Market Solutions for Managing Ramp Flexibility With High Penetration of Renewable Resource

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***Abstract*—The impact of increased penetration of renewable generation has been the subject of much discussion related to system operations. As the percentage of generation from renewable generation provides us a greener and more sustainable future, it also introduces new challenges in scheduling and dispatching controllable resources to follow the net load and control the power balance in the system. The increased renewable generation tends to introduce more variability that must be met by the traditionally more flexible generation resources. Incentives are needed to encourage the existing generators of all types to maximize the availability of their operational "load following" flexibility and to encourage entry of new flexible suppliers such as energy storage devices or demand response.**

***Index Terms*—Ancillary service, load following, ramp capability, renewable generation, robust dispatch, security constrained economic dispatch (SCED).**

I. INTRODUCTION

THE wholesale electricity markets administered by Independent System Operators (ISOs) or Regional Transmission Operators (RTOs) include day-ahead and real-time markets. In real-time markets, the market clearing engine is most often based on a single interval security constraint economic dispatch solution [1]–[4]. Occasionally, the market designs lead to short duration price volatility that indicate desired market actions but challenge the reaction times of the market participants. Among the variety of reasons for such price spikes are temporary scarcity conditions created by resource ramp shortages. The main causes of ramp shortages in real time include the forecasted variability of load, interchange transactions, and noncontrollable variable energy resources at or beyond the dispatch horizon and the uncertainty associated with the short-term forecasts. Generating unit deviations from their set point instructions are another source of uncertainty in real-time operations. The highest contributor of variability and uncertainty with the current penetration level of renewable resources in RTO/ISO systems is still load. However, a higher penetration level of renewable resources which often provide limited control of their variable generation intensifies this problem both in forecast variability as well as uncertainty. Additionally, some of the SMART Grid initiatives or technologies (e.g., demand response and electrical vehicles) could increase uncertainty and variability, too.

Current practices in wholesale energy markets to compensate for such ramp shortages can be categorized as: increasing reserve margins, withholding some generation capacity and/or adding offset value to the forecasted load, starting fast start up units (mainly gas turbines), keeping some additional units online (not through market mechanisms), and in some cases utilizing look-ahead dispatch (multi-interval dispatch) in the real-time market (please refer to MISO, NYISO, CAISO, PJM, and NE-ISO websites and look for their market designs' manuals). Each of these solutions (or a combination of them) can handle the rampable capacity shortage problem at least from the reliability perspective. However, each can create some unwilling market distortion or remedy the issue not to its full scale.

What is required is a comprehensive approach in market clearing processes to address the required resource ramp capability to cover the multiple sources of variability and uncertainty to reduce the chances for ramp shortages and price spikes and maintain the robustness of reliable system operations. In other words, the market clearing process should manage the required level of flexibility among the generation resources by ensuring adequate flexible capacity is available and sending appropriate price signals to provide incentive for resources to continue offering their flexibility.

The next sections describe a methodology and problem formulation enhancements to meeting these objectives. The results of the method are demonstrated on a small test system.

II. METHODOLOGY

Within the Security Constrained Economic Dispatch (SCED) time frame, the ISOs/RTOs rely on dispatchable (controllable) resources responding to dispatch signals to maintain the power balance. The RTO uses the SCED to ramp these resources to maintain the power balance and to restore regulation capability that was employed to maintain system balance between SCED cycles. Controllable resources respond to the net load which includes the variability and uncertainty from load, noncontrollable resources and scheduled interchange where net load is defined as the following:

$$\begin{aligned}\text{Net Load} = {} & \text{Load} - \text{Noncontrollable Generation}\\ & + \text{Scheduled Interchanges (Exports} - \text{Imports).}\end{aligned}$$

The approach for quantifying the system ramp capability required to respond to expected net load variations in the load

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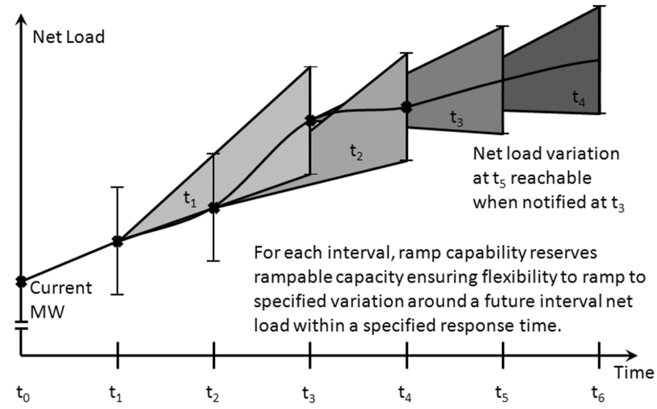

Fig. 1. Up- and down-ramp capability in SCED.

forecast, interchange schedules, noncontrollable generation, and resource deviation from set point instructions plus the additional variability due to uncertainty in the forecasts has been addressed in MISO white paper [5]. The requirement for following net load is identified for both upward and downward ramping needs in the form of rampable capacity within a specified time-frame (e.g., 10 min). These requirements are referred to as up- and down-ramp capability.

The proposed ramp capability model can be applied to operations planning, e.g., the day-ahead market at the MISO, through real-time economic dispatch to provide a determined quantity of ramp capability provided by controllable resources to respond to the net load variability. The purpose of this model is to provide robustness of system operations for a wider range of potential operating conditions and to reduce the frequency of short-term scarcity conditions which occur when resource ramp constraints lead to the inability to keep up with net load variations. With an expected increase in the variability of net load from planned higher penetrations of renewable resources, it follows that scarcity conditions may increase in frequency without additional efforts to achieve increased responsiveness from the existing controllable resources.

The proposed approach manages the ramp capability from controllable resources responding to dispatch instructions in a way that better positions them to be able to respond to variations and uncertainty in net load. The response available with the defined ramp capability is depicted in Fig. 1. As opposed to infrequent large net load variations which are compensated by deploying contingency reserve, these forecasted and unexpected variations in forecast are from many sources and happen frequently. A side advantage of this method is the fact that it creates a more robust dispatch which will shield the next SCED solution from facing an unattainable change in requirements. [6], [7].

Scheduling and dispatching resources in a way that increases their response capability may result in additional costs, but it has the benefit of increased responsiveness and reduction in the number of scarcity events. Attempting to eliminate all scarcity events with this approach is not practical as there could be some very rare events with high variations beyond the level of ramp capability that can be achieved at reasonable expense. A balance must be struck between the additional operating costs that are required to provide additional ramp capability and the avoided costs of prevented scarcity events.

The key features of the proposed model include the following:

- Ramp capability requirements (system-wide and zonal if required) which are specified to meet forecasted and uncertain variability within a defined response time.
- Resource contribution to ramp capability including allowance for availability offers and contributions from offline units if desired.
- Ramp capability demand curve to model the value of meeting the desired level variability coverage.
- Prices for up- and down-ramp capability products to provide market transparency and market-based incentives.
- Simultaneous cooptimization of the ramp capability with energy and ancillary services.

III. SOLUTION OPTIONS

With the similar purpose of providing a more robust market dispatch, the potential of time-coupled multi-interval optimization is also considered in conjunction with the ramp capability model. The ramp capability model and time-coupled multi-interval dispatch are related in their objective, but provide distinctly different functionality. The time-coupled dispatch allows preramping of units to maximize the economic use of ramp capability by enabling trading off the costs between intervals. By including future intervals in a time-coupled dispatch, the near-interval resource dispatch can adjust to accommodate *forecasted* variations in future intervals. The capacity reserved by the ramp capability model is available to respond to needed variation in demand, *either expected or unexpected*, for subsequent real-time dispatches. Both time-coupled dispatch and ramp capability are tools that can be used either alone or in combination to enable response to larger ramp requirements with the same generating fleet. As an alternative, ramp capability can be implemented as a requirement on a single interval dispatch in which the future interval forecasts are not directly included as part of the SCED.

IV. PROBLEM FORMULATION

The dispatch engine performs an optimization to identify the least cost dispatch subject to a number of operational requirements such as maintaining power balance, reserve requirements, transmission constraints, and the characteristics of supply resources. The detailed formulation of all of these constraints can vary with the implementation so this section describes the changes to the SCED objective function and constraints to implement the ramp capability model on a system-wide and zonal basis. In this formulation, the system-wide elements are represented as zonal elements where the zone would be defined to cover the entire system.

A. Objective Function

The up- and down-ramp capability demand curves can be specified for either system-wide or zonal ramp capability. The demand curve's incremental value of procured ramp capability may vary with quantity as the first few MWs may be more valuable than the last few MWs. For a cost minimization optimization where production costs are positive, the up- and down-ramp capability demand curves at the system-wide and zonal levels are represented by the following objective function term:

$$\sum\nolimits_t \left[\sum\nolimits_z C\left(\mathrm{RCup}_{\mathrm{DC}_{\mathrm{z,t}}}\right) + \sum\nolimits_z C\left(\mathrm{RCdn}_{\mathrm{DC}_{z,t}}\right)\right]$$

where

$\mathrm{RCup}_{\mathrm{DC}_{z,t}}$	cleared up-ramp capability from system-wide or zone z demand curve at time t;
$\mathrm{RCdn}_{\mathrm{DC}_{z,t}}$	cleared down-ramp capability from system-wide or zone z demand curve at time t;
$C(*)$	cost of the cleared demand from the demand curve.

B. Constraints

Provision of ramp capability requires 1) system-wide and zonal constraints which model the quantity of cleared ramp capability relative to the desired system-wide and zonal quantities as cleared by the demand curves, and 2) resource constraints which describe the ability of resources to provide ramp capability based on resource capabilities and other cleared products.

1) System and Zonal Constraints: The following constraints support system and zonal ramp capability constraints.

System and Zonal up-ramp capability

$$\forall t, \forall z : \sum\nolimits_{i \in z} \mathrm{RCup}_{G_{i,t}} \geq \mathrm{RCup}_{\mathrm{DC}_{z,t}}.$$

System and Zonal down-ramp capability

$$\forall t, \forall z : \sum\nolimits_{i \in z} \mathrm{RCdn}_{G_{i,t}} \geq \mathrm{RCdn}_{\mathrm{DC}_{z,t}}.$$

System and Zonal up-ramp demand curve max

$$\forall t, \forall z : \mathrm{RCup}_{\mathrm{DCmax}_{z,t}} \geq \mathrm{RCup}_{\mathrm{DC}_{z,t}}.$$

System and Zonal ramp down demand curve max

$$\forall t, \forall z : \mathrm{RCdn}_{\mathrm{DCmax}_{z,t}} \geq \mathrm{RCdn}_{\mathrm{DC}_{z,t}}$$

where

$\mathrm{RCup}_{G_{i,t}}$	up-ramp capability cleared for generator i at time t;
$\mathrm{RCdn}_{G_{i,t}}$	down-ramp capability cleared for generator i at time t;
$\mathrm{RCup}_{\mathrm{DCmax}_{z,t}}$	maximum desired up-ramp capability specified by the system-wide demand curve at time t;
$\mathrm{RCdn}_{\mathrm{DCmax}_{z,t}}$	maximum desired down-ramp capability specified by the system-wide demand curve at time t.

2) Resource Constraints: Online resources contributing ramp capability must coordinate the supply of the ramp capability with the supply of other products. Specifically, the capacity reserved for ramp capability cannot be shared with other products and the resource ramp rate can limit the ramp capability that can be delivered in the defined response time. The resource model used in the MISO formulation [1] is used in the following constraints. Other formulations are possible. Offline contributions toward up-ramp capability may be included if the offline resource can respond in the required time. For simplicity, offline resources are not considered in the following constraints.

Resource capacity maximum

$$\forall t, \forall i : P_{G_{i,t}} + \mathrm{RCup}_{G_{i,t}} + \mathrm{Reg}_{i,t} + \mathrm{Spin}_{i,t} + \mathrm{Supp}_{i,t} \leq P_{G\mathrm{max}_{i,t}} - \rho_{i,t}(P_{G\mathrm{max}_{i,t}} - P_{\mathrm{RegMax}_{i,t}}).$$

Resource capacity minimum

$$\forall t, \forall i : P_{G_{i,t}} - \mathrm{RCdn}_{G_{i,t}} - \mathrm{Reg}_{i,t} \geq P_{G\mathrm{min}_{i,t}} - \rho_{i,t}(P_{G\mathrm{min}_{i,t}} - P_{\mathrm{RegMin}_{i,t}}).$$

Resource up-ramp capability ramp rate

$$\forall t, \forall i : [\mathrm{RCupRM}/\mathrm{RCupDT}] \cdot \mathrm{RCup}_{G_{i,t}} \leq R_{i,t}^{\mathrm{up}}.$$

Resource down-ramp capability ramp rate

$$\forall t, \forall i : [\mathrm{RCdnRM}/\mathrm{RCdnDT}] \cdot \mathrm{RCdn}_{G_{i,t}} \leq R_{i,t}^{\mathrm{dn}}$$

where

$P_{G_{i,t}}$	energy cleared for generator i at time t;
$\mathrm{Reg}_{i,t}$	regulation cleared for generator i at time t;
$\mathrm{Spin}_{i,t}$	spinning reserve cleared for generator$i$ at time t;
$\mathrm{Supp}_{i,t}$	supplemental reserve cleared for generator i at time t;
$P_{G\mathrm{max}_{i,t}}$	maximum capacity when not regulating for generator i at time t;
$P_{G\mathrm{min}_{i,t}}$	minimum capacity when not regulating;
$\rho_{i,t}$	regulating flag l if generator i is regulating at time t;
$P_{\mathrm{RegMax}_{i,t}}$	maximum capacity when regulating for generator i at time t;
$P_{\mathrm{RegMin}_{i,t}}$	minimum capacity when regulating for generator i at time t;
RCupRM	up-ramp capability ramp multiplier; 1 for full ramp capability available to ramp capability;
RCupDT	up-ramp capability response time;
$R_{i,t}^{\mathrm{up}}$	maximum upward ramp rate for generator i at time t;

TABLE I
RESOURCE CHARACTERISTICS

Gen	Min (MW)	Max (MW)	Up Ramp Rate (MW/min)	Dn Ramp Rate (MW/min)	Offer Price ($/MWh)	Initial Output (MW)
G1	100	400	1	-1	25	400
G2	10	130	4	-4	30	130
G3	10	130	1	-1	31	33
G4	10	100	1	-1	36	10
G5	0	50	-	-	-	41

RCdnRM	down-ramp capability ramp multiplier; 1 for full ramp capability available to ramp capability;
RCdnDT	down-ramp capability response time;
$R_{i,t}^{\mathrm{dn}}$	minimum downward ramp rate for generator i at time t.

V. NUMERICAL ANALYSIS

The revised dispatch formulations were tested against a five-generator test system. The results from existing market rules and the revised formulation are compared. To focus the results on the impact of the ramp capability constraints, operating reserve constraints and transmission constraints are not included in the examples. The generator characteristics are described in Table I where generators G1–G4 are thermal generators and G5 is an intermittent resource not able to control to a dispatch signal. In this example, the controllable generators G1–G4 are dispatched to respond to the net load comprised of the load forecast minus the forecasted output of G5.

The examples show the application of the new ramp capability formulation over 20 min of market operation with a new dispatch calculated every 5 min. The following three examples are described: similar to the current MISO real-time, a series of single-interval dispatches is simulated with and without the ramp capability model; a series of four-interval time-coupled dispatches, which allows future expectations to influence the current interval dispatch through preramping of resources, is simulated with and without ramp capability model; and the second example is extended to include resources offering prices, or availability offers, for providing the ramp capability products.

A. Single Interval Dispatch

The current MISO real-time market dispatch is performed every 5 min for the next dispatch interval. A sequence of four market clearing solutions with and without the ramp capability model demonstrates the impact of the proposed approach on the robustness of the solution against future variations. The dispatch for each interval uses updated forecast data available at the time of that dispatch. The ramp capability response time is 10 min (two dispatch intervals) and the ramp capability requirement for the next 10 min is calculated as the difference in net load forecast (expected variation in the combined load and G5 forecasts) plus an additional 12 MWs of uncertainty with a minimum requirement of 0-MW ramp capability in both the up- or down-directions. The current forecast for T3 is used when calculating the ramp capability requirement for interval T1. By the time the T3 interval is calculated, its load forecast will have been updated, realizing the uncertainty modeled in the ramp capability requirement. For simplicity in presenting the data in this example, only the ramp capability requirement results are shown for each interval. For more detailed information about the load forecast for T3 when solving T1, see the additional data in the multi-interval dispatch example. The net load and desired up- and down-ramp capability for each interval are shown in Table II. The demand curve price for ramp capability is $20/MWh, but does not influence the results of these examples.

TABLE II
SINGLE INTERVAL LOAD AND RAMP REQUIREMENTS

	T1	T2	T3	T4
Load	614	620.5	624	621
G5 Wind	39	35	36	30
Net Load	575	585.5	588	591
Up Ramp	21	17.5	18	21
Dn Ramp	3	6.5	6	3

TABLE III
SINGLE INTERVAL DISPATCH CLEARED PRODUCTS

	Product	T1 (MW)		T2 (MW)		T3 (MW)		T4 (MW)	
		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
G1	Energy	400	400	400	400	400	400	400	400
	Up Ramp	-	0	-	0	-	0	-	0
	Dn Ramp	-	10	-	10	-	10	-	10
G2	Energy	130	129	130	130	130	130	130	129
	Up Ramp	-	1	-	0	-	0	-	1
	Dn Ramp	-	40	-	40	-	40	-	40
G3	Energy	35	36	40	41	45	46	50	51
	Up Ramp	-	10	-	10	-	10	-	10
	Dn Ramp	-	10	-	10	-	10	-	10
G4	Energy	10	10	15	14.5	13	12	11	11
	Up Ramp	-	10	-	10	-	10	-	10
	Dn Ramp	-	0	-	4.5	-	2	-	1
G5	Energy	39	39	35	35	36	36	30	30
	Up Ramp	-	0	-	0	-	0	-	0
	Dn Ramp	-	0	-	0	-	0	-	0

The cleared energy and ramp capability for each interval's dispatch in the simulated 20-min period are in Table III where the column numbers identify the dispatch scenario:

1) single interval dispatch without ramp capability;
2) single interval dispatch with ramp capability.

Although there is residual ramp capability available in Scenario 1, the up- and down-ramp capability values are not reported since ramp capability is not modeled. The up- and down-ramp capability reported in dispatch Scenario 2 includes the full available ramp capability when the ramp capability clearing price is zero since there is no cost for procuring additional ramp capability. This will result in the reported ramp capability in excess of the requirement. The following observations can be made about each of the generators:

TABLE IV
SINGLE INTERVAL DISPATCH CLEARING PRICES

Product	T1 ($/MWh)		T2 ($/MWh)		T3 ($/MWh)		T4 ($/MWh)	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Energy	31	31	3500	36	36	36	36	36
Up Ramp	-	1	-	0	-	0	-	6
Dn Ramp	-	0	-	0	-	0	-	0

- G1 is the least expensive base load unit that is loaded at its maximum in each interval with or without the ramp capability model. Being at its maximum, it does not provide any up-ramp capability, but does provide down-ramp capability.
- G2 is an inexpensive unit with a high ramp rate. It is economically loaded at its maximum most of the time, but with ramp capability, its output is reduced in some intervals to provide additional up-ramping capability within its 130-MW maximum operating limit. In dispatch Scenario 2, G2 is ramped up in the T1 interval and G3 is ramped down to provide more ramp capability which enables power balance to be maintained in dispatch Scenario 2, where it could not be maintained in dispatch Scenario 1. With G2's large ramp rate, it is able to provide 40 MW of ramp down capability.
- G3 is the marginal unit for energy in the T1 interval. In the subsequent intervals, it is ramping at its maximum ramp rate to reduce the use of more expensive generation and thus not setting the price. G3 provides future ramp capability in both up- and down directions in all intervals. In dispatch Scenario 2, the up-ramp capability constraint in T1 causes G3's T1 output to be increased by 1 MW. This increased output continues through G3's ramp constrained intervals T2, T3, and T4.
- G4 is an expensive unit. It is dispatched above its minimum when additional power is required and the other units are out of capacity and/or ramp capability. Being near its minimum, it is able to provide up-ramp capability in all intervals, but down-ramp capability only to the extent it is dispatched above its minimum.
- G5 is assumed to operate at its forecasted output with or without ramp capability model. Since it does not respond to dispatch, it is not eligible to provide ramp capability products.

The dispatch prices for energy and ramp capability are shown in Table IV for dispatch Scenarios 1 and 2 where both up- and down-ramp capability products are priced in dollars per MW per hour ($/MWh). Generation shortages are priced at $3500/MWh.

The largest difference in the prices is in T2 where without the ramp capability model, the generation is not able to ramp to match the change in net load and power balance is not maintained. The dispatch Scenario 1 T2 energy price rises to $3500/MWh to reflect this short-term ramping shortage. The inclusion of the ramp capability model provides the T2 dispatch with enough flexibility that it can maintain power balance and the energy price of $36/MWh is set by G4. This type of short-duration price spike will be reduced by the additional operational flexibility provide by the ramp capability model.

The up-ramp capability price is nonzero in T1 and T4 when the inexpensive G2 was brought down from its max to provide ramp capability. In T2, the $1/MWh up-ramp capability price represents the redispatch between G2 ($30/MWh) and G3 ($31/MWh) that would be required to respond to an incremental change in ramp up requirements. Similarly, the $6/MWh price in T4 represents redispatch between G2 and G4 ($36/MWh). With excess down-ramp capability, the down-ramp capability price is zero in every interval.

B. *Multiple Interval Time-Coupled Dispatch*

Extending the real-time dispatch from a single interval to multiple intervals in each dispatch and coupling the time intervals through resource ramp constraints allows the dispatch to consider the forecasted future intervals and adjust resource outputs to begin earlier ramping for anticipated changes. When combined with the ramp capability model designed to provide operational flexibility to address the uncertainties in the forecast, the dispatch can be even more robust for future operating conditions.

Two dispatch scenarios are provided to demonstrate the application of the ramp capability model to a multiple interval dispatch:

3) time-coupled multi-interval dispatch without ramp capability;
4) time-coupled multi-interval dispatch with ramp capability.

Each 5-min dispatch includes a number of future intervals beyond the target dispatch interval. In these examples, three additional 5-min intervals are included with each dispatch interval. As in dispatch Scenario 2, the ramp capability requirement is calculated using a 10-min response time plus an additional 12 MWs of uncertainty in both the up and down direction. With each dispatch, the future interval forecast changes. Table V below shows the load forecast that is in effect at the time of each dispatch. An additional two intervals, e.g., T5 and T6 for the first interval, are included for each dispatch to support 10-min ramp capability requirement calculations.

Tables VI and VII show the results of the first interval of each dispatch in Scenarios 3 and 4. With the multi-interval dispatch approach, only the first interval would normally be deployed since the next dispatch will recalculate the results for the subsequent intervals with more up-to-date forecast assumptions. For example, the T2 multi-interval dispatch covers intervals T2 through T5. Only the T2 results are shown since the subsequent dispatch for T3 will become the final dispatch for the T3 interval and is displayed in the T3 column.

For dispatch Scenarios 3 and 4, the difference with and without the ramp capability model are relatively small. Based on economic savings of avoiding G4 generation in T2 seen by the multi-interval dispatch, G3 output is increased and G2 output decreased in T1 which provides more ramping capability to meet the change in load required for the T2 dispatch in both dispatch Scenario 3 and 4. This enables both scenarios to reach the energy demand in T2. In fact, the response to the future interval forecasts supplies enough up-ramp capability such that ramp capability constraints are not binding in T1. The dispatch

TABLE V
EXAMPLE LOAD AND RAMP REQUIREMENTS

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Load	614	620	620	617	613	614			
G5 Wind	39	38	36	29	20	15			
Net Load	575	582	584	588	593	599			
Up Ramp	21	18	21	23					
Dn Ramp	3	6	3	1					
Load		620.5	622	622	618	618	619		
G5 Wind		35	34	31	24	18	15		
Net Load		585.5	588	591	594	600	604		
Up Ramp		17.5	18	21	22				
Dn Ramp		6.5	6	3	2				
Load			624	624	620	619	617	617	
G5 Wind			36	33	26	19	13	10	
Net Load			588	591	594	600	604	607	
Up Ramp			18	21	22	19			
Dn Ramp			6	3	2	5			
Load				621	618	617	616	616	619
G5 Wind				30	24	17	12	9	8
Net Load				591	594	600	604	607	611
Up Ramp				21	22	19	19		
Dn Ramp				3	2	5	5		

TABLE VI
MULTIPLE INTERVAL DISPATCH CLEARED PRODUCTS

	Product	T1 (MW)		T2 (MW)		T3 (MW)		T4 (MW)	
		(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)
G1	Energy	400	400	400	400	400	400	400	400
	Up Ramp	-	0	-	0	-	0	-	0
	Dn Ramp	-	10	-	10	-	10	-	10
G2	Energy	128	128	130	130	130	130	130	129
	Up Ramp	-	2	-	0	-	0	-	1
	Dn Ramp	-	40	-	40	-	40	-	40
G3	Energy	37	37	42	42	47	47	51	52
	Up Ramp	-	10	-	10	-	10	-	10
	Dn Ramp	-	10	-	10	-	10	-	10
G4	Energy	10	10	13.5	13.5	11	11	10	10
	Up Ramp	-	10	-	10	-	10	-	10
	Dn Ramp	-	0	-	3.5	-	1	-	0
G5	Energy	39	39	35	35	36	36	30	30
	Up Ramp	-	0	-	0	-	0	-	0
	Dn Ramp	-	0	-	0	-	0	-	0

TABLE VII
MULTIPLE INTERVAL DISPATCH CLEARING PRICES

Product	T1 ($/MWh)		T2 ($/MWh)		T3 ($/MWh)		T4 ($/MWh)	
	(3)	(4)	(3)	(4)	(3)	(4)	(3)	(4)
Energy	30	30	36	36	36	36	31	36
Up Ramp	-	0	-	0	-	0	-	6
Dn Ramp	-	0	-	0	-	0	-	0

TABLE VIII
RESOURCE RAMP CAPABILITY AVAILABILITY OFFERS

Gen	Up Ramp Cap. Price ($/MWh)	Dn Ramp Cap. Price ($/MWh)
G1	1.2	0.8
G2	0.6	0.5
G3	0.75	0.3
G4	2.65	2.2
G5	-	-

TABLE IX
CLEARED PRODUCTS WITH AVAILABILITY OFFERS

	Product	T1 (MW)	T2 (MW)	T3 (MW)	T4 (MW)
G1	Energy	400	400	400	400
	Up Ramp	0	0	0	0
	Dn Ramp	0	0	0	0
G2	Energy	127	130	130	128
	Up Ramp	3	0	0	2
	Dn Ramp	0	0	0	0
G3	Energy	38	43	48	53
	Up Ramp	10	10	10	10
	Dn Ramp	3	6.5	6	3
G4	Energy	10	12.5	10	10
	Up Ramp	8	7.5	8	9
	Dn Ramp	0	0	0	0
G5	Energy	39	35	36	30
	Up Ramp	0	0	0	0
	Dn Ramp	0	0	0	0

difference Scenarios 3 and 4 can be seen in the T4 dispatch where the ramp capability model dispatches G3 up and G2 down to create additional ramp capability in preparation for future uncertainty. With this change in dispatch, G3 becomes ramp constrained and G4 becomes the marginal unit for energy.

C. *Ramp Capability Availability Offers*

In the previous examples, resources providing ramp capability are paid a nonzero ramp capacity price when a resource experiences an opportunity cost to economically provide another product such as energy. This reflection of opportunity cost in ramp capability pricing makes resources economically indifferent to providing ramp capability if they incur no additional operating costs in providing the ramp capability service. If market designers believe that there are costs associated with providing ramp capability, availability offers for up- and down-ramp capability can be introduced to allow these costs to be explicitly modeled in the market clearing decisions. With resource availability offers modeled in the market clearing objective function, the ramp capability clearing prices become the sum of opportunity cost and availability offers.

To demonstrate the application of availability offers for ramp capability, dispatch Scenario 4 is extended to include availability offers. The generator availability offers are shown in Table VIII.

Similar to Tables VI and VII, Tables IX and X report the cleared products and prices with the availability offers included. The availability offers influence the market clearing solution with changes in both product clearing quantities and prices. For

TABLE X
PRODUCT CLEARING PRICES WITH AVAILABILITY OFFERS

Product	T1 ($/MWh)	T2 ($/MWh)	T3 ($/MWh)	T4 ($/MWh)
Energy	32.05	36	36	32.05
Up Ramp	2.65	2.65	2.65	2.65
Dn Ramp	0.3	0.3	0.3	0.3

example, in T1, the change in the relative economics of the resources redispatch of G2 and G3 up to the G3 ramp limit to provide up-ramp capability on G2 has become more economic than clearing additional up-ramp capability on G4. Since G4 is the marginal resource for up-ramp capability and has no opportunity cost for providing additional ramp capability, the up-ramp capability price is equal to the G4 availability offer. By changing the relationships between costs, the availability offers also impact the energy prices. Finally, the nonzero down-ramp capability price has significantly changed the reported down-ramp capability on each resource. When the price is zero, all available down-ramp capability quantities are reported since the price to procure the down-ramp capability is zero. When the price is nonzero, only amounts up to the requirement are reported since excess ramp capability would have an additional cost.

VI. CONCLUSION

With expected increases in the variability of net load experienced in real-time operations, particularly in the uncertain component of the variability, the proposed approach is a viable option for providing increased response capability from the same set of resources with either a single interval or time-coupled multi-interval SCED dispatch. The formulation allows the amount of ramp capability required to be adjusted based on the forecasted deviations, historical uncertainties, and/or the current policy for the degree of variability to be covered. The ramp capability model could be implemented relatively simply using opportunity cost payments as a mechanism to reimburse resources providing additional ramp capability, or it could be implemented as a product with its own pricing to provide clearer economic signals to the marketplace. The proposed approach provides a low impact method to address the operational needs accompanying increasing variations which if unaddressed may in turn cause increasing frequency of scarcity events.

The preliminary results of this approach demonstrate the effectiveness of the positioning of the dispatchable generators to reduce the instances of short-term scarcity conditions and the associated price volatility caused by insufficient ramp capability in the real-time market, without an undue increase in costs. The same set of ramp constraints and objective function components can be included in the day-ahead and real-time markets to encourage price convergence. Comparing these results with those obtained from the legacy approach show a slight potential increase in real-time LMP, but overall reduction is expected when considering all components of the settlements such as uplifts, revenue sufficiency guarantee, and scarcity pricing events.

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