i,t}^s)\\
&+\sum_{s=1}^{N_s}\sum_{t=1}^{N_T}\sum_{i=1}^{N_I}\lambda_{i,t}^s\cdot(C_{i,t}-I_{i,t}^s) + \sum_{s=1}^{N_s}\sum_{t=1}^{N_T}\sum_{i=1}^{N_I} w^s\cdot|C_{i,t}-I_{i,t}^s|
\end{aligned} \tag{2}$$

where $\mathbf{P}=[p_{i,t}^s]_{N_I\times N_T\times N_S}$, $\mathbf{I}=[I_{i,t}^s]_{N_I\times N_T\times N_S}$, $\boldsymbol{\lambda}=[\lambda_{i,t}^s]_{N_I\times N_T\times N_S}$, and $\mathbf{w}=[w^s]_{N_S}$. By using duality theory and the decomposable structure of (2), the two-level optimization structure is formed. Given a set of multipliers, the low-level optimization consists of individual scenario subproblems, which are defined as follows:

$$\begin{aligned}
&L_s(\mathbf{P}^{(s)},\mathbf{I}^{(s)},\boldsymbol{\lambda}^{(s)},\mathbf{w}^{(s)}) =\\
&\quad[\sum_{t=1}^{N_T}\sum_{i=1}^{N_I}\Pr^s\cdot(NL_i\cdot I_{i,t}^s + SU_{i,t}^s + \sum_{d=1}^{N_G}c_{d,i}\cdot p_{d,i,t}^s) - \sum_{t=1}^{N_T}\sum_{i=1}^{N_I}\lambda_{i,t}^s\cdot I_{i,t}^s]\\
&=\sum_{t=1}^{N_T}\sum_{i=1}^{N_I}[(\Pr^s\cdot NL_i - \lambda_{i,t}^s)\cdot I_{i,t}^s + w^s\,|C_{i,t}-I_{i,t}^s| + \Pr^s\cdot SU_{i,t}^s\\
&\quad + \Pr^s\cdot\sum_{d=1}^{N_G}c_{d,i}\cdot p_{d,i,t}^s]
\end{aligned} \tag{3}$$

Then the Lagrangian function (2) is translated into the following function:

$$L(\mathbf{P},\mathbf{I},\boldsymbol{\lambda},\mathbf{w}) = \sum_{s=1}^{N_S}L_s + \sum_{t=1}^{N_T}\sum_{i=1}^{N_I}C_{i,t}\sum_{s=1}^{N_S}\lambda_{i,t}^s \tag{4}$$

Finally, the dual problem at a high level is as follows:

$$\max_{\lambda,w}\ \Phi(\lambda,w)=\sum_{s=1}^{N_s}\sum_{t=1}^{N_T}\sum_{i=1}^{N_I}\lambda_{i,t}^{s}\cdot C_{i,t}+\sum_{s=1}^{NS}\min_{P^{(s)},I^{(s)}} L_i(\lambda,P^{(s)},I^{(s)}) \quad (5)$$

The low-level and high-level problems are solved iteratively until the iterative process converges. The formulation of a dual-objective function and the steps for obtaining the subgradients can be found in [12],[13]. Here, the progressive hedging algorithm (PHA) is applied to solve the stochastic DASCUC [11]. PHA is a scenario-based decomposition technique that has been shown to be an efficient way to solve the problem described in (1)-(5). Constrained ordinal optimization (COO) is utilized to accelerate the solution of individual scenario subproblems by offering "good enough" solutions as a "warm start" [8]. The "good enough" solutions are the top *n*-percentile solutions selected by applying an extremely fast but crude feasibility model. This gives a significantly reduced solution set as a starting point and speeds up the solution process.

B. *Modeling Framework of Flexible Energy Scheduling Tool for Integration of VG (FESTIV)*

To study the impact of the stochastic DASCUC model on power system operations at multiple timescales, we develop the stochastic DASCUC model that is then embedded in the FESTIV modeling framework, which represents all of the scheduling applications that are used in typical ISO/RTO system operations [14]. FESTIV is a steady-state power system operation simulation tool that integrates multiple scheduling sub-models across multiple time resolutions accounting for the inter-temporal coupling between sub-models. The FESTIV model consists of DASCUC, real-time SCUC (RTSCUC), real-time security-constrained economic dispatch (RTSCED), and AGC (see Fig. 1). Each of them has a user-configurable temporal resolution and optimization horizon. These models are integrated in a simulation environment with the flexibility to study the time-varying effects of variability and uncertainty of VG.

Major steps in the FESTIV framework, shown in Fig. 1, are described as follows:

Preprocessing: The input data that are needed for a FESTIV simulation are read. These data include system topology, generator and transmission line information, and time series of forecasted hourly load and renewable generation in each scenario. A Monte Carlo simulation (MCS) is used to generate the scenario time series based on a probabilistic distribution. A scenario reduction technique is then used to balance the modeling accuracy and the solution speed.

Stochastic DASCUC: The input data that are generated in preprocessing will be passed on to the stochastic DASCUC. The stochastic DASCUC is solved by PHA with COO to accelerate the individual scenario solution. The day-ahead UC obtained here is passed on to the next step after the PHA converges. The DASCUC is typically run at an hourly resolution for 24-hour to 48-hour horizons.

Deterministic RTSCUC: Taking the day-ahead UC as input, the RTSCUC respects the DA-UC but may commit or turn off quick-start units. The day-ahead UC along with the commitments of quick-start units are further passed on to the RTSCED. This model is typically run at 15-minute to hourly resolutions for 2-hour to 4-hour horizons.

Deterministic RTSCED: In RTSCED, the UC is fixed and the dispatch and reserve schedules of the generation resources are decision variables to be determined. These schedules are passed further to the AGC sub-model. The RTSCED sub-model is typically run at 5-minute to hourly resolutions for single solutions with up to 1-hour time horizons.

AGC/ACE calculation: AGC is the final scheduling tool to correct realized imbalance as the system approaches real time. The AGC will take the regulation schedules from the RTSCED and use those regulating units to correct the ACE. All other units are not given control signals and are essentially given schedules that linearly interpolate one RTSCED dispatch schedule to the next. The production costs and ACE are all calculated from the AGC sub-model. AGC is typically run every 2 seconds to 6 seconds.

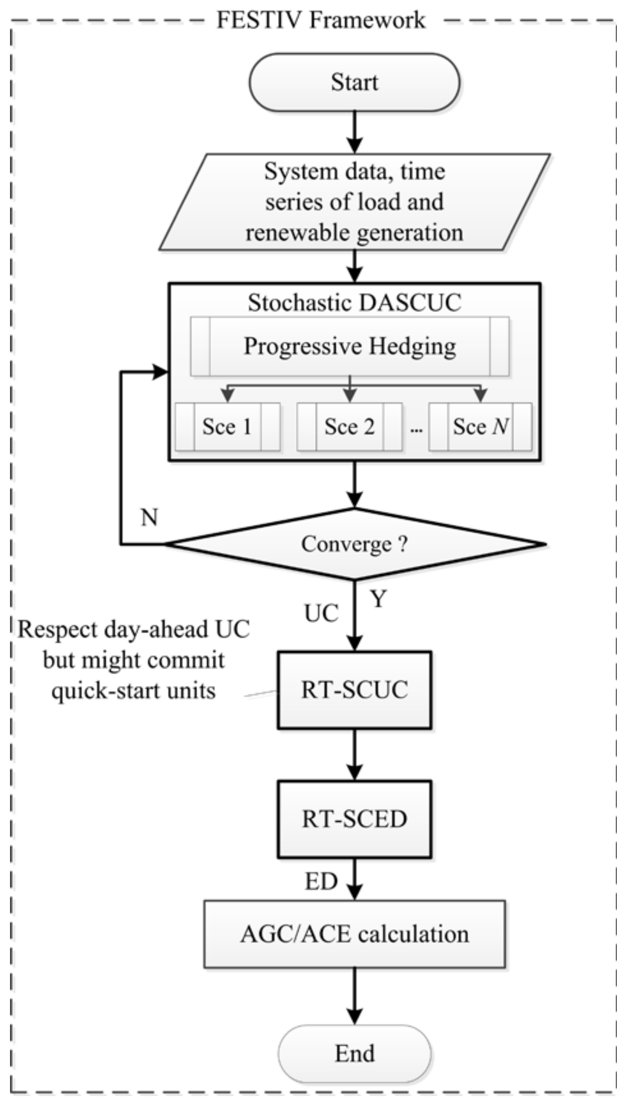

Fig. 1. Stochastic DASCUC in the multi-timescale scheduling framework

TABLE I. PRODUCTION COST AND RELIABILITY METRICS FOR SIMULATION CASES

	1 Day					1 Week		
	D-Perfect	**D-3%**	**S-3%**	**D-6%**	**S-6%**	**D-Perfect**	**D-3%**	**S-3%**
Prod. Cost ($)	292,660	302,196	292,746	302,026	311,033	2,118,254	2,148,085	2,124,554
AACEE (MWh)	82.3	103.6	101.7	230.1	167.1	465.0	716.5	542.2
Sigma ACE	8.7	10.5	10.4	29.2	17.2	9.0	13.8	11.2
CPS2 Violations	2	5	4	11	11	11	37	15
CPS2 score	98.6%	96.5%	97.2%	92.3%	92.3%	98.9%	96.3%	98.5%

III. NUMERICAL RESULTS

Numerical case studies are performed on the RTS-96 system [15]. The PHA and COO are implemented in MATLAB. The MILP formulation is modelled in the General Algebraic Modeling System (GAMS) [16] and solved using ILOG CPLEX 12.6 [17]. The uncertainty in the DA net load is considered in the case studies. The net load is determined as the total load minus the total VG. To illustrate the impact of stochastic DASCUC on economic and reliability metrics at multiple timescales, the following cases are investigated, in which the DASCUC is run at an hourly resolution for 24 hours (once a day):

D-Perfect: Deterministic DASCUC with perfect DA load forecast, which is calculated by averaging the 4-second actual load.

D-3% and D-6%: Deterministic DASCUC with imperfect DA load forecast. Here, the load forecast errors are assumed to follow truncated normal distributions, where 3% and 6% represent the corresponding standard deviation (STD) and are equal to 3% and 6% of the mean. Auto-regressive moving average (ARMA) is used to sample one time series of load profile for each STD case.

S-3% and S-6%: 20 equally weighted scenarios are generated by ARMA, in which the mean is equal to the one in its deterministic counterpart and the percentage is the STD.

The RTSCUC and the RTSCED, as shown in Fig. 1, are both deterministic in the above cases. The RTSCUC is run at a 15-minute resolution with a 3-hour horizon, and the RTSCED is run at a 5-minute resolution with an hourly horizon.

Table I shows the simulated production cost and reliability metrics for each case, where the ACE represents the energy imbalance that is calculated every 4 seconds—i.e., at the AGC time resolution; AACEE represents the absolute ACE in energy, the sum of the absolute value of the ACE in MWh [12]; sigma ACE represents the standard deviation of the ACE; a CPS2 violation takes place when the average ACE exceeds the ACE limit (L10) in a 10-min compliance interval.

In Table I, D-Perfect is featured with the lowest production cost and the best reliability performance among D-Perfect, D-3%, and S-3%. It is expected that the perfect forecast would lead to the optimal production cost and highest level of reliability, because a scenario with perfect knowledge will find the optimal solution. It is interesting to compare the production cost of the deterministic case to that of the stochastic case. In the daily simulation, the production cost in S-3% is $292,746, which is lower than $302,196 in D-3%. In this case, the stochastic DASCUC performs better than the deterministic DASCUC in both reducing costs and improving reliability.

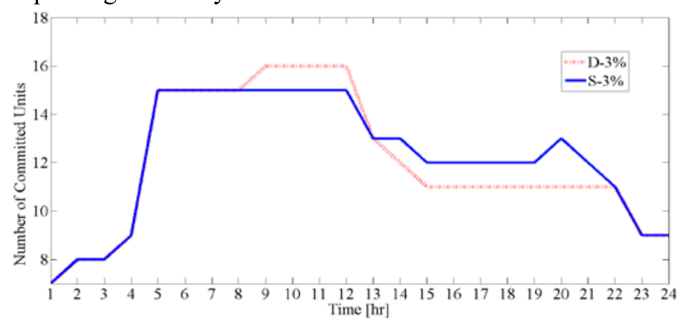

Fig. 2. Number of committed units in D-3% and S-3%

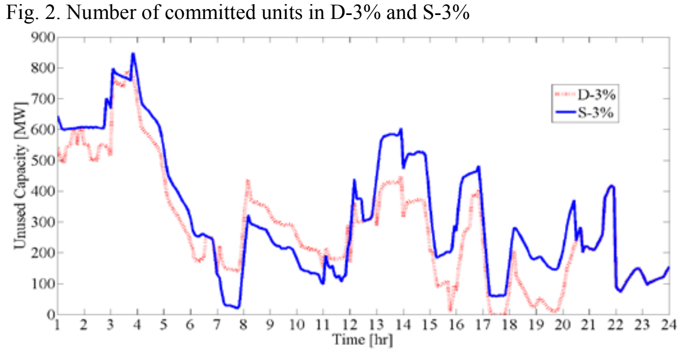

Fig. 3. Unused thermal capacity in D-3% and S-3%

The reduced production cost in S-3% can be explained by investigating the number of committed units, as shown in Fig. 2. Compared to D-3%, S-3% commits one less thermal unit from hours 9–12 (see Fig. 2.) and uses a cheaper middle-capacity thermal unit instead. This results in the de-commitment of more expensive peak units. However, S-3% keeps more units online from hours 14–21 to handle the increasing net load uncertainty as the forecast errors increase over time. These results show that stochastic DASCUC may result in reduced production costs by committing cheaper units and reducing the number of start-ups for expensive peak units.

Table I also shows that the stochastic DASCUC can help improve system reliability in terms of lowering AACEE, sigma ACE, and the number of CPS2 violations. This benefit is achieved by providing excess capacity in real time, as shown in Fig. 3, and such capacity can be used to reduce the imbalance in real time. For the weekly simulation, the AACEE is reduced by 24.3% from 716.5 MWh in D-3% to 542.2 MWh in S-3%. For the daily simulation, the standard deviation of the ACE is decreased by 41.1% from 29.2 in D-6% to 17.2 in S-6%. The reduction in the standard deviation of the ACE implies improved balancing of generation and load in real time.

Note that only one simulation trajectory is provided in Table I. The manner in which the case studies are conducted includes hourly DASCUC intervals, fifteen-minute RTSCUC intervals, five-minute RTSCED intervals, and 4-second AGC intervals. Getting realistic data at this resolution is difficult. Also, running the simulations with all timescales and stochastic DASCUC is very time consuming. Although representing multiple trajectories can assist in better understanding the impact of stochastic DASCUC, it is challenging to do so with the multi-timescale model because of computation and data issues. In future work, we will attempt to model more trajectories.

TABLE II. WEEKLY SIMULATION WITHOUT QUICK-START UNITS

	D-3% without QS	S-3% without QS
Prod. Cost	2,089,494	2,112,460
AACEE	1445.4	1326.6
Sigma ACE	23.7	21.4
CPS2 Violations	89	79
CPS2 score	91.2%	92.2%

Table II lists weekly simulation results without quick-start units, in which the UC decisions are made only in the DASCUC. Compared to the weekly simulation results (last two columns) in Table I that are with quick-start units, including the quick-start units in the RTSCUC helps both the deterministic and stochastic cases achieve better economic and reliability performance. In Table II, the production cost in S-3% without QS is higher than that in D-3% without QS. This observation is opposite to what we observed in Table I, where the production cost in S-3% is lower than that in D-3%. The result suggests that the quick-start units could have a greater impact on the stochastic case than the deterministic case.

IV. CONCLUSIONS

The introduction of greater amounts of VG, together with the increase in distributed resources and demand participation, is increasing system uncertainty and making a case for stochastic modeling for bulk power system operations. This paper evaluates the impacts of stochastic DASCUC with real-time commitment, dispatch, and control occurring at multiple timescales. Numerical results show that stochastic DASCUC could result in better reliability and cost metrics than the deterministic approach by better preparing for uncertainty. Future work will consider a full multi-timescale stochastic model including stochastic DASCUC, RTSCUC, and RTSCED with probability distributions as modeled in [18] to allow for more accurate probability distributions for wind and load forecasting errors.

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