Ramp Requirement Design for Reliable and Efficient Integration of Renewable Energy

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***Abstract*—With increasing renewable penetration, several ISOs are instituting ramp capability products to manage the operational challenge of balancing power in real-time. For example, in MISO's plan, ramp capabilities would be secured 10 min ahead based on the Gaussian-sigma rule (2.5 standard deviations for 99% confidence level). These products are used to manage both net load variations (foreseeable changes) and uncertainties (unforeseeable changes) through economic dispatches every 5 min. Ramp capabilities secured at time t may not be available to meet the uncertain net load at after the dispatch at $t + 5\,\text{min}$. As a result, the required confidence level may not be satisfied. Also, the Gaussian-sigma rule is for reliability only, and might not be cost efficient. The requirement design can thus be subtle. This paper is on the analysis and design of reliable and efficient ramp capability products. To truly satisfy the required confidence level, our idea is to keep enough of the ramp capabilities secured at t for $t + 10\,\text{min}$ by adding constraints on the dispatch at $t + 5\,\text{min}$. Moreover, costs are minimized by selecting the proper number of standard deviations through simulation-based optimization. Numerical results show that net load variations and uncertainties are effectively managed with significant cost savings.**

***Index Terms*—Monte-Carlo simulation, ramp capabilities, real-time dispatch, renewable energy, requirement design.**

NOMENCLATURE

Indices

i, t, l, k	index for unit, time, line, node.
n	index for load trajectory.

Functions

$V(\cdot)$	value function of optimal dispatch cost.
$G(\cdot)$	Gaussian distribution function.
$f(\cdot)$	expected cost function.
$C_i(\cdot)$	energy cost function of unit *i*.

Parameters

L	number of transmission lines.
K	number of nodes.
a	number of standard deviations.
${p_i}^{\min}$	minimal generation level of unit *i*.
${p_i}^{\max}$	maximal generation level of unit *i*.
$\Delta_{i,5\min}$	five-minute ramp rate of unit *i*.
$\Delta_{i,10\min}$	ten-minute ramp rate of unit *i*.
$p_{i,t-5\min}$	generation level obtained at $t - 5\,\min$.
${p_{kt}}^D$	load at node *k* and time *t*.
${p_t}^D$	net load at time *t*.
${p^D}_{t+5\min}$	net load at time $t + 5\,\min$.
s_{lk}	shift factor of line *l* at node *k*.
${F_{lt}}^{\max}$	limit of transmission line *l* at time *t*.
$s_{t,10\ \min}$	standard deviation of 10 min uncertainty at time *t*.
$s_{t+5\min,5\ \min}$	standard deviation of 5 min uncertainty at $t + 5\,\min$.
$R^{\text{up}}_{t,10\ \min}$	up ramp requirement enforced at time *t* for $t + 10\,\min$.
$R^{\text{dn}}_{t,10\ \min}$	down ramp requirement enforced at *t* for $t + 10\ \min$.
$R^{\text{up}}_{t+5\ \min,5\ \min}$	up requirement enforced at $t + 5\,\min$ for $t + 10\,\min$.
$R^{\text{dn}}_{t+5\ \min,5\ \min}$	down requirement enforced at $t + 5\,\min$ for $t + 10\,\min$.
$\hat{p}^D_{t+10\,min\|t}$	net load for $t + 10\,\min$ forecasted at time *t*.
$\hat{p}^D_{t+10\,min\|t+5\ \min}$	net load for $t + 10\,\min$ forecasted at time $t + 5\,\min$.

Variables

p_{it}	generation output.
$R^{\text{up}}_{\text{it},10\ \min}$	up ramp capability of unit *i* at time *t* for $t + 10\,\min$.
$R^{\text{dn}}_{\text{it},10\ \min}$	down ramp capability of unit *i* at *t* for $t + 10\,\min$.
$R^{\text{up}}_{i,t+5\ \min,5\ \min}$	up ramp capability secured at $t + 5\,\min$ for $t + 10\,\min$.
$R^{\text{dn}}_{i,t+5\ \min,5\ \min}$	down capability secured at $t + 5\,\min$ for $t + 10\,\min$.
$\lambda^{\text{up}}_{\text{it},10\ \min}$	shadow price for ten-minute ramp requirement from *t* to $t + 10$ min.
$\lambda^{\text{up}}_{i,t+5\ \min,5\ \min}$	shadow price for additional five-minute ramp requirement from $t + 5$ min to $t + 10$ min.

I. INTRODUCTION

WITH the increasing penetration of intermittent renewable energy such as wind or solar, variations and uncertainties in the net load have increased significantly over the past several years [1]. The net load variations are the foreseeable

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changes and the net load uncertainties are the unforeseeable changes, e.g., wind generation forecast errors [2]. When wind suddenly drops, real-time dispatches can be short of ramp capabilities from online units, and offline units may not be able to respond fast enough [3]. Scarcity events or ad hoc operations to commit expensive fast-start resources have been experienced in RTOs'/ISOs' real-time operations, indicating issues for reliable operations and effective markets [4]. Under extreme situations, system security can be impacted as severely as the sudden loss of several nuclear plants such as the wind ramp event that occurred in Texas on February 26, 2008 [2], [5]. Those impacts could be much more severe as the levels of renewable penetration increase. To manage the operational challenge of maintaining real-time power balance, conventional generators should be committed and dispatched with flexibility. Many studies have been conducted on stochastic unit commitment, which can be computationally complex for implementation and challenges remain to obtain flexibility at the dispatch level. More reserves have been considered [6], but can be costly and may not be effective [7].

Several ISOs are instituting new ramp capability products for their real-time dispatch operations to manage both the net load variations and uncertainties [8], [9]. At each economic dispatch that is sequentially performed every five minutes, ramp capabilities would be secured five minutes [8] or ten minutes [9] in advance. Longer time periods ahead, e.g., 15 or 20 minutes, are also possible. While planning five minutes ahead for the next dispatch is straightforward, planning ahead a longer time period can have more flexibility, e.g., generating resources can be ramped up ten minutes ahead in view of an upcoming sudden wind drop, while within only five minutes ahead much less ramp capability can be prepared [2]. Too long time ahead, however, are not necessary since there will be enough time for more appropriate actions, e.g., committing fast-start resources. In MISO's plan, ramp capabilities would be secured ten minutes ahead for a required level of confidence. Their required amounts would be set as the net load variations plus a number of standard deviations of the uncertain net load based on the Gaussian-sigma rule (e.g., 2.5 standard deviations for the 99% level) assuming a Gaussian distribution [9], [10]. Is the uncertain net load after ten minutes truly satisfied at the required level of confidence? Moreover, costs are not considered in the design but are significantly impacted through economic dispatches [11], [12]. Will costs be increased or can be minimized by optimizing the design?

This paper is on the analysis and design of ramp capability products for the reliable and efficient integration of renewable energy. The current system operations to balance the real-time power and the initiatives to obtain ramp capabilities are first reviewed in Section II. By securing ramp capabilities ten minutes ahead in the real-time dispatch problem, the ramp capability product is formulated following [13] in Section III. The ramp requirement design will be based on this model, and can be generalized to other models such as 15 minutes ahead. Unlike traditional ten-minute reserves which are usually not deployed but only used to restore system balance in response to a contingency event, the ramp capability products are regularly used to manage the frequent net load changes in the economic dispatch operations every five minutes [9], [15]. If the ramp capabilities secured at time t for $t + 10\,\mathrm{min}$ are exhausted in the dispatch at $t + 5\,\mathrm{min}$, then the load at $t + 10\,\mathrm{min}$ may not be met, even though it is within the originally specified level of confidence. Moreover, while obtaining ramp capabilities may increase the dispatch costs, deploying these capabilities in the subsequent dispatches can decrease the costs by avoiding scarcities or by using less of expensive fast-start resources. Therefore, costs across a series of dispatches are not monotonically increased by the ramp capability products, and the required amounts determined based on the Gaussian-sigma rule might not be the most cost-efficient ones. The ramp requirement design is thus subtle, and there are not enough operational experiences to evaluate the initiatives and recommend a "best practice" [15].

To obtain system reliability and cost efficiency, ramp requirements are designed in Section III. Our key idea is to keep enough of the ramp capabilities secured at time t for $t + 10\,\mathrm{min}$ by imposing additional ramp requirement constraints on the economic dispatch at $t + 5\,\mathrm{min}$. The required confidence level is then satisfied if there is a feasible solution. This idea can be easily extended if we look ahead further in time, e.g., 15 or 20 minutes ahead. While satisfying the required level of confidence, the required amounts of ramp capabilities are optimized by selecting the number of standard deviations to minimize the cost across a series of economic dispatches. However, this cost as a function of the required amounts depends on the embedded sequential optimization of real-time dispatches with uncertain net load. The idea is then to evaluate the cost by using Monte-Carlo simulation mimicking the real-time dispatch process. Simulation-based optimization such as in [16], [17] is then used to minimize the expected cost by selecting the number of standard deviations "a." Unlike the Gaussian-sigma rule, such selection of "a" does not rely on the Gaussian assumption. The optimization problem with a scalar decision variable "a" is efficiently solved by using the stochastic-gradient search method [18].

Numerical results of three examples are presented in Section V. Example 1 is a simple example to show the effectiveness of our additional ramp requirement constraints. Example 2 is based on a five-bus system to demonstrate the cost efficiency while satisfying the required level of confidence. Example 3 is based on the IEEE 118-bus system to show the effectiveness of our design to manage high-level net load variations and uncertainties for large-scale systems and to highlight its effects to relieve transmission congestions.

II. LITERATURE REVIEW

For U.S. wholesale electricity markets operated by the RTOs/ISOs, e.g., ISO-NE, MISO and CAISO, there is a day-ahead energy market to clear supply and demand for the next day with one hour as the time interval (the day-ahead unit commitment and economic dispatch problem), and a real-time energy market to dispatch units to meet the load on a five-minute basis (the real-time economic dispatch problem). In-between the day-ahead and the real-time markets, adjustments can be made as needed by, e.g., the Reliability Assessment

Commitment at MISO or the Real-Time Unit Commitment at CAISO. Ancillary service products, including regulation, spinning and non-spinning reserves are instituted in a co-optimization process with energy or separately.

With increasing penetration of intermittent renewable energy, variations and uncertainties of the net load (the aggregation of load, wind generation and net scheduled interchanges) have increased significantly over the past several years, causing difficulties to balance the power in real-time [1]. Extensive studies have been conducted on the operational impacts of intermittent renewables such as in [1], [2] and [3]. While increasing reserve requirements have been considered, it may be costly and ineffective [7] and dispatch of units with sufficient ramp capabilities to follow the load within the time frame of economic dispatch is needed and can be less expensive [2].

The ramp capability product is designed to manage net load variations and uncertainties to maintain power balance in the real-time dispatch process every five minutes, different from traditional ancillary service products [9], [15]. Specifically, regulation is to manage the deviations from the actual load through a different process of Automatic Generation Control every four seconds. In addition, regulation is obtained at a higher cost than the ramp product and only a small portion of units are qualified to provide regulation. Contingency reserve shares the similar timeframe with the ramp capability product. Nevertheless, they can only fulfill the load following needs in the upward direction. Moreover, contingency reserve is to restore system balance in response to a sudden loss of generation or an infrequent contingency event [14], whereas the ramp capability product is to manage the frequent net load changes in each economic dispatch.

Currently, ramp capability products are being instituted to manage both the variations *and* uncertainties of the net load. For example, ISO-NE recognized the need for ramp capabilities in its strategic planning document [19]. CAISO published a design document for the implementation of its ramp capability product [8]. At MISO, the ramp capability product is developed for both the real-time and the day-ahead markets [20]. Ramp requirements would be determined to satisfy the variable and uncertain net load at a specified level of confidence [8], [9], [10]. The design for real-time market is then projected to the hourly value for the day-ahead market and incorporated in the unit commitment problems [20].

III. THE RAMP CAPABILITY PRODUCT AND SUBTLE ISSUES

The current ramp capability product design within the real-time dispatch problem is formulated in Section A following [13]. The subtle issues in satisfying the reliability and cost-efficiency are then analyzed and illustrated in Section B.

A. Formulation of the Current Ramp Capability Product

The single-interval dispatch is considered following the practice of ISOs such as MISO and ISO-NE. The formulation can also be extended to a multi-interval dispatch that is used at several other ISOs [9]. Ancillary services are not considered without affecting the ramp requirement design in view of their different purposes and different deployment procedures as reviewed in Section II, although market outcomes can be affected depending on the product penalty price, which is another important design issue as discussed more in [9]. Consider the real-time energy market with *L* transmission lines, *K* nodes and the time horizon of one five-minute interval. The unit commitment decisions have been obtained in the unit commitment process satisfying the minimum up/down time constraints.

Each online unit *i* should satisfy the generation capacity constraints and ramp rate constraints:

$$p_i^{\min} \le \ p_{\text{it}} \le p_i^{\max} \qquad\qquad \forall\, i, \tag{1}$$

$$-\,\Delta_{i,5\min} \le \ p_{\text{it}} - p_{i,t-5\min} \le \Delta_{i,5\min}\ \forall\, i, \tag{2}$$

where ${p_i}^{\min}$ and ${p_i}^{\max}$ are the minimal and maximal generation levels, $\Delta_{i,5\ \min}$ is the five-minute ramp rate and $p_{i,t-5\ \min}$ is the generation level obtained in previous dispatch. Transmission capacity constraints are satisfied to maintain power balance:

$$\sum_{k=1}^{K}\left(s_{lk}\big(\sum_{i\in I_k} p_{\text{it}} - p_{kt}^{D}\big)\right) \le F_{lt}^{\max} \quad \forall\, i, \tag{3}$$

$$\sum_{k=1}^{K}\left(\sum_{i\in I_k} p_{\text{it}} - p_{kt}^{D}\right) = 0 \tag{4}$$

where transmission losses are not considered for simplicity without affecting the ramp requirement design whose purpose is to manage net load variations and uncertainties. In the above, ${p_{kt}}^D$ is the load at node k, s_{lk} is the shift factor of line *l* at node *k*, and ${F_{lt}}^{\max}$ is the limit of transmission line *l*. The objective is to minimize the total dispatch cost:

$$\min_{\{p_{\text{it}}\}} \ \sum_{i=1}^{I} C_i(p_{\text{it}}) \tag{5}$$

where the convex and piecewise energy cost function $C_i(p_{\text{it}})$ can be easily reformulated in a linear form as in [21].

On top of this standard dispatch problem at time *t*, ramp capabilities are obtained to manage the net load variations *and* uncertainties over the next ten minutes [13]. For simplicity of presentation, the ramp up product is discussed and the ramp down product is symmetric. The net load variations are obtained as the forecasted net load $p^D{}_{t+10\ \min|t}$ minus the current net load ${p_t}^D$. The net load uncertainties are approximated by the standard deviations of load and wind forecast errors as $\sigma_{t,10\ \min}$ [9]. The current design assumes that the uncertain net load follows a Gaussian distribution and determines a number "*a*" of the standard deviations based on the Gaussian-sigma rule (e.g., 2.5 standard deviations for the 99% level of confidence) [9]. The required amount of ramp up capabilities is then set as the net load variations plus "a" times of uncertainties:

$$R_{t,10\min}^{\text{up}} = \max\{0,\ \hat{p}_{t+10\min|t}^{D} - p_t^{D} + a\sigma_{t,10\min}\}. \tag{6}$$

The ramp up capabilities provided by online unit *i* are limited by its ramp rate over the next ten minutes $\Delta_{i,10\ \min}$, and cannot exceed the available generation capacity:

$$0 \le r^{\mathrm{up}}_{\mathrm{it,10min}} \le \Delta_{i,\mathrm{10min}} \qquad \forall\, i, \tag{7}$$

$$p_{\mathrm{it}} + r^{\mathrm{up}}_{\mathrm{it,10min}} \le p^{\max}_i \qquad \forall\, i. \tag{8}$$

The total ramp up capabilities should satisfy the requirement:

$$\sum_{i=1}^{I} r^{\mathrm{up}}_{\mathrm{it,10min}} \ge R^{\mathrm{up}}_{t,\mathrm{10min}}. \tag{9}$$

The shadow price $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$ associated with ramp requirement constraint (9) establishes the market-clearing price for the ramp capability product $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$. With the ramp requirement (9) enforced at the system-wide level, post-deployment transmission constraints can be further enforced to ensure that the required ramp capability can be transmitted to certain locations. That is, when the ramp capability is procured at time *t* network constraints for the post-deployment flow at $t + 10\,\mathrm{min}$ can be added following [9].

Symmetric constraints are for ramp down capabilities:

$$0 \le\ r^{\mathrm{dn}}_{\mathrm{it},10\,\mathrm{min}} \le \Delta_{i,10\,\mathrm{min}} \quad \forall i, \tag{10}$$

$$p^{\min}_i \le\ p_{\mathrm{it}} - r^{\mathrm{dn}}_{\mathrm{it},10\,\mathrm{min}} \qquad \forall\, i. \tag{11}$$

$$\sum_{i=1}^{I} r^{\mathrm{dn}}_{\mathrm{it},10\,\mathrm{min}} \ge R^{\mathrm{dn}}_{t,10\,\mathrm{min}},\ \text{with} \tag{12}$$

$$R^{\mathrm{dn}}_{t,\mathrm{10min}} =\ \max\{0,\ \hat{p}^{D}_{t+\mathrm{10min}|t} - p^{D}_{t} - a\sigma_{t,\mathrm{10min}}\}. \tag{13}$$

The ramp capability products impact the dispatch of energy in the co-optimization process through equations (8) and (11). The associated costs are thus reflected in the cost function (5). Additional procurement costs of the ramp capability products are not considered here [9], but can be included to (5) similarly as in [8]. With the ramp capability products included, the real-time dispatch problem at time *t* is deterministic given the load and ramp requirements. By obtaining these capabilities in advance, the system is positioned at p_{it} with flexibility to satisfy possible realizations of the uncertain net load over the next ten minutes. Obtaining the ramp capabilities by additional requirement constraints (9) and (12) may incur a small amount of "premium" at the current interval, whereas utilizing the capabilities at future interval dispatches given the better system position p_{it} can much reduce the cost by reducing scarcities and real-time commitment of expensive fast-start resources.

B. The Subtle Issues on Reliability and Efficiency

The ramp capability products as formulated above would be used to manage both net load variations *and* uncertainties in ten minutes. However, unlike traditional ten-minute reserves which are only deployed to restore system balance in response to a contingency event, the ramp capability product would be used to manage the frequent net load changes through economic dispatches every five minutes. If the ramp capabilities secured at time *t* for $t + 10\,\mathrm{min}$ are exhausted in the dispatch at $t + 5\,\mathrm{min}$, then the load at $t + 10\,\mathrm{min}$ may not be met, even though it is within the originally specified level of confidence. Moreover, while obtaining ramp capabilities may increase the dispatch costs, deploying these capabilities in the subsequent dispatches can decrease the costs by avoiding scarcities or by using less of expensive fast-start resources, and the Gaussian Sigma rule may not be most cost efficient.

TABLE I
GENERATION PARAMETERS

Gen	Min MW	Max MW	Ramp MW/min	Price $/MWh	Initial MW
G1	100	400	1	25	400
G2	10	130	4	30	130
G3	10	130	1	31	33
G4	10	100	1	36	10

TABLE II
NET LOAD MW

Time	08:00	08:05	08:10	08:15	08:20	08:25
Forecast at 08:00	575	579	588			
Forecast at 08:05		585.5	588	591		
Forecast at 08:10			596	591	594	
Forecast at 08:15				591	594	600

TABLE III
DISPATCH SOLUTIONS WITH AND W/O THE RAMP CAPABILITY PRODUCT

		08:00		08:05		08:10		08:15	
Time		with	w/o	with	w/o	With	w/o	with	w/o
$p_{\mathrm{it}}\,;\lambda^{\mathrm{up}}{}_{\mathrm{it,10\,min}}$	G1	400; 0	400	400; 0	400	400; 0	400	400; 0	400
	G2	125; 5	130	130; 0	130	130; 0	130	129; 1	130
	G3	38; 10	35	43; 10	40	48; 10	45	49.5; 10	46
	G4	12; 10	10	12.5; 10	15	17.5; 10	20	12.5; 10	15
Penalty MW		0	0	0	0.5	0.5	1	0	0
Cost $		1280	1279	1307	1411	1439	1543	1321	1322

In view of the subtlety of these issues, a small example is used for illustration with unit parameters specified in Table I. The net load including its forecast and one realization are given in Table II. Assume that the five-minute net load uncertainties are Gaussian with zero mean and standard deviation $\sigma_{t,5\ \mathrm{min}} = 3.4\ \mathrm{MW}$. The ten-minute uncertainties are thus also Gaussian with zero mean and standard deviation $\sigma_{t,10\ \mathrm{min}} = \sqrt{2}\sigma_{t,5\ \mathrm{min}} = 4.8\,\mathrm{MW}$. The 99% confidence level, i.e., 2.5 standard deviations is required in (6), and the ramp down product is not shown for the convenience of illustration. If there is a ramp shortage to manage sudden net load changes and commitment and dispatch of offline fast-start units are not fast enough, the penalty is $ 2500/MWh.

The problem in Section III-A is solved for 8:00 am–8:15 am in Table III, compared with results without ramp products. At *t* = 8:00 am, the required 25 MW/10 min ramp capabilities are provided by G2 (5 MW/10 min), G3 (10 MW/10 min) and G4 (10 MW/10 min). At $t + 5\,\mathrm{min} = 8:05\ \mathrm{am}$, the realized net load turned out to be 585.5 MW. Ramp capabilities secured at 8:00 am are used to satisfy the load. However, G2's 5 MW ramp capability is exhausted and only 10 MW/5 min ramp capabilities (G3 5 MW/5 min, G4 5 MW/5 min) are left. With these

TABLE IV
DISPATCH OF ENERGY AND RAMP CAPABILITIES FOR EXAMPLE 1

Time		08:00	08:05	08:10	08:15
$p_{\mathrm{it}}\,;\lambda_{\mathrm{it}}{}^{\mathrm{up}}$	G1	400; 0	400; 0	400; 0	400; 0
	G2	125; 5	129; 1	130; 0	128.5; 1.5
	G3	38; 10	43; 10	48; 10	49.5; 10
	G4	12; 10	13.5; 10	18; 10	13; 10
Penalty MW		0	0	0	0

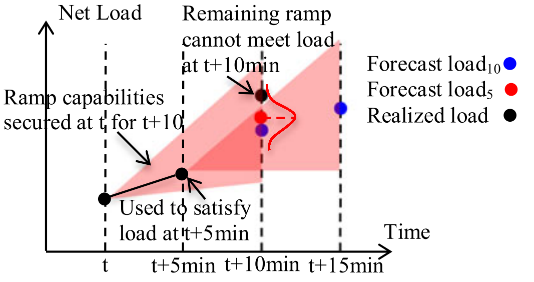

Fig. 1. Ramp capabilities secured at t for $t + 10\,\mathrm{min}$ is used at $t + 5\,\mathrm{min}$.

remaining ramp capabilities, generation can only ramp up to 595.5 MW at $t + 10\,\mathrm{min} = 8:10\,\mathrm{am}$, unable to satisfy the realized net load of 596 MW even though it is within $2.5\sigma_{t,5\ \mathrm{min}}$ (8.5 MW) of the forecasted 588 MW as shown in Fig. 1.

In addition, the costs showing in Table III are surprising. At 8:00 am, the dispatch cost is increased by \$1 to obtain the ramp capabilities. However, in the subsequent dispatches the costs are decreased by avoiding the penalty of unsatisfied load and by using less of the relatively more expensive unit G4. The total dispatch cost across the four intervals is reduced by \$208 for the given net load realization in Table II. For a different realization the cost across the series of economic dispatches can vary, and cost impact for different net load realizations is demonstrated at the 99% level of significance in Example 2.

IV. SOLUTION METHODOLOGY

To effectively manage the uncertain net load at the required level of confidence, ramp requirement constraints are added at $t + 5\,\mathrm{min}$ to keep enough of the ramp capabilities secured at *t* for $t + 10\,\mathrm{min}$ when they are used in Section A. Simulation-based optimization is then used to optimize the number of standard deviations a minimizing the expected cost across a series of dispatches in Section B.

A. Additional Ramp Requirement Constraints

In the dispatch at $t + 5\,\mathrm{min}$ when the ramp capabilities secured at *t* for $t + 10\,\mathrm{min}$ are used, additional ramp requirement constraints are imposed to ensure that enough of these secured capabilities are kept for the uncertain net load at $t + 10\,\mathrm{min}$.

Specifically, among the ramp up capabilities $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$ of unit *i* secured at time *t* for $t + 10\,\mathrm{min}$, the portion $(p_{i,t+5\ \mathrm{min}} - p_{\mathrm{it}})$ is used at $t + 5\,\mathrm{min}$. The ramp capabilities available at $t + 5\,\mathrm{min}$ for $t + 10\,\mathrm{min}$ are limited by the remaining ramp capabilities:

$$r^{\mathrm{up}}_{i,t+5\,\mathrm{min},5\mathrm{min}} \le r^{\mathrm{up}}_{\mathrm{it},10\mathrm{min}} - (p_{i,t+5\,\mathrm{min}} - p_{\mathrm{it}})\,\forall i, \tag{14}$$

and are also limited by the ramp rate over five minutes:

$$0 \le r^{\mathrm{up}}_{i,t+5\,\mathrm{min},5\mathrm{min}} \le \Delta_{i,5\mathrm{min}}\,\forall i. \tag{15}$$

In addition, these ramp capabilities for the next five minutes are not more than those to be secured for the next ten minutes:

$$r^{\mathrm{up}}_{i,t+5\,\mathrm{min},5\mathrm{min}} \le r^{\mathrm{up}}_{i,t+5\,\mathrm{min},10\mathrm{min}}\,\forall i. \tag{16}$$

The total ramp capabilities for the next five minutes should be kept enough to manage the uncertain net load at $t + 10\,\mathrm{min}$:

$$\sum_{i=1}^{I} r^{\mathrm{up}}_{i,t+5\,\mathrm{min},5\mathrm{min}} \ge R^{\mathrm{up}}_{t+5\,\mathrm{min},5\mathrm{min}}, \tag{17}$$

where the required amount is the net load variations plus a number "*a*" of standard deviations over the next five minutes:

$$\begin{aligned} R^{\mathrm{up}}_{t+5\mathrm{min},5\mathrm{min}} = {} & \max\{0,\ \hat{p}^{D}_{t+10\mathrm{min}|t+5\mathrm{min}} - p^{D}_{t+5\mathrm{min}} \\ & + a\sigma_{t+5\,\mathrm{min},5\,\mathrm{min}}\}. \end{aligned} \tag{18}$$

The net load uncertainty $\sigma_{t+5\ \mathrm{min},5\ \mathrm{min}}$ in (18) is related to $\sigma_{t,10\ \mathrm{min}}$ in the ten-minute ahead requirement (6), since the uncertain net load at $t + 10\,\mathrm{min}$ depends on the realization of the uncertain net load at $t + 5\,\mathrm{min}$. To truly satisfy the required confidence level, their exact relationship is quantified based on total probability theory in [21] as $\sigma_{t,10\ \mathrm{min}} = \sqrt{2}\sigma_{t+5\ \mathrm{min},5\ \mathrm{min}}$ for Gaussian.

The additional five-minute ramp requirement constraint (17) and its associated shadow price $\lambda^{\mathrm{up}}_{i,t+5\ \mathrm{min},5\ \mathrm{min}}$ introduce a new 5-minute ramp capability product $\lambda^{\mathrm{up}}_{i,t+5\ \mathrm{min},5\ \mathrm{min}}$. However, as described by (14), this 5-minute ramp product differs from the standard 5-minute ramp product such as the one in [8] in that it is the remaining portion of the ramp capability $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$ after it is partially used to produce energy at $t + 5\,\mathrm{min}$. As a result, appropriate market payment scheme is essential to avoid double counting of ramp capabilities as the 10-minute ramp capability product evolves to a 5-minute ramp capability product as time proceeds. The new 5-minute ramp capability product is paid based on the difference between its shadow price $\lambda^{\mathrm{up}}_{i,t+5\ \mathrm{min},5\ \mathrm{min}}$ and the shadow price $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$ of the original 10-minute ramp requirement (9), i.e.,

$$\max\{(\lambda^{\mathrm{up}}_{t+5\mathrm{min},\ 5\mathrm{min}} - \lambda^{\mathrm{up}}_{t,10\mathrm{min}})r^{\mathrm{up}}_{t+5\mathrm{min},5\mathrm{min}}, 0\}. \tag{19}$$

This is because unit *i* is obligated to provide the 10-minute ramp capability $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$ to meet load at $t + 10\,\mathrm{min}$ by being paid at the shadow price of $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$. As time proceeds to $t + 5\,\mathrm{min}$, the payment scheme in (19) further compensates unit i for continuing to provide the capability $\lambda^{\mathrm{up}}_{i,t+5\ \mathrm{min},5\ \mathrm{min}}$ over the remaining 5 minutes if its price $\lambda^{\mathrm{up}}_{i,t+5\ \mathrm{min},5\ \mathrm{min}}$ is higher than the original price $\lambda^{\mathrm{up}}_{\mathrm{it},10\ \mathrm{min}}$. The payment scheme is heuristic and more investigations on revenue adequacy and economic incentives can be valuable future research topics.

Symmetric constraints are for the ramp down capabilities:

$$r^{\mathrm{dn}}_{i,t+5\,\mathrm{min},5\,\mathrm{min}} \le r^{\mathrm{dn}}_{i,t,10\,\mathrm{min}} - (p_{\mathrm{it}} - p_{i,t+5\,\mathrm{min}})\,\forall i, \tag{20}$$

$$0 \le r^{\rm dn}_{i,t+5\,\rm min,5\,min} \le \Delta_{i,5\,\rm min}\,\forall i, \tag{21}$$

$$r^{\rm dn}_{i,t+5\,\rm min,5min} \le r^{\rm dn}_{i,t+5\,\rm min,10min}\,\forall i, \tag{22}$$

$$\sum_{i=1}^{I} r^{\rm dn}_{i,t+5\,\rm min,5\,min} \ge R^{\rm dn}_{t+5\,\rm min,5\,min},\ \text{with}, \tag{23}$$

$$R^{\rm dn}_{t+5\rm min,5min} = \max\{0,\ \hat{p}^D_{t+10\rm min|t+5min} - p^D_{t+5\rm min} - a\sigma_{t+5\,\rm min,5min}\}. \tag{24}$$

The ramp requirement constraints looking five minutes ahead are added to each economic dispatch, on top of the existing ones looking ten minutes ahead. At time *t*, the additional ramp requirement constraints are obtained by changing the time index from $t+5\,\rm min$ to *t* in constraints (14)–(18) and (20)–(24). The resulting constraints are then added to the formulation in Section III-A and the complete dispatch problem for time *t* is thus:

$$\min_{\{p_{\rm it}\},\{r^{\rm up}_{\rm it,10min}\},\{r^{\rm up}_{\rm it,5min}\},\{r^{\rm dn}_{\rm it,10min}\},\{r^{\rm dn}_{\rm it,5min}\}} \sum_{i=1}^{I} C_i(p_{\rm it}), \tag{25}$$

subject to constraints (1)–(4), (6)–(13), (14)–(18) and (20)–(24) whose time index is changed to *t*. Since the new constraints are linear, the resulting dispatch problem with given net load and ramp requirements can be easily implemented within the existing dispatch packages. As such, the subtle issue on reliability as discussed in Section III-B is effectively addressed by a simple method of adding five-minute ramp requirements. The dispatch solution $p_{\rm it}(R_t{}^D(a))$ and dispatch cost $V_t(R_t{}^D(a); p_t{}^D)$ are functions of the number of standard deviations *a* [23].

B. Simulation-Based Optimization

While satisfying the required level of confidence, the ramp requirements based on the Gaussian-sigma rule might not be the most cost-efficient ones as analyzed in Section III-B. In this section, the number of standard deviations *a* in the required amounts (6), (13), (18) and (24) is selected to minimize the cost across a series of economic dispatches. This cost, however, depends on the embedded sequential optimization of economic dispatches with uncertain net load. Simulation-based optimization is therefore used with the cost evaluated via Monte-Carlo simulation mimicking the real-time dispatch process. The problem with a scalar decision variable *a* is then solved by using a stochastic-gradient method.

Specifically, given the realized net load $p^D_{n,t}$ at time *t*, the uncertain net load at time $t+5\,\rm min$ is sampled from a distribution based on the realization at time *t*. A trajectory of the realized net load is then obtained for the series of economic dispatches, and the process repeats to obtain a statistically sufficient number of *N* load trajectories [24]. The distribution of wind forecast error has been studied by NERL in [25] and [26]. Different systems can have different distributions for the uncertainties [25]. The Gaussian distribution $G(p^D_{t+5\,\rm min|t}, \sigma_{t,5\,\rm min})$ is used here as in the MISO design [9]. The study in [26] based on ERCOT system shows that the uncertainties have a thicker tail than Gaussian. In that case, the Gaussian assumption can underestimate the optimal number of standard deviation *a*. This issued can be resolved by sampling trajectories of the realized net load from the appropriate distribution rather than Gaussian. Therefore, the simulation does not rely on the Gaussian assumption but can be generalized to other distributions. Moreover, when the design is performed for practical systems, the load trajectories can be directly obtained from historical data.

For each load trajectory *n*, the real-time dispatch problem (25) is solved sequentially to satisfy the realized net load. The total expected cost as evaluated through the Monte-Carlo simulation process is minimized by selecting *a:*

$$\min_{a \ge \underline{a}} \quad f(a) = \frac{1}{N}\left\{\sum_n \sum_t \left(V_{n,t}(R^D_t(a); p^D_{n,t}\right)\right\}, \tag{26}$$

where *a* is the lower bound on the number of standard deviations that can be determined based on the Gaussian-sigma rule to satisfy the reliability requirement.

This simulation-based optimization problem with a scalar decision variable *a* can be efficiently solved by using a stochastic-gradient search method [18]. An initial range of *a* is first determined by heuristics as $[\underline{a}^0, \overline{a}^0]$ and the initial value a^0 is selected as its midpoint. Given a^k, Monte-Carlo simulation is performed, and each iteration *k* uses the same load trajectories. The stochastic-gradient of the expected cost function *f*(*a*) is approximated by using the difference formula:

$$\nabla f(a) = \frac{f(a+\Delta a) - f(a)}{\Delta a}, \tag{27}$$

and a^k is improved along the stochastic-gradient direction as:

$$a^{k+1} = a^k + \alpha \nabla f(a^k). \tag{28}$$

Since *a* is a scalar, Δa and step-size α are easily selected by using line search methods in [27]. The process repeats until the range is less than the stopping threshold ε

$$\left|\underline{a}^{k+1} - \overline{a}^{k+1}\right| \le \varepsilon. \tag{29}$$

The ramp capability requirement is thus designed to reliably manage net load variations and uncertainties at the optimal cost by using the simulation based optimization method.

The number of standard deviation *a* would be optimized offline by using historical data, and the simulation-based optimization is efficient for the offline implementation. In real-time, ramp requirements such as in (6) would then be determined by using the optimized number a^* and the forecasted net load variations and uncertainties per the schemes planned by CAISO and MISO. Different operating conditions may require different amounts of ramp capabilities. This difference can be mostly captured by the forecasted net load variations and uncertainties. The optimized value of *a* is relatively robust, e.g., against different wind penetration levels as to be shown in the numerical studies. If the number of standard deviations *a* still varies at different times of day according to the daily renewable generation pattern, then it can be designed with different values for different times of day. Moreover, if there is a structural change in the system, then *a* can be re-optimized based on the new system condition.

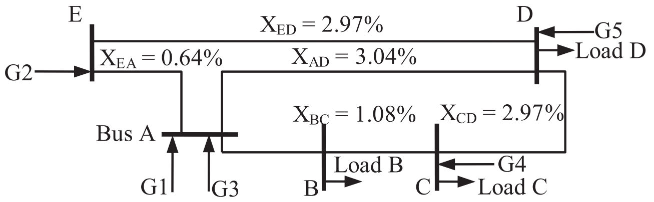

Fig. 2. Five-bus system.

V. NUMERICAL RESULTS

The ramp requirement design was implemented in AIMMS 3.8 on a Dell M4600 laptop with Intel Core i7-2820 QM CPU 2.30 GHz RAM 8 GB. In Example 1, the simple problem in Section III-B is solved to show the effectiveness of our additional ramp requirement constraints. In Example 2, ramp requirements are designed for a five-bus system to demonstrate the cost efficiency while satisfying the required level of confidence. In Example 3, a problem based on the IEEE 118-bus system is solved to show the effectiveness of robustly managing different levels of high net load variations and uncertainties and the impacts on relieving transmission congestion. The required level of confidence is set at 99%.

A. Example 1

Consider the small example as specified in Tables I and II. Since the realized load at 8:10 am within the required level of confidence was not satisfied as discussed in Section III-B, the additional ramp requirement constraints as formulated in Section III-A are used to keep enough of the secured ramp capabilities. The resulting dispatch problem (25) is solved and the solutions of energy and ramp capabilities are shown below.

At 8:00 am, 25 MW/10 min ramp capabilities are obtained to manage the variable and uncertain net load at 8:10 am. At 8:05 am, these capabilities are used through the dispatch to satisfy the realized net load of 585.5 MW. Different from the dispatch results in Table III, 11 MW/5 minutes ((588 -585.5) MW plus 8.5 MW of $2.5\sigma_{5\,\min}$) ramp capabilities are kept by the additional 5-minute ramp requirement for the net load at 8:10 am (G2 1 MW/5 min, G3 5 MW/5 min and G4 5 MW/5 min). By using these remaining 11 MW/5 minutes ramp capabilities, the 596 MW realized net load at 8:10 am is effectively satisfied.

B. Example 2

Consider a five-bus system as shown in Fig. 2. Among the five units in the system, units G1-G4 are committed and their parameters are the same as those specified in Table I, except that the initial generation in this example is [400; 130; 90; 10]. Ramp requirements are designed for the morning ramp up hour from 8:00 am to 8:55 am. The ten minute-ahead net load forecast $p^D_{t+10\ \min\,|\,t}$ is shown in Table V and the net load uncertainty is $\sigma_{t,10\ \min} = 4.8\,\mathrm{MW}$ following the specifications in [9]. The net load forecasted five-minute ahead should be slightly different from that forecasted ten-minute ahead. It is assumed to be the same for simplicity while the uncertainty is $\sigma_{t,5\ \min} = 3.4\,\mathrm{MW}$. The forecasted net load and uncertainties are used in determining the required amounts of ramp capabilities. They are also used to simulate the net load based on Gaussian distribution $G(p^D_{t+5\,\min\,|t}, \sigma_{t,5\,\min})$. The penalty for not satisfying the load is $2500/MWh.

TABLE V
FORECASTED NET LOAD OF EXAMPLE 2

Time	8:00	8:05	8:10	8:15	8:20	8:25	8:30
Load	632	633	634	637	648	649	650
Time	8:35	8:40	8:45	8:50	8:55	9:00	9:05
Load	652	653	655	657	659	660	661

TABLE VI
SIMULATION RESULTS OF EXAMPLE 2

a	Expect Cost $	Realized Conf. %	Aver.	Gaussian Conf. % Min
w/o	18189.4	91.4	41.3	–
2	17602.1	98.9	97.9	95
2.5	17582.2	99.6	99.3	99
2.8	17576.7	99.8	99.7	99.5
3	17574.7	99.9	99.8	99.8
3.5*	17572.8	>99.9	>99.9	>99.9
4	17575.2	>99.9	>99.9	>99.9

To design ramp requirements that minimize the cost across the twelve dispatch intervals from 8:00 am-8:55 am, the number of standard deviations a is selected by solving the simulation-based optimization problem (26) with the number of simulation runs selected as $N = 1000$. The initial range for a is determined by heuristics as $a \ \in$ [2], [4]. The number of standard deviations a is iteratively updated by using the stochastic-gradient search method until the stopping criteria (29) is satisfied with stopping threshold $\varepsilon = 0.1$.

Simulation results for different numbers a of standard deviations are first shown in Table VI to illustrate the cost as a function of ramp requirements. In addition, the realized levels of confidence are obtained at each time t as the percentage of simulation runs with load successfully satisfied. Across the twelve dispatches, both the average percentage and the minimum percentage are obtained and are compared with the Gaussian-sigma rule. Simulation results for the case without the ramp product are also obtained for comparison.

As can be seen, without the ramp capability product, power balance can only be maintained at 91.4% on average or 41.3% at the minimum. With the ramp capability product, the realized confidence levels for $a \geq 2.5$ effectively satisfy the required 99% level of confidence. In addition, the realized confidence levels are not exactly the same as the required levels based on the Gaussian distribution. That is because the ramp requirement constraints are inequality ($\geq$). If ramp capabilities are obtained larger ($>$) than the required amount, then the realized confidence level can be larger than the required level; if the ramp capabilities are obtained equal ($=$) to the required amount, then the realized confidence level equals the required level.

Besides the reliability effectiveness of our ramp requirement design, cost efficiency is also demonstrated. Without the

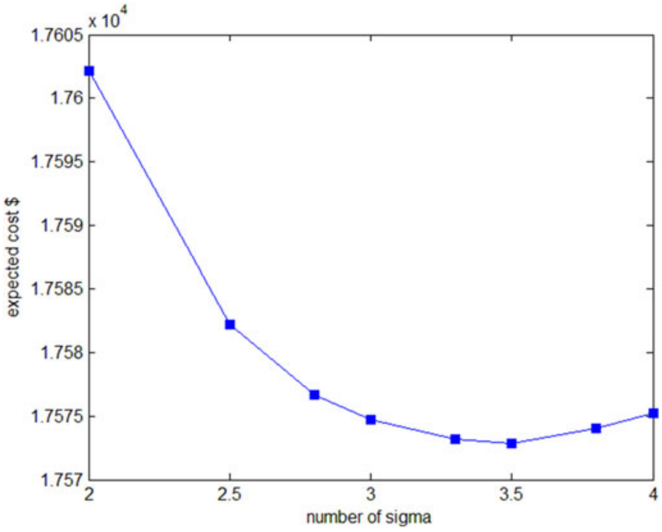

Fig. 3. Expected cost as a function of the number of standard deviations.

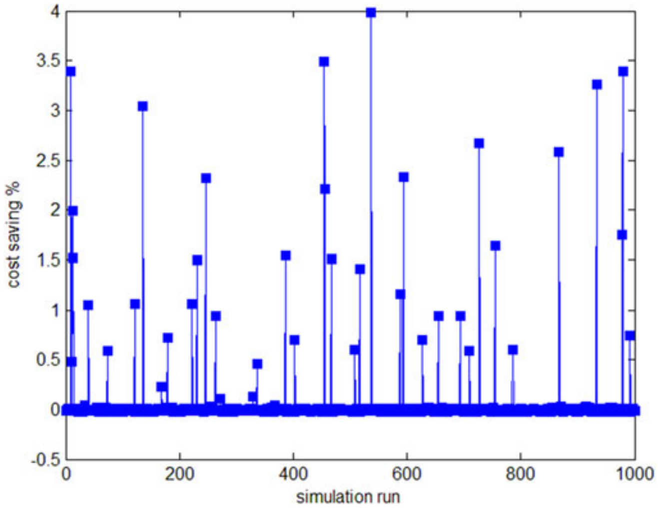

Fig. 4. Cost savings for individual simulation runs.

ramp capability product the expected cost is \$18189.4 including penalties for not satisfying the load. The expected cost decreases as more ramp capabilities are obtained to manage the net load variations and uncertainties and then increases after about 3.5 when excessive ramp capabilities are wasteful. The cost function is not monotonically increasing as shown in Fig. 3. The number of sigma a is optimized at a relatively large value of 3.5, because for this small example with only four units, the system can be short of ramp capabilities and incur heavy penalty costs. The optimal a can be affected by the penalty price and the large value of a is a result of cost minimization to avoid the heavy penalty.

By optimizing the number of standard deviations at $a^* = 3.5$, the expected cost is reduced by 0.054% compared with that for $a = 2.5$ determined based on the Gaussian-sigma rule. To check the significance of this saving, statistical analysis is performed following [24]. The sample mean of the cost savings $\bar{\bar{\Delta}} = \$9.4$ and its standard error $\sigma_\Delta = \$2.0$. The significance threshold $\mu = \overline{\Delta}/\sigma_\Delta = 4.7$. Therefore, the cost saving is statistically significant at the 99% level. The cost savings at individual simulation runs are plotted in Fig. 4. As can be seen, the saving can be up to 4% when the wind suddenly drops, while at other simulation runs the dispatch costs are similar.

C. Example 3

Consider the IEEE 118-bus example [28]. The system includes 54 thermal generating units with quadratic cost functions, a transmission network with 186 branches, hourly load and ancillary services. Since step offer curves are used in the current practice of most ISOs, the quadratic cost functions are converted to piecewise linear. Assuming a DC power flow network, shift factors are obtained from the parameters of the transmission network. The study period is for one evening ramp up hour from 20:00 pm to 20:55 pm. The forecasted net load is created based on the hourly load as shown in Table VII. According to the load and wind generation forecast errors described in [9], the five-minute net load uncertainty is set as 0.4% of the average forecasted net load assuming a high wind penetration level of 30%. A penalty of \$500/MWh is used for this large system as commitment of offline fast-start units may be possible in some shortage situations.

TABLE VII
FORECASTED LOAD OF EXAMPLE 2

Time	20:00	20:05	20:10	20:15	20:20	20:25	20:30
Load	5150	5153	5160	5230	5235	5250	5285
Time	20:35	20:40	20:45	20:50	20:55	21:00	21:05
Load	5400	5415	5440	5477	5512	5527	5540

TABLE VIII
RESULTS OF EXAMPLE 3 FOR THE 0.4% UNCERTAINTY LEVEL

a		Exp. Cost \$	Realized Conf. Level %
2.5	w/o ramp	81167.9	77.0
	w/o 5 min-require	78942.1	90.4
	with 5 min-require	78216.6	99.7
2.8		78215.2	99.8

Simulation-based optimization is used to select the number of standard deviations from an initial range of [2], [6]. The number of simulation runs is selected as $N = 1000$. The optimization process stops when (29) is satisfied with stopping threshold $\varepsilon = 0.1$. The optimal number of standard deviation is obtained as $a^* = 2.8$ after 5 iterations, about 6 minutes for each iteration. The simulation-based optimization method is thus computationally efficient for the offline implementation of the ramp requirement design as discussed in Section IV-B. The optimized expected costs and realized confidence levels are shown in Table VIII as compared with the case without the ramp capability product and two cases based on the Gaussian-sigma rule, one without and one with the additional ramp requirement constraints in Section III-A.

TABLE IX
COMPARISON OF TRANSMISSION CONGESTION VALUES FOR EXAMPLE 2

a	w/o	2.5	2.8
Total value	\$7654.2	\$5463.2	\$2590.8
% of congestion	5.4%	2.2%	1.1%

TABLE X
RESULTS OF EXAMPLE 3 FOR DIFFERENT UNCERTAINTY LEVELS

	Exp. Cost \$			Realized Conf. Level %		
Uncertainty Level	w/o	$a = 2.5$	$a = 2.8$	w/o	$a = 2.5$	$a = 2.8$
0.3%	80707.7	78205.4	78203.6	79.9	99.7	99.9
0.4%	81167.9	78216.6	78215.2	77.0	99.7	99.8
0.5%	81927.2	78238.1	78232.5	74.6	99.5	99.9

The high-level net load variations and uncertainties are managed at 77.0% without the ramp capability product. If the ramp requirement constraints are enforced only ten minutes ahead based on the Gaussian-sigma rule, the realized level of confidence is 90.4%. The required 99% level of confidence is not satisfied as analyzed in Section III-B. By imposing the additional ramp requirement constraints five-minute ahead, the 99% level of confidence is effectively satisfied with a cost saving of 3.6% as a result of the better ramp management. By optimizing the number of standard deviations a, the cost is further reduced by \$1.4 at the expected level. This reduction can be up to 0.3% when wind suddenly drops.

In the above process, transmission constraints are not binding. To show the effectiveness of our design in relieving transmission congestions, the limit of each transmission line is reduced by 20% and the number of standard deviation is still optimized at $a^* = 2.8$. The value of congestion (\$) is quantified by the product of transmission constraint violation (MW) and the shadow price (\$/MWh) of that constraint over the twelve time intervals (5 minutes). The total value of congestion and the percentage when congestion occurs over the 1000 simulation runs are compared in Table IX. As can be seen, the transmission congestion is effectively relieved by our optimized design in terms of both the value of congestion and the percentage of occurrence.

The design is shown effective in achieving both reliability and cost-efficiency and its robustness with respect to different levels of wind penetration is then investigated by considering different net load uncertainties. Using the same initial range and stopping criteria, ramp requirements are designed for the net load uncertainty levels of 0.3%, 0.4% and 0.5% of the average net load. The optimized number of standard deviations is obtained at $a^* = 2.8$ for all the three cases. The associated expected cost and the realized confidence level are shown below as compared with the case without the ramp product and the case based on the Gaussian-sigma rule.

As can be seen, for different uncertainty levels, the net load is effectively satisfied at the required 99% level of confidence at the optimized number of standard deviations $a^* = 2.8$. By effectively managing the net load variations and uncertainties, major cost savings are obtained at $a^* = 2.8$. These cost savings are more than those obtained at $a = 2.5$ based on the Gaussian-sigma rule. The ramp requirement design is thus robust with respect to different levels of wind penetration.

VI. CONCLUSION

Different from traditional reserves, the ramp capability product is used to manage both net load variations and uncertainties. Its design can be subtle. This paper analyzed the subtle issues in satisfying the system reliability and cost efficiency. By imposing ramp requirement constraints on the economic dispatch at $t + 5\,\mathrm{min}$ to keep enough of the ramp capabilities secured at time t, the net load variations and uncertainties at $t + 10\,\mathrm{min}$ are effectively managed at the required level of confidence. Moreover, costs are minimized by using simulation-based optimization mimicking the real-time dispatch process through Monte Carlo simulation. This method can be used for generic system design when both system reliability and cost efficiency are concerned.

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