California ISO

Flexible Ramping Product Refinements: Appendix B

Procurement and Deployment Scenarios
Draft Technical Description

George Angelidis, Ph.D.
Power System Technology Development

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1 INTRODUCTION

This technical paper describes an enhancement to the Flexible Ramping Product (FRP) procurement in the Real-Time Market (RTM) to address situations where FRP awards are awarded behind binding transmission constraints that would prevent their deployment when uncertainty materializes. FRP awards are awarded based on the opportunity cost of reserved capacity versus the revenue from dispatching this capacity as energy. For resources constrained by binding transmission constraints, there is no opportunity cost for reserving capacity above their constrained energy dispatch; therefore, the RTM awards FRP to that capacity to minimize the overall operating cost. This is because the current FRP procurement in the RTM, with its extension to the Energy Imbalance Market (EIM), is at the Balancing Authority Area (BAA) level without any regard to binding transmission constraints.

The existing method seriously undermines the quality and objective of the FRP initiative, and it also raises a reliability concern because the system may be ill-prepared to respond to large amounts of uncertainty when they materialize in real time. The proposed method in this technical paper, as part of the FRP Refinements initiative, procures locational FRP awards that their full deployment does not violate transmission constraints or scheduling limits in the entire EIM Area. This is achieved by augmenting the RTM mathematical optimization problem with FRP deployment scenarios subject to the same transmission constraints that are enforced in the original problem of serving the demand forecast. Although there are potentially many FRP deployment scenarios depending on how much and where uncertainty may materialize in the system, only the two following deployment scenarios are selected for simplicity:

1) Flexible Ramp Up (FRU) deployment of all FRU awards to meet the maximum upward uncertainty requirement (97.5 uncertainty percentile) that materializes pro rata on the demand forecast for each BAA in the EIM Area, net of any FRU elastic demand relaxation.
2) Flexible Ramp Down (FRD) deployment of all FRD awards to meet the maximum downward uncertainty requirement (2.5 uncertainty percentile) that materializes pro rata on the demand forecast for each BAA in the EIM Area, net of any FRD elastic demand relaxation.

The enhancement provides also an opportunity to redesign the FRP procurement in EIM, which is currently overly complex and not entirely accurate in modeling EIM diversity.

1.1 CURRENT FRP PROCUREMENT IMPLEMENTATION

In the current implementation, FRU/FRD is procured with different constraints for each BAA and a constraint for the entire EIM Area. If a BAA has passed the FRU/FRD sufficiency test, the FRU/FRD requirement for that BAA is not only reduced by the FRU/FRD demand elasticity, but also by the available net import/export transfer capacity from/to other BAAs in the EIM Area to maximize the benefits of BAA diversity and economic displacement by participating in the EIM. On the contrary, if a BAA has failed the FRU/FRD sufficiency test, the FRU/FRD requirement for that BAA is only reduced by the FRU/FRD demand elasticity and a FRU/FRD credit equal to the net transfer that is optimally scheduled above/below the net base transfer. The justification for the credit is that it can be recalled in the next market run if needed to address materialized uncertainty. An additional constraint is enforced for each BAA that has failed the FRU/FRD sufficiency test to limit its net transfer import/export below/above its net base transfer to prevent leaning on other BAAs in the EIM Area.

Besides ignoring transmission constraints, the current implementation has the following drawbacks:

- For a BAA that has passed the FRU/FRD sufficiency test, the calculation of the net import/export transfer capacity from/to other BAAs in the EIM Area considers only the available transfer capacity on the transfers of that BAA alone. Subtracting that net import/export transfer capacity from the FRU/FRD requirement of that BAA assumes that it can be fully used to satisfy the FRU/FRD requirement in that BAA from other BAAs in the EIM Area. However, that may not be possible due to transfer constraints beyond the BAA boundary and resource ramp capability constraints, which are not considered in this evaluation.
- Similarly, when the uncertainty materializes in a BAA that has failed the FRU/FRD sufficiency test, it is assumed that the FRU/FRD credit for that BAA can be fully cashed out by recalling net export/import transfer above/below the net base transfer. However, that may not be possible due to transfer constraints beyond the BAA boundary and resource ramp capability constraints, which are not considered in this evaluation.
- The FRU/FRD awards in a BAA satisfy the FRU/FRD requirements not only in that BAA, but also in the EIM Area. Similarly, the FRU/FRD demand elasticity in a BAA reduces the FRU/FRD requirements not only in that BAA, but also in the EIM Area, because otherwise, the demand elasticity in that BAA may be substituted by additional FRU/FRD awards outside that BAA, or by FRU/FRD demand elasticity at the EIM Area level. Nevertheless, additional constraints must be enforced to prevent FRU/FRD demand elasticity in excess of the minimum required to result in no FRU/FRD awards in that BAA when the cost of the former is less than the cost of the latter. These constraints compound on the complexity of the FRP procurement method resulting in an overly complex and non-transparent model.

1.2 PROPOSED ENHANCEMENT

In the proposed enhancement, the FRU/FRD procurement is significantly simplified for BAAs that have passed the FRU/FRD sufficiency test by formulating a single constraint for the extreme uncertainty in the entire BAA group, reduced by the FRU/FRD demand elasticity in that BAA group, while enforcing all transmission and transfer constraints in the FRU/FRD deployment scenarios. The result is locational FRU/FRD awards that their full deployment does not violate any transmission or transfer constraints in the entire EIM Area. Furthermore, for each BAA that has failed the FRU/FRD sufficiency test, FRU/FRD is procured separately for the respective FRU/FRD requirement, which is only reduced by the FRU/FRD demand elasticity in that BAA, without any FRU/FRD credit. An additional constraint is enforced for each BAA that has failed the FRU/FRD sufficiency test to limit its net transfer import/export below/above its net base transfer to prevent leaning on other BAAs in the EIM Area.

FRU/FRD credit is not supported in this method because the FRU/FRD procurement for BAAs that have failed the FRU/FRD sufficiency test is strictly separate from the FRU/FRD procurement for BAAs that have passed the FRU/FRD sufficiency test. Allowing a FRU/FRD credit for BAAs that have failed the FRU/FRD sufficiency test must appear as an additional FRU/FRD requirement for the group of BAAs that have passed the FRU/FRD sufficiency test. This would overly complicate the FRU/FRD cost allocation.

Without FRU/FRD credit, the FRU/FRD cost allocation is greatly simplified because the FRU/FRD cost is contained within each BAA that has failed the FRU/FRD sufficiency test, and the group of BAAs that have passed the FRU/FRD sufficiency test. Moreover, the FRU/FRD credit for a BAA depends on the net transfer for that BAA, which is the mismatch of the power balance constraint for that BAA. Including FRU/FRD credit in the FRU/FRD procurement constraints would couple the Energy schedule directly with the FRU/FRD awards, resulting in complex price formation where the marginal price for Energy would have price contributions from the FRU/FRD procurement constraints. Without FRU/FRD credit, the marginal price for Energy is free from FRU/FRD price contributions, with the exception of marginal congestion contributions from binding transmission constraints in the FRU/FRD deployment scenarios.

2 ASSUMPTIONS

The following assumptions are made in this technical paper:

- There are no capacity bids for FRU/FRD; they are priced at opportunity costs.
- Variable Energy Resources (VERs) are scheduled up to their forecast and they may be awarded FRD; VER FRD awards are deployed in the FRD deployment scenario.
- The FRU/FRD deployment scenarios ignore additional marginal losses due to FRU/FRD award deployment. This allows a simple formulation of transmission constraints in the deployment scenarios extending the linearization from the AC Power Flow (ACPF) in the original problem of serving the demand forecast. This also simplifies the locational marginal price formation for FRU/FRD awards because there will not be a marginal loss component. Moreover, the pricing of Energy is not coupled directly with the pricing of FRU/FRD, save for marginal congestion contributions from binding transmission constraints in the FRU/FRD deployment scenarios.
- All physical transmission constraints that are enforced in the original problem including base case and contingency constraints are also enforced in the FRU/FRD deployment scenarios.
- All scheduling constraints that are enforced in the original problem such as transfer and ITC/ISL constraints are also enforced in the FRU/FRD deployment scenarios.

3 NOTATION

The following notation is used in this technical paper:

i	Resource/node index.
j, k	BAA indices (0 for CISO).
l	Energy transfer schedule (ETSR) index.
r	Ancillary services region index.
m	Transmission or ITC/ISL constraint index.
$^{(u)}$	Superscript denoting FRU deployment scenario values.
$^{(d)}$	Superscript denoting FRD deployment scenario values.
T_5	Flexible Ramp time domain (5min).
T_{10}	Ancillary Services time domain (10min).
T_{15}	Ancillary Services awards duration (15min).
T_{30}	Sustained energy time period for contingency reserve dispatch (30min).
ΔT	Time period duration (15min in FMM and 5min in RTD).
N	Number of time periods in the FMM/RTD time horizon.
GAF	Granularity adjustment factor (⅓ in FMM and 1 in RTD).
ASF	Ancillary Services adjustment factor (1 in FMM and ½ in RTD).
$\forall$	For all…
$\in$	Member of…
$\notin$	Not member of…
$\wedge$	Logical and…
$\cup$	Union…
$\cap$	Intersection…
$\rightarrow$	Leads to…
Δ	Denotes incremental values from the previous iteration.
BAA_j	Set of resources in BAA *j*.
EIM	Set of resources in the EIM Area.
PU_t	Set of BAAs that pass the Flexible Ramp Up sufficiency test in time period *t*.
PD_t	Set of BAAs that pass the Flexible Ramp Down sufficiency test in time period *t*.
S_5	Set of 5min-start units ($SUT \leq 5$min) that can provide FRU from offline status ($u = 0$).
S_{10}	Set of Fast-Start Units ($SUT \leq 10$min) that can be certified to provide Non-Spinning Reserve from offline status ($u = 0$).
S_r	Set of resources in Region *r*.
I_m	Set of import resources, including ETSRs, associated with ITC/ISL *m*.
E_m	Set of export resources, including ETSRs, associated with ITC/ISL *m*.
S_m	Set of intertie resources, including ETSRs, associated with ITC/ISL m; $S_m = I_m \cup E_m$.
S_{PSH}	Set of Pumped-Storage Hydro Resources.
S_{LESR}	Set of Limited Energy Storage Resources.

$u_{i,t}$	Binary (0/1) variable indicating commitment status (offline/online) for Resource *i* in time period *t*. For Pumped-Storage Hydro Resources, 1 indicates generating mode operation. For Limited Energy Storage Resources, 1 indicates discharging mode operation.
$v_{i,t}$	Binary (0/1) variable for Pumped-Storage Hydro Resources indicating pumping mode operation in time period *t*.
$y_{i,t}$	Binary (0/1) variable indicating that Resource *i* has a start-up in time period *t*.
η_i	Pumping efficiency of Pumped-Storage Hydro Resource *i*, or charging efficiency of Limited Energy Storage Resource *i*.
C	Objective function.
$LOL_{i,t}$	Lower Operating Limit of Resource *i* in time period *t*.
$UOL_{i,t}$	Upper Operating Limit of Resource *i* in time period *t*.
$LRL_{i,t}$	Lower Regulating Limit of Resource *i* in time period *t*.
$URL_{i,t}$	Upper Regulating Limit of Resource *i* in time period *t*.
$LEL_{i,t}$	Lower Economic Limit of Resource *i* in time period *t*.
$UEL_{i,t}$	Upper Economic Limit of Resource *i* in time period *t*.
$CL_{i,t}$	Capacity Limit for Resource *i* in time period *t*; $UEL_{i,t} \leq CL_{i,t} \leq UOL_{i,t}$; it defaults to $UOL_{i,t}$; it is used to limit regulation awards.
$LCL_{i,t}$	Lower Capacity Limit of Resource *i* in time period *t*.
$UCL_{i,t}$	Upper Capacity Limit of Resource *i* in time period *t*.
$SUC_{i,t}$	Start-Up Cost for Resource *i* in time period *t*.
$SUT_{i,t}$	Start-Up Time for Resource *i* in time period *t*.
$MLC_{i,t}$	Minimum Load Cost for Resource *i* in time period *t*.
$PC_{i,t}$	Pumping cost for Pumped Storage Hydro Resource *i* in time period *t*.
$PL_{i,t}$	Pumping level for Pumped Storage Hydro Resource *i* in time period *t*.
$EN_{i,t}$	Energy schedule of Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
$D_{j,t}$	Demand forecast for BAA *j* in time period *t*.
$T_{j,t}$	Net transfer of EIM BAA *j* in time period *t*; positive for export and negative for import.
$\tilde{T}_{j,t}$	Net base transfer of EIM BAA *j* in time period *t*.
$\underline{T}_{j,t}$	Lower scheduling limit on net transfer of BAA *j* in time period *t*.
$\overline{T}_{j,t}$	Upper scheduling limit on net transfer of BAA *j* in time period *t*.
$IT_{j,k,l,t}$	Import energy transfer schedule (ETSR) *l* to BAA *j* from BAA *k* in time period *t*.
$ET_{j,k,l,t}$	Export energy transfer schedule (ETSR) *l* from BAA *j* to BAA *k* in time period *t*.
$\widetilde{IT}_{j,k,l,t}$	Base import energy transfer schedule (ETSR) *l* to BAA *j* from BAA *k* in time period *t*.
$\widetilde{ET}_{j,k,l,t}$	Base export energy transfer schedule (ETSR) *l* from BAA *j* to BAA *k* in time period *t*.

$\overline{IT}_{j,k,l,t}$	Scheduling limit of the import energy transfer schedule (ETSR) l to BAA j from BAA k in time period t.
$\overline{ET}_{j,k,l,t}$	Scheduling limit of the export energy transfer schedule (ETSR) l from BAA j to BAA k in time period t.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i for potential delivery in time period t.
$FRD_{i,t}$	Flexible Ramp Down award of Resource i for potential delivery in time period t.
$FRUS_{j,t}$	Flexible Ramp Up surplus (elastic demand) in BAA j in time period t.
$FRDS_{j,t}$	Flexible Ramp Down surplus (elastic demand) in BAA j in time period t.
$FRUS_{t}$	Flexible Ramp Up surplus (elastic demand) in the group of BAAs that pass the Flexible Ramp Up sufficiency test in time period t.
$FRDS_{t}$	Flexible Ramp Down surplus (elastic demand) in the group of BAAs that pass the Flexible Ramp Down sufficiency test in time period t.
$RU_{i,t}$	Regulation Up award of Resource i in time period t.
$RD_{i,t}$	Regulation Down award of Resource i in time period t.
$SR_{i,t}$	Spinning Reserve award of Resource i in time period t.
$NR_{i,t}$	Non-Spinning Reserve award of Resource i in time period t.
$RUBC_{i,t}$	Regulation Up bid capacity of Resource i in time period t.
$RDBC_{i,t}$	Regulation Down bid capacity of Resource i in time period t.
$SRBC_{i,t}$	Spinning Reserve bid capacity of Resource i in time period t.
$NRBC_{i,t}$	Non-Spinning Reserve bid capacity of Resource i in time period t.
$ENBP_{i,t}$	Energy bid price of Resource i in time period t.
$FRUSP_{j,t}$	Flexible Ramp Up surplus (elastic demand) price in BAA j in time period t.
$FRDSP_{j,t}$	Flexible Ramp Down surplus (elastic demand) price in BAA j in time period t.
$FRUSP_{t}$	Flexible Ramp Up surplus (elastic demand) price in the group of BAAs that pass the Flexible Ramp Up sufficiency test in time period t.
$FRDSP_{t}$	Flexible Ramp Down surplus (elastic demand) price in the group of BAAs that pass the Flexible Ramp Down sufficiency test in time period t.
$RUBP_{i,t}$	Regulation Up bid price of Resource i in time period t.
$RDBP_{i,t}$	Regulation Down bid price of Resource i in time period t.
$SRBP_{i}$	Spinning Reserve bid price of Resource i in time period t.
$NRBP_{i,t}$	Non-Spinning Reserve bid price of Resource i in time period t.
$FRUR_{j,t}$	Flexible Ramp Up requirement in BAA j in time period t.
$FRDR_{j,t}$	Flexible Ramp Down requirement in BAA j in time period t.
$FRUR_{t}$	Flexible Ramp Up requirement in the group of BAAs that pass the Flexible Ramp Up sufficiency test in time period t.
$FRDR_{t}$	Flexible Ramp Down requirement in the group of BAAs that pass the Flexible Ramp Down sufficiency test in time period t.
$RUR_{r,t}$	Regulation Up requirement in Region r and time period t.
$RDR_{r,t}$	Regulation Down requirement in Region r and time period t.
$SRR_{r,t}$	Spinning Reserve requirement in Region r and time period t.
$NRR_{r,t}$	Non-Spinning Reserve requirement in Region r and time period t.
$RRU_{i}(p,\tau)$	Piecewise linear ramp up capability function of Resource i from energy schedule p for time domain τ.

$RRD_i(p,\tau)$	Piecewise linear ramp down capability function of Resource *i* from energy schedule *p* for time domain τ.
$\underline{RRU}_{i,t}(\tau)$	Lowest ramp up capability within the applicable operating range of Resource *i* in time period *t* for time domain τ.
$\underline{RRD}_{i,t}(\tau)$	Lowest ramp down capability within the applicable operating range of Resource *i* in time period *t* for time domain τ.
$LPF_{i,t}$	Loss penalty factor for node *i* in time period *t*.
$SF_{i,m,t}$	Shift factor for energy injection at node *i* on network constraint *m* in time period *t*.
$F_{m,t}$	Active power flow or scheduled flow on network constraint *m* in time period *t*.
$\tilde{F}_{m,t}$	Initial active power flow or scheduled flow from the ACPF solution on network constraint *m* in time period *t*.
$LFL_{m,t}$	Lower active power flow or scheduling limit on network constraint *m* in time period *t*.
$UFL_{m,t}$	Upper active power flow or scheduling limit on network constraint *m* in time period *t*.
α	Shared ramping coefficient for Regulation.
β	Shared ramping coefficient for Spinning Reserve.
γ	Shared ramping coefficient for Non-Spinning Reserve.
δ	Shared ramping coefficient for Flexible Ramp.
$\overline{EN}_i$	Maximum Energy Limit for Resource *i* in a given RTM run.
$\underline{EN}_i$	Minimum Energy Limit for Resource in a given RTM run.
$SOC_{i,t}$	State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\overline{SOC}_{i,t}$	Maximum State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\underline{SOC}_{i,t}$	Minimum State of Charge for Limited Energy Storage Resource *i* in time period *t*.
$\lambda_{j,t}$	Shadow price of energy balance constraint for BAA *j* in time period *t*.
$\rho_{j,t}$	Shadow price of FRU deployment scenario constraint for BAA *j* in time period *t*.
$\sigma_{j,t}$	Shadow price of FRD deployment scenario for BAA *j* in time period *t*.
ρ_t	Shadow price of FRU deployment scenario constraint for the group of BAAs that pass the FRU sufficiency test in time period *t*.
σ_t	Shadow price of FRD deployment scenario for the group of BAAs that pass the FRD sufficiency test in time period *t*.
$\mu_{m,t}$	Shadow price of network constraint *m* in time period *t*.
$LMP_{i,t}$	Locational Marginal Price for Energy at node *i* in time period *t*.
$FRUMP_{i,t}$	Marginal Price for the Flexible Ramp Up award of Resource *i* in time period *t*.
$FRDMP_{i,t}$	Marginal Price for the Flexible Ramp Down award of Resource *i* in time period *t*.

4 MATHMATICAL FORMULATION

The focus of the mathematical formulation in this technical paper is on the extension of the EIM problem with the network constraints in the FRU/FRD deployment scenarios. Emphasis is given on the particular elements that are required for this task. Known existing features that apply in general to the Security Constrained Unit Commitment (SCUC) engine, such as unit commitment, inter-temporal constraints, MSG modeling, nomograms, and soft constraint penalty relaxation or scarcity treatment, are not included for simplicity. These features do not materially affect the extension of the EIM problem with the FRU/FRD deployment scenarios.

4.1 GENERAL PROBLEM FORMULATION

The SCUC problem is a Mixed Integer Linear Programming (MILP) formulation of minimizing the objective function subject to equality and inequality constraints:

$$\begin{array}{cc} \min & C(\mathbf{x}) \\ \text{s.t.} & \begin{array}{c} \mathbf{A}_{eq}\,\mathbf{x} = \mathbf{b}_{eq} \\ \mathbf{A}\,\mathbf{x} \leq \mathbf{b} \end{array} \end{array}$$

4.2 FLEXIBLE RAMP CAPACITY MODEL

This section gives a brief overview of the Flexible Ramp Capacity model without any ancillary services and EIM transfers for simplicity. Figure 1 below shows the Energy schedule and the FRU/FRD deployment scenario targets in a given time interval.

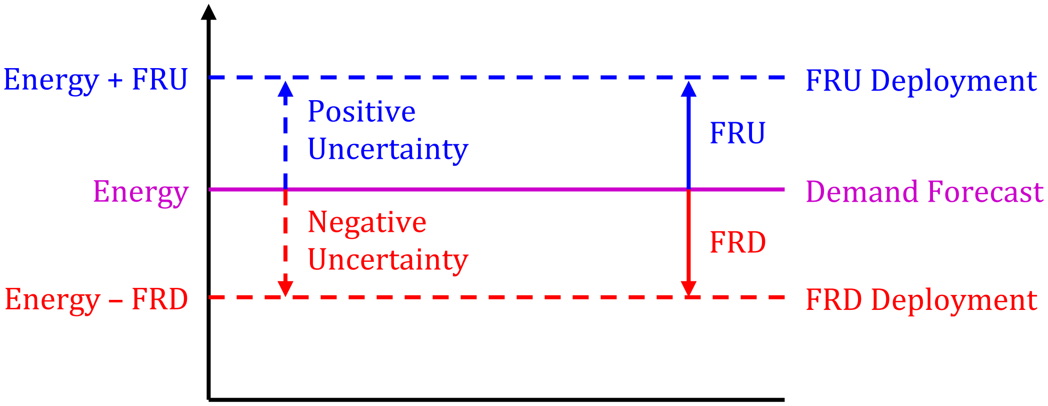

Figure 1. RTM targets for Energy and FRU/FRD

The constraints to meet these targets in the RTM problem are as follows:

$$\left.\begin{array}{l}\sum_i EN_{i,t} = D_t \\ \sum_i FRU_{i,t} \geq FRUR_t \\ \sum_i FRD_{i,t} \geq FRDR_t\end{array}\right\}, t = 1,2,\ldots,N$$

FRU/FRD is ramping capacity between intervals reserved to meet uncertainty in the net demand forecast that may materialize in the next market run. Figure 2 shows the potential FRU/FRD awards for a physical resource in a given time interval that can be reserved based on its energy schedule in the previous time interval and its ramp capability.

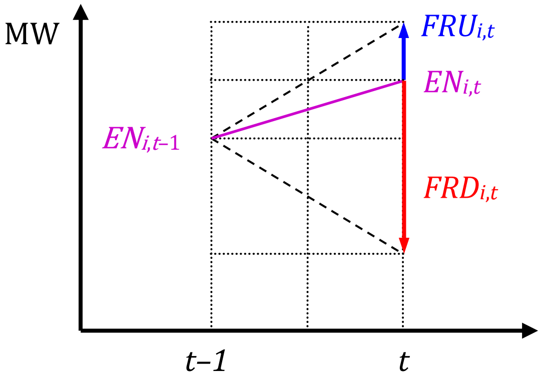

Figure 2. Energy schedules and FRU/FRD awards

The dashed lines represent the upward and downward ramp capability of the resource from its energy schedule in the previous time interval. The FRU/FRD awards are limited by that ramp capability; they represent ramping capacity that is reserved from the scheduled ramp from the previous time interval to the next time interval to meet any uncertainty that may materialize in next market run.

The energy schedules and FRU/FRD awards are calculated simultaneously by co-optimizing all commodities. They are constrained by the following set of capacity and ramp capability constraints:

$$\left.\begin{array}{l}LEL_{i,t} + FRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t} - FRU_{i,t} \\ GAF\left(EN_{i,t} - EN_{i,t-1}\right) \leq RRU_i\left(EN_{i,t-1}, T_5\right) - \delta\, FRU_{i,t} \\ GAF\left(EN_{i,t} - EN_{i,t-1}\right) \geq -RRD_i\left(EN_{i,t-1}, T_5\right) + \delta\, FRD_{i,t}\end{array}\right\}, \forall i \wedge t = 1,2,\ldots,N$$

The granularity adjustment factor (*GAF*) converts the energy schedule ramp to the 5min time domain of FRU/FRD awards; it is 1/3 in FMM and 1 in RTD. These constraints are more complicated when considering ancillary services awards, as shown in §4.12 and §4.13.

4.3 OBJECTIVE FUNCTION

The objective function, ignoring MSG state transitions and regulation mileage, but including the FRU/FRD demand elasticity, and assuming flat (single segment) energy bids for simplicity, is as follows:

$$
\begin{aligned}
C = {} & \sum_{t=1}^{N}\sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{N}\sum_{i} u_{i,t}\, MLC_{i,t} - \sum_{t=1}^{N}\sum_{i \in S_{PSH}} v_{i,t}\, PC_{i,t} + \\
& \sum_{t=1}^{N}\sum_{i} u_{i,t}\left(EN_{i,t} - LOL_{i,t}\right) ENBP_{i,t} + \sum_{t=1}^{N}\sum_{i \in BAA_0} RU_{i,t}\, RUBP_{i,t} + \\
& \sum_{t=1}^{N}\sum_{i \in BAA_0} RD_{i,t}\, RDBP_{i,t} + \sum_{t=1}^{N}\sum_{i \in BAA_0} SR_{i,t}\, SRBP_{i,t} + \sum_{t=1}^{N}\sum_{i \in BAA_0} NR_{i,t}\, NRBP_{i,t} + \\
& \sum_{t=1}^{N} FRUS_t\, FRUSP_t + \sum_{t=1}^{N} FRDS_t\, FRDSP_t + \sum_{t=1}^{N}\sum_{j \in EIM-PU_t} FRUS_{j,t}\, FRUSP_{j,t} + \\
& \sum_{t=1}^{N}\sum_{j \in EIM-PD_t} FRDS_{j,t}\, FRDSP_{j,t}
\end{aligned}
$$

The unit commitment binary variables are fixed in RTD. All online services are zero when the resource is offline, whereas Non-Spinning Reserve can be provided by offline Fast-Start Units ($SUT \leq 10$min) and FRU can be provided by offline 5min-start units ($SUT \leq 5$min),:

$$
u_{i,t} = 0 \rightarrow \begin{Bmatrix} EN_{i,t} = RU_{i,t} = RD_{i,t} = SR_{i,t} = FRD_{i,t} = 0 \\ NR_{i,t} = 0, \forall i \notin S_{10} \\ FRU_{i,t} = 0, \forall i \notin S_5 \end{Bmatrix}, \forall i \wedge t = 1,2,\ldots,N
$$

System Resources (SRs), Intertie Transactions (TIDs), and Non-Generator Resources (NGRs) have no discontinuities or inter-temporal constraints and are modeled as always online ($u = 1$). Ancillary services and FRU/FRD can only be awarded to resources certified to provide them. Any 5min dispatchable physical resource can be certified to provide FRU/FRD. Any resource certified for FRU/FRD with energy bids can be awarded FRU/FRD.

The FRU/FRD surplus (demand elasticity) price is derived from the histogram of net demand forecast errors.

4.4 POWER BALANCE CONSTRAINTS

A power balance constraint is enforced for each BAA in the EIM Area, as follows:

$$
\sum_{i \in BAA_j} EN_{i,t} - D_{j,t} = T_{j,t}, \forall j \in EIM \wedge t = 1,2,\ldots,N
$$

The net transfer for each BAA is the mismatch of the respective power balance constraint. The demand forecast is distributed to the load nodes in each BAA using load distribution factors that are adopted from the State Estimator solution for the relevant season, type of day, and time of day. The distributed load, accounting for transmission losses, is adjusted by the distributed load slack in the AC power flow (ACPF) solution while maintaining the Nest Scheduled Interchange (NSI) for each BAA, but it is not a variable in the RTM, hence the linearized power balance constraints are as follows:

$$\sum_{i \in BAA_j} \frac{\Delta EN_{i,t}}{LPF_{i,t}} = \Delta T_{j,t}, \forall j \in EIM \wedge t = 1,2,\dots,N$$

The incremental energy injections are divided by the corresponding loss penalty factors to account for changes in transmission losses from the previous AC power flow solution. The loss penalty factors are derived from the Jacobian (matrix of first partial derivatives) of the AC power flow equations.

4.5 TRANSFERS

The net transfer may be constrained by scheduling limits, e.g., when the BAA has failed the flexible ramping sufficiency test or when it is under contingency, as follows:

$$\underline{T}_{j,t} \le T_{j,t} \le \overline{T}_{j,t}, \forall j \in EIM \wedge t = 1,2,\dots,N$$

The net transfer is distributed optimally to the energy transfer schedules (ETSRs) defined on various interties between BAAs, as follows:

$$T_{j,t} = \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t} - IT_{j,k,l,t} \right), \forall j \in EIM \wedge t = 1,2,\dots,N$$

For any given intertie, the power flow will be in one direction; hence, only the export or the import ETSR may have a positive schedule.

The energy transfer schedules are symmetric:

$$ET_{j,k,l,t} = IT_{k,j,l,t}, \forall j,k \in EIM \wedge j \neq k \wedge t = 1,2,\dots,N$$

Due to the symmetry, the sum of all net transfers nets to zero:

$$\sum_{j \in EIM} T_{j,t} = 0, t = 1,2,\dots,N$$

This is expected because the sum of all power balance constraints yields the system power balance constraint for the entire EIM Area.

The distribution of the net transfer observes the applicable ETSR scheduling limits:

$$\left. \begin{array}{l} 0 \le ET_{j,k,l,t} \le \overline{ET}_{j,k,l,t} \\ 0 \le IT_{j,k,l,t} \le \overline{IT}_{j,k,l,t} \end{array} \right\}, \forall j,k \in EIM \wedge j \neq k \wedge \forall l \wedge t = 1,2,\dots,N$$

It is assumed that the ETSR scheduling limits are also symmetric:

$$\overline{ET}_{j,k,l,t} = \overline{IT}_{k,j,l,t}, \forall j,k \in EIM \wedge j \neq k \wedge \forall l \wedge t = 1,2,\dots,N$$

There are three different transfer types:

a) Base transfers are fixed in both FMM and RTD at their base schedules. Currently, there are no base transfers with the CISO; they are defined only between EIM BAAs.

b) Static transfers are variable in FMM, but fixed in RTD.

c) Dynamic transfers are variables in both FMM and RTD. However, at interties where static transfers are defined, dynamic transfers are scheduled only in RTD.

The net base transfer is derived as the net of all base transfers, as follows:

$$\tilde{T}_{j,t} = \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(\widetilde{ET}_{j,k,l,t} - \widetilde{IT}_{j,k,l,t} \right), \forall j \in EIM \wedge t = 1,2, \dots, N$$

Since, base transfers are not defined with the CISO:

$$\tilde{T}_{0,t} = 0, t = 1,2, \dots, N$$

Transfer constraints are also enforced under the FRU/FRD deployment scenarios as described in §4.11

4.6 ANCILLARY SERVICES PROCUREMENT CONSTRAINTS

With regional ancillary services procurement, the constraints are as follows:

$$\left.\begin{array}{r} \sum_{i \in S_r} RD_{i,t} \geq RDR_{r,t} \\ \sum_{i \in S_r} RU_{i,t} \geq RUR_{r,t} \\ \sum_{i \in S_r} RU_{i,t} + \sum_{i \in S_r} SR_{i,t} \geq RUR_{r,t} + SRR_{r,t} \\ \sum_{i \in S_r} RU_{i,t} + \sum_{i \in S_r} SR_{i,t} + \sum_{i \in S_r} NR_{i,t} \geq RUR_{r,t} + SRR_{r,t} + NRR_{r,t} \end{array}\right\}, \forall r \wedge t = 1,2, \dots, N$$

Ancillary services are procured in FMM and they are fixed in RTD. FRU/FRD awards are procured in FMM and then re-procured in RTD. Currently in the EIM, ancillary services are procured only in the CISO. Ancillary services base schedules can be submitted for resources in EIM BAAs, but they are not optimized. The ancillary services regions are nested under the CISO region and the regional requirements are the minimum requirements for the region. Cascaded procurement is employed where higher quality services can meet the requirements for lower quality services. FRU/FRD do not overlap or cascade with ancillary services because they are reserved capacity that can be dispatched or re-procured in real time irrespective of regulation or contingency response needs.

4.7 UPPER/LOWER CAPACITY BOUNDS

The ancillary services and FRU/FRD upper/lower bound constraints are as follows:

$$\left.\begin{array}{l} 0 \leq RD_{i,t} \leq RDBC_{i,t} \\ 0 \leq RU_{i,t} \leq RUBC_{i,t} \\ 0 \leq SR_{i,t} \leq SRBC_{i,t} \\ 0 \leq NR_{i,t} \leq NRBC_{i,t} \\ 0 \leq FRU_{i,t} \\ 0 \leq FRD_{i,t} \end{array}\right\} , \forall i \wedge t = 1,2, \dots, N$$

The ancillary services capacity bids are limited by the corresponding certified quantities. There are no capacity bids for FRU/FRD.

The ancillary services and FRU/FRD awards are further constrained by ramp capability and capacity constraints, described in §4.12 and §4.13, respectively.

4.8 FLEXIBLE RAMP PROCUREMENT CONSTRAINTS

FRU/FRD is procured separately for the BAAs that have failed the FRU/FRD sufficiency test:

$$\left.\begin{array}{l} \left.\begin{array}{r} \sum_{i \in BAA_j} FRU_{i,t} + FRUS_{j,t} = FRUR_{j,t} \\ 0 \leq FRUS_{j,t} \end{array}\right\} , \forall j \in EIM - PU_t \\ \left.\begin{array}{r} \sum_{i \in BAA_j} FRD_{i,t} + FRDS_{j,t} = FRDR_{j,t} \\ 0 \leq FRDS_{j,t} \end{array}\right\} , \forall j \in EIM - PD_t \end{array}\right\} , t = 1,2, \dots, N$$

Additionally, the net transfer for these BAAs is constrained from below/above by the net base transfer as follows:

$$\left.\begin{array}{l} T_{j,t} \geq \tilde{T}_{j,t}, \forall j \in EIM - PU_t \\ T_{j,t} \leq \tilde{T}_{j,t}, \forall j \in EIM - PD_t \end{array}\right\} , t = 1,2, \dots, N$$

For the BAAs that have passed the FRU/FRD sufficiency test, FRU/FRD is procured for the entire group to maximize the benefits of BAA diversity and economic displacement by participating in the EIM:

$$\left.\begin{array}{r} \sum_{j \in PU_t} \sum_{i \in BAA_j} FRU_{i,t} + FRUS_t = FRUR_t \\ 0 \leq FRUS_t \\ \sum_{j \in PD_t} \sum_{i \in BAA_j} FRD_{i,t} + FRDS_t = FRDR_t \\ 0 \leq FRDS_t \end{array}\right\} , t = 1,2, \dots, N$$

The FRU/FRD requirements are calculated as the extreme historical net demand forecast error within a specified confidence interval (95%), adjusted to reflect forecasted real-time conditions. The net demand forecast is the demand forecast reduced by the Variable Energy Resource (VER) forecast. For the binding 15min interval in FMM, the net demand forecast error is measured as the difference between the extreme net demand forecast among the underlying 5min intervals in RTD and the net demand forecast in that 15-min interval. For the binding 5min interval in RTD, the net demand forecast error is measured as the difference between the net demand forecast in the next advisory 5min interval and the net demand forecast in that 5-min interval.

The proposed FRU/FRD procurement requires a dynamic calculation of the FRU/FRD requirements and demand elasticity prices from harvesting the net demand forecast histograms for each BAA in each interval because the sets of BAAs that pass or fail the FRU/FRD sufficiency tests may vary.

4.9 TRANSMISSION CONSTRAINTS

In this technical paper, only base-case transmission constraints are considered for simplicity. Transmission constraints are enforced for active power flows on transmission elements as follows:

$$LFL_{m,t} \leq F_{m,t} \leq UFL_{m,t}, \forall m \wedge \; t = 1,2, \dots , N$$

These constraints are two-sided algebraic thermal limits (the lower limit is negative) on either single transmission lines and transformers, or a group of transmission lines (branch groups, flowgates, or transmission corridors). In the latter case, the limit may be a simultaneous power transfer capability limit.

These constraints are nonlinear, but they are linearized at an AC power flow solution are as follows:

$$LFL_{m,t} \leq \tilde{F}_{m,t} + \sum_{i} \Delta EN_{i,t} \, SF_{i,m,t} \leq UFL_{m,t}, \forall m \wedge t = 1,2, \dots , N$$

The incremental energy injections are multiplied by the corresponding shift factor for the relevant transmission constraint to account for changes in the active power flow from the AC power flow solution. Linear lossless shift factors are used in this linearization; they are derived from the imaginary part of the Nodal Admittance matrix of the transmission network; therefore, they solely depend on the transmission network configuration.

Transmission constraints are also enforced under the FRU/FRD deployment scenarios as described in §4.11

4.10 SCHEDULING LIMITS

Besides the scheduling limits on net transfers and ETSRs, described in §4.5, Intertie Transmission Corridor (ITC) or Intertie Scheduling Limit (ISL) constraints limit energy schedules and ancillary services awards from intertie resources at a single intertie or a group of interties. ITC/ISL constraints may also limit ETSRs at the corresponding intertie(s). The ITC/ISL constraint formulation allows netting of import and export energy schedules, but it prevents netting between energy schedules and ancillary services awards because they are not simultaneously dispatched. Their generic formulation is as follows:

$$\left.\begin{array}{l}\max\left(0,\sum_{i\in S_m} EN_{i,t}\right)+\sum_{i\in I_m}\left(RU_{i,t}+SR_{i,t}+NR_{i,t}\right)\le UFL_{m,t}\\ LFL_{m,t}\le\min\left(0,\sum_{i\in S_m} EN_{i,t}\right)-\sum_{i\in I_m} RD_{i,t}\end{array}\right\},\forall m\wedge t=1,\dots,N$$

The ITC/ISL constraints are linearized as follows:

$$\left.\begin{array}{l}\sum_{i\in S_m} EN_{i,t}+\sum_{i\in I_m}\left(RU_{i,t}+SR_{i,t}+NR_{i,t}\right)\le UFL_{m,t}\\ \sum_{i\in I_m}\left(RU_{i,t}+SR_{i,t}+NR_{i,t}\right)\le UFL_{m,t}\\ LFL_{m,t}\le\sum_{i\in S_m} EN_{i,t}-\sum_{i\in I_m} RD_{i,t}\\ LFL_{m,t}\le-\sum_{i\in I_m} RD_{i,t}\end{array}\right\},\forall m\wedge t=1,\dots,N$$

In the case of ITC constraints, the set S_m includes all intertie resources bound by the ITC m, and in the case of ISL constraints, the set S_m includes all intertie resources associated with (tagged at) the corresponding intertie of the ISL m. For ITC/ISL constraints, the upper limit is an import limit, whereas the lower limit is an algebraic export limit. By convention, the import direction in ITC constraints is to the associated BAA, and the import direction in ISL constraints is to the "from" BAA of the associated intertie.

Intertie bids are only allowed at CISO interties. Ancillary services can only be provided by certified import resources at CISO interties. Intertie resources may not be certified for FRU/FRD awards because they cannot be dispatched in RTD with the exception of Dynamic Schedules at CISO interties.

Scheduling limits are also enforced in the FRU/FRD deployment scenarios.

4.11 FLEXIBLE RAMP DEPLOYMENT SCENARIOS

In the FRU/FRD deployment scenarios, the FRU/FRD awards are deployed while the demand forecast is increased/decreased pro rata by the FRU/FRD requirements net of the FRU/FRD surplus (demand elasticity). The transfers are optimally calculated in the FRU/FRD deployment scenarios and they may be different from the transfers in the base scenario of serving the demand forecast.

For the BAAs that have failed the FRU/FRD sufficiency test, the net transfer in the FRU/FRD deployment scenarios is kept fixed to the net transfer in the base scenario of serving the demand forecast, but the ETSRs may vary to allow loop flow:

$$\left.\begin{aligned} T_{j,t}^{(u)} &= T_{j,t} = \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(u)} - IT_{j,k,l,t}^{(u)} \right), \forall j \in EIM - PU_t \\ T_{j,t}^{(d)} &= T_{j,t} = \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(d)} - IT_{j,k,l,t}^{(d)} \right), \forall j \in EIM - PD_t \end{aligned}\right\}, t = 1,2, \dots, N$$

For the group of BAAs that have passed the FRU/FRD sufficiency test, the net transfer is optimally calculated in the FRU/FRD deployment scenarios and then distributed to ETSRs as follows:

$$\left.\begin{aligned} &\left.\begin{aligned} T_{j,t}^{(u)} &= T_{j,t} + \sum_{i \in BAA_j} FRU_{i,t} - (FRUR_t - FRUS_t) \frac{D_j}{\sum_{j \in PU_t} D_j} \\ T_{j,t}^{(u)} &= \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(u)} - IT_{j,k,l,t}^{(u)} \right) \end{aligned}\right\}, \forall j \in PU_t \\ &\left.\begin{aligned} T_{j,t}^{(d)} &= T_{j,t} - \sum_{j \in BAA_j} FRD_{j,t} + (FRDR_t - FRDS_t) \frac{D_j}{\sum_{j \in PD_t} D_j} \\ T_{j,t}^{(d)} &= \sum_{\substack{k \in EIM \\ k \neq j}} \sum_{l} \left(ET_{j,k,l,t}^{(d)} - IT_{j,k,l,t}^{(d)} \right) \end{aligned}\right\}, \forall j \in PD_t \end{aligned}\right\}, t = 1,2, \dots, N$$

The ETSRs in the FRU/FRD deployment scenarios are constrained by the same transfer limits that apply in the base scenario of serving the demand forecast:

$$\left.\begin{aligned} 0 &\le ET_{j,k,l,t}^{(u)} \le \overline{ET}_{j,k,l,t} \\ 0 &\le IT_{j,k,l,t}^{(u)} \le \overline{IT}_{j,k,l,t} \\ 0 &\le ET_{j,k,l,t}^{(d)} \le \overline{ET}_{j,k,l,t} \\ 0 &\le IT_{j,k,l,t}^{(d)} \le \overline{IT}_{j,k,l,t} \end{aligned}\right\}, \forall j, k \in EIM \wedge j \neq k \wedge \forall l \wedge t = 1,2, \dots, N$$

The transmission constraints enforced in the FRU/FRD deployment scenarios are as follows:

$$\left.\begin{aligned} LFL_{m,t} \le \tilde{F}_{m,t} + \sum_{i} \Delta EN_{i,t} \, SF_{i,m,t} + \sum_{i} FRU_{i,t} \, SF_{i,m,t}^{(u)} \le UFL_{m,t} \\ LFL_{m,t} \le \tilde{F}_{m,t} + \sum_{i} \Delta EN_{i,t} \, SF_{i,m,t} - \sum_{i} FRD_{i,t} \, SF_{i,m,t}^{(d)} \le UFL_{m,t} \end{aligned}\right\}, \forall m \wedge t = 1,2, \dots, N$$

The same linearization from the AC power flow solution for the base scenario is used to extend the linearized transmission constraints in the FRU/FRD deployment scenarios. This approximation results in significant performance gain by avoiding two additional AC power flow solutions per interval per iteration. Furthermore, the approximation simplifies price formation because it allows price decoupling between Energy and FRU/FRD, and it results in no marginal loss component in the FRU/FRD locational marginal prices. The only price coupling is through the binding transmission constraints in the FRU/FRD deployment scenarios. The simpler price formation also simplifies FRU/FRD settlement and cost allocation.

Although the same transmission network is used in the FRU/FRD deployment scenarios as in the base scenario of serving the demand forecast, the shift factors for the FRU/FRD deployment for any given transmission constraint may be different in general. This is because unless all BAAs in the EIM Area have passed the FRU/FRD sufficiency test, the distribution of the FRU/FRD requirement net of the FRU/FRD surplus down to load nodes is different. In the base scenario, the shift factor reference is the distributed load in the EIM Area. However, in the FRU/FRD deployment scenarios, the shift factor reference for the FRU/FRD deployment in each BAA that has failed the test is the distributed load in that BAA, whereas the shift factor reference for the FRU/FRD deployment in the group of BAAs that have passed the test is the distributed load in the entire group. Because linear shift factors are used in the linearization of transmission constraints, the shift factors for the FRU/FRD deployment scenarios can be easily derived from the ones in the base scenario via a simple linear transformation.

4.12 RAMP CAPABILITY CONSTRAINTS

This section describes the ramp capability constraints. The ancillary services awards are simultaneously constrained by the 10min ramp capability from the energy schedules, as follows:

$$\left.\begin{array}{l} RU_{i,t} + SR_{i,t} + NR_{i,t} \leq RRU_i\left(EN_{i,t}, T_{10}\right) \\ RD_{i,t} \leq RRD_i\left(EN_{i,t}, T_{10}\right) \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, N$$

The ramp capability constraint for offline Non-Spinning Reserve is as follows:

$$NR_{i,t} \leq LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_{10} - SUT_{i,t}\right), \forall i \in S_{10} \wedge u_{i,t} = 0 \wedge t = 1,2, \dots, N$$

Where the ramp up from LOL starts after the SUT has elapsed.

Ancillary services can be dispatched at any time during the ramp between hourly schedules; hence, the performance hit for using the dynamic ramp capability from the average hourly energy schedules in the above constraints is not justified. A more conservative approach can be used instead, formulating the constraints conservatively with the lowest ramp capability within the applicable operating range of the resource, calculated as follows:

$$\left.\begin{array}{l} \underline{RRU}_{i,t}\left(T_{10}\right) \cong \min\left(RRU\left(p_i, T_{10}\right)\Big|_{p_i=\max\left(LOL_{i,t}, LEL_{i,t}\right)}^{p_i=UOL_{i,t}-RRD\left(UOL_{i,t}, T_{10}\right)}\right) \\ \underline{RRD}_{i,t}\left(T_{10}\right) \cong \min\left(RRD\left(p_i, T_{10}\right)\Big|_{p_i=LOL_{i,t}+RRU\left(LOL_{i,t}, T_{10}\right)}^{p_i=UOL_{i,t}}\right) \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, N$$

Although ancillary services can be dispatched at any time, FRU/FRD awards are deployed from the energy schedules; hence, the dynamic ramp capability should be used for ramp capability constraints on FRU/FRD awards. The FRU/FRD awards are simultaneously constrained with energy schedules in FMM by the dynamic 5min ramp capability, as follows:

$$\left.\begin{array}{l} GAF\ \left(EN_{i,t} - EN_{i,t-1}\right) \leq RRU_i\left(EN_{i,t-1}, T_5\right) - \delta\ FRU_{i,t} \\ GAF\ \left(EN_{i,t} - EN_{i,t-1}\right) \geq -RRD_i\left(EN_{i,t-1}, T_5\right) + \delta\ FRD_{i,t} \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, N$$

The granularity adjustment factor (GAF) converts the 15min FMM energy schedule ramp to the 5min time domain of FRU/FRD awards.

The ramp capability constraint for offline FRU in FMM is as follows:

$$NR_{i,t}/2 + FRU_{i,t} \le LOL_{i,t} + RRU_i\left(LOL_{i,t}, T_5 - SUT_{i,t}\right), \forall i \in S_5 \wedge u_{i,t} = 0 \wedge t = 1,2,\dots,N$$

Where the ramp up from LOL starts after the SUT has elapsed.

The energy schedules and the ancillary services and FRU/FRD awards are simultaneously constrained by dynamic ramp capability constraints in both FMM and RTD. For resources that remain online across time intervals, these constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \le RRU_i\left(EN_{i,t-1}, \Delta T\right) - \left(\alpha\, RU_{i,t} + \beta\, SR_{i,t} + \gamma\, NR_{i,t}\right) ASF - \delta\, FRU_{i,t} \\ EN_{i,t} - EN_{i,t-1} \ge -RRD_i\left(EN_{i,t-1}, \Delta T\right) + \alpha\, RD_{i,t}\, ASF + \delta\, FRD_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = u_{i,t} = 1 \wedge t = 1,2,\dots,N$$

For resources that start up, the ramp capability constraints are as follows:

$$EN_{i,t} \le LOL_{i,t} + RRU_i\left(LOL_{i,t}, \Delta T/2\right) - \left(\alpha\, RU_{i,t} + \beta\, SR_{i,t} + \gamma\, NR_{i,t}\right) ASF - \delta\, FRU_{i,t}\},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2,\dots,N$$

Where the ramp up from LOL is for half of the interval ramp.

For resources that shut down, the ramp capability constraints are as follows:

$$EN_{i,t} \le LOL_{i,t} + RRU_i\left(LOL_{i,t}, \Delta T/2\right) - \alpha\, RD_{i,t}\, ASF - \delta\, FRD_{i,t}\},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2,\dots,N-1$$

Where the ramp down to LOL is for half of the interval ramp. No resources are shut down at the end of the time horizon.

The ancillary services factor (ASF) is used in RTD to convert the time domain of ancillary services (10min) to the time interval duration (5min). The shared ramping coefficients (α, β, γ, and δ) specify how the various commodities share the resource ramp capability. The ramp capability constraint reserves ramp capability for the ancillary services and FRU/FRD awards over the ramp between the time interval midpoints or the half ramp after startup or before shutdown. A coefficient of one reserves all the ramp capability that is required for a service that is continuously dispatched concurrently with energy, such as Regulation and FRU/FRD, whereas smaller coefficients may be used to reserve ramp capability for contingency reserves.

4.13 CAPACITY CONSTRAINTS

This section describes the capacity constraints. In the RTM, an energy bid is required for energy schedules, Spinning and Non-Spinning Reserve awards, and FRU/FRD awards, but not for Regulation awards. Therefore, energy schedules, Spinning and Non-Spinning Reserve awards, and FRU/FRD awards are limited by the LEL/UEL, whereas Regulation awards are limited by the CL and the LRL/URL. To formulate the resource capacity constraints generally for all cases, it is convenient to define upper and lower capacity limits as follows:

$$\left.\begin{array}{l} RU_{i,t} + RD_{i,t} > 0 \rightarrow \begin{cases} UCL_{i,t} = \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) \\ LCL_{i,t} = \max\left(LOL_{i,t}, LRL_{i,t}\right) \end{cases} \\ RU_{i,t} + RD_{i,t} = 0 \rightarrow \begin{cases} UCL_{i,t} = UOL_{i,t} \\ LCL_{i,t} = LOL_{i,t} \end{cases} \end{array}\right\}, \forall i \wedge t = 1,2,\ldots,N$$

$$\left.\begin{array}{l} UEL'_{i,t} = \min\left(UCL_{i,t}, UEL_{i,t}\right) \\ LEL'_{i,t} = \max\left(LCL_{i,t}, LEL_{i,t}\right) \end{array}\right\}, \forall i \wedge t = 1,2,\ldots,N$$

Then, the capacity constraints for online resources are as follows:

$$\left.\begin{array}{l} EN_{i,t} \leq UCL_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LCL_{i,t} + RD_{i,t} + FRD_{i,t} \leq EN_{i,t} \\ LEL'_{i,t} + FRD_{i,t} \leq EN_{i,t} \leq UEL'_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,N$$

Similarly, the capacity constraints for offline resources are as follows:

$$NR_{i,t} \leq UEL'_{i,t}, \forall i \in S_{10} \wedge u_{i,t} = 0 \wedge t = 1,2,\ldots,N$$

$$NR_{i,t} + FRU_{i,t} \leq UEL'_{i,t}, \forall i \in S_5 \wedge u_{i,t} = 0 \wedge t = 1,2,\ldots,N$$

4.14 ENERGY LIMIT CONSTRAINTS

Energy limit constraints apply to resources that have energy limitations. There are two kinds of energy limit constraints in the RTM:

a) Daily energy limits as they apply in real time; and

b) State of Charge (SOC) limits.

Daily energy limits restrict the hourly energy schedules so that the total energy production over the Trading Day is limited by a maximum daily energy limit. These constraints are typically enforced in the DAM for resources with a limited fuel supply, such as hydro resources with water reservoirs and water management limitations. If these limits are enforced in the DAM, they are also enforced in RTM with an allocation of the allowed daily energy over the RTM time horizon as follows:

$$\sum_{t=1}^{N} EN_{i,t} \leq \overline{EN}_i$$

For Pumped-Storage Hydro (PSH) Resources that can operate in either generating mode (positive energy schedule) or pumping mode (negative energy schedule), the daily energy limit constraints are two-sided; they limit the total algebraic energy production over the Trading Day between a negative minimum and a positive maximum daily energy limit, as follows:

$$\underline{EN}_i \leq \sum_{t=1}^{N} \left(u_{i,t} + v_{i,t}\,\eta_i\right) EN_{i,t} \leq \overline{EN}_i$$

Where the pumping energy is multiplied by the pumping efficiency and the operating modes are mutually exclusive:

$$\left.\begin{array}{l} u_{i,t} = 1 \rightarrow EN_{i,t} \geq 0 \\ v_{i,t} = 1 \rightarrow EN_{i,t} = -PL_{i,t} \\ u_{i,t} = v_{i,t} = 0 \rightarrow EN_{i,t} = 0 \\ u_{i,t} + v_{i,t} \leq 1 \end{array}\right\}, \forall i \in S_{PSH} \wedge t = 1,2,\dots,N$$

The SOC limits constrain the energy schedules, ancillary services awards, and FRU/FRD awards for Limited Energy Storage Resources (LESR), a specific type of a Non-Generator Resource (NGR) that can operate in either discharging (positive energy schedule) or charging mode (negative energy schedule). The SOC for a LESR is calculated as follows:

$$\left.\begin{array}{l} SOC_{i,t} = SOC_{i,t-1} - \dfrac{EN_{i,t-1}^{(+)} + EN_{i,t}^{(+)} + \eta_i \left(EN_{i,t-1}^{(-)} + EN_{i,t}^{(-)}\right)}{2} \\ 0 \leq EN_{i,t}^{(+)} \leq u_{i,t}\, UEL'_{i,t} \\ \left(1 - u_{i,t}\right) LEL'_{i,t} \leq EN_{i,t}^{(-)} \leq 0 \\ EN_{i,t} = EN_{i,t}^{(+)} + EN_{i,t}^{(-)} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2,\dots,N$$

Where the charging energy is multiplied by the charging efficiency. Then, the SOC limit constraints in FMM and RTD are as follows:

$$\left.\begin{array}{l} \underline{SOC}_{i,t} + \left(RU_{i,t} + SR_{i,t} + NR_{i,t}\right) \dfrac{T_{30}}{\Delta T} + FRU_{i,t} \dfrac{T_{15}}{\Delta T} \leq SOC_{i,t} \\ SOC_{i,t} \leq \overline{SOC}_{i,t} - \eta_i \left(RD_{i,t} + FRD_{i,t}\right) \dfrac{T_{15}}{\Delta T} \end{array}\right\}, \forall i \in S_{LESR} \wedge t = 1,2,\dots,N$$

A sustained 30min energy period is used for contingency reserves, and for regulation up that can substitute for contingency reserves through the cascaded ancillary services procurement discussed in §4.6.

5 PRICE FORMATION

This section presents the price formation for Energy schedules and FRU/FRD awards in the RTM. The marginal prices for these commodities for each interval in the time horizon are derived from the shadow prices of the power balance and FRU/FRD procurement constraints:

$$\left.\begin{array}{ll}
\sum\limits_{i \in BAA_j} EN_{i,t} - D_{j,t} = T_{j,t}, \forall j \in EIM & \lambda_{j,t} \\
\sum\limits_{i \in BAA_j} FRU_{i,t} + FRUS_{j,t} = FRUR_{j,t} - FRUC_{j,t}, \forall j \in EIM - PU_t & \rho_{j,t} \\
\sum\limits_{j \in PU_t} \sum\limits_{i \in BAA_j} FRU_{i,t} + FRUS_t = FRUR_t & \rho_t \\
\sum\limits_{i \in BAA_j} FRD_{i,t} + FRDS_{j,t} = FRDR_{j,t} - FRDC_{j,t}, \forall j \in EIM - PD_t & \sigma_{j,t} \\
\sum\limits_{j \in PD_t} \sum\limits_{i \in BAA_j} FRD_{i,t} + FRDS_t = FRDR_t & \sigma_t
\end{array}\right\}, t = 1,2, \dots, N$$

There are additional price contributions from binding transmission constraints in the base scenario and the FRU/FRD deployment scenarios, described in §4.9 and §4.11. Including these contributions, the marginal prices of the Energy schedules and FRU/FRD awards in the RTM are calculated as follows:

$$\left.\begin{array}{l}
LMP_{i,t} = \dfrac{\lambda_{j,t}}{LPF_{i,t}} - \sum\limits_{m} SF_{i,m,t}\, \mu_{m,t} - \sum\limits_{m} SF_{i,m,t}^{(u)}\, \mu_{m,t}^{(u)} + \sum\limits_{m} SF_{i,m,t}^{(d)}\, \mu_{m,t}^{(d)}, \forall i \in BAA_j \wedge j \in EIM \\
FRUMP_{i,t} = \rho_{j,t} - \sum\limits_{m} SF_{i,m,t}^{(u)}\, \mu_{m,t}^{(u)}, \forall i \in BAA_j \wedge j \in EIM - PU_t \\
FRUMP_{i,t} = \rho_t - \sum\limits_{m} SF_{i,m,t}^{(u)}\, \mu_{m,t}^{(u)}, \forall i \in BAA_j \wedge j \in PU_t \\
FRDMP_{i,t} = \sigma_{j,t} + \sum\limits_{m} SF_{i,m,t}^{(d)}\, \mu_{m,t}^{(d)}, \forall i \in BAA_j \wedge j \in EIM - PD_t \\
FRDMP_{i,t} = \sigma_t + \sum\limits_{m} SF_{i,m,t}^{(d)}\, \mu_{m,t}^{(d)}, \forall i \in BAA_j \wedge j \in PD_t
\end{array}\right\},$$

$$t = 1,2, \dots, N$$

The settlement of Energy schedules and FRU/FRD awards is based on these marginal prices. The FRU/FRD cost allocation remains the same as the current tiered approach; however, for the group of BAAs that have passed the FRU/FRD sufficiency test, the cost allocation applies to the entire group, whereas for BAAs that have failed the test, the cost allocation applies to each BAA individually.