California ISO

Day-Ahead Market Enhancements

Appendix C: Draft Technical Description

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1 INTRODUCTION

This technical paper describes the optimization problem formulation of the proposed Day-Ahead Market Enhancements (DAME) for discussion purposes. The DAME is an extension of the Integrated Forward Market (IFM) that includes Flexible Ramping Up (FRU) and Flexible Ramping Down (FRD). In the DAME, FRU/FRD is reserved capacity above/below the Day-Ahead Schedule (DAS) that must be available for dispatch in the Real-Time Market (RTM) to meet upward/downward uncertainty from the DAS to the Fifteen-Minute Market (FMM) demand forecast. Furthermore, the DAME clears in 15min intervals producing a DAS with same granularity as the FMM schedule, reducing load following and imbalance energy requirements in RTM.

1.1 EXISTING DAY-AHEAD MARKET STRUCTURE

Currently the Day-Ahead Market includes three separate market applications that are executed in sequence: Market Power Mitigation (MPM), IFM, and Residual Unit Commitment (RUC). The MPM is a trial IFM pass that identifies and mitigates bids based on specific criteria. The IFM commits resources, clears physical and virtual energy supply and demand schedules, and procures ancillary services awards. The RUC commits additional resources and schedules additional capacity beyond physical energy schedules to meet the day-ahead demand forecast while ignoring virtual energy schedules. The resources that are committed in IFM are modeled as must-run in RUC, i.e., they are kept online. Moreover, the energy schedules from these committed resources are protected in RUC with penalty functions seeking an incremental capacity solution on the IFM to meet the day-ahead demand forecast. Furthermore, ancillary services awarded in IFM are fixed in RUC.

1.2 DAY-AHEAD MARKET ENHANCEMENTS

The current DAS at an hourly granularity does not provide sufficient flexibility required by sharp ramps that materialize in RTM due to ever-increasing levels of renewables. By contrast, the DAME will schedule resources in the same 15min granularity as the FMM. Furthermore, the DAME will procure FRU/FRD to address uncertainty that may materialize in FMM. To mitigate the quadruple increase in the DAME performance requirements due to the 15min scheduling intervals, the resource commitment and Multi-State Generator (MSG) state transitions are limited to hourly boundaries in the time horizon. These can later be refined on 15min interval boundaries in FMM as needed.

1.3 MARKET COMMODITIES IN THE DAY-AHEAD MARKET ENHANCEMENTS

Besides optimal resource commitment, the market commodities procured in the DAME are the following:

- Day-Ahead Energy schedules for physical and virtual resources;
- Flexible Ramping Up and Down awards for physical resources;

- Day-Ahead Regulation Up and Down awards for physical resources;
- Day-Ahead Mileage Up and Down awards for physical resources;
- Day-Ahead Spinning Reserve awards for physical resources;
- Day-Ahead Non-Spinning Reserve awards for physical resources; and
- Day-Ahead Corrective Capacity awards for physical resources.

2 ASSUMPTIONS

The optimization problem formulation for the DAME in this technical paper is based on the following assumptions:

- The optimal solution composed of the unit commitment and the cleared schedules and awards for the market commodities simultaneously calculates:
    1) Cleared physical and virtual energy supply bids balance cleared demand bids and losses; this is accomplished by the power balance constraint.
    2) Congestion management for network constraints and preventive contingencies.
    3) Ancillary services awards satisfy cascaded ancillary services requirements.
    4) FRU/FRD awards satisfy FRU/FRD requirements.
    5) Corrective capacity awards to recover from corrective transmission contingencies.
- The objective function is the maximization of the total merchandizing surplus over the time horizon including the following:
    - the minimization of physical and virtual Energy supply schedules cost;
    - the maximization of physical and virtual Energy demand schedules benefit;
    - the minimization of the Start-Up Cost of committed resources;
    - the minimization of the Minimum Load Cost of committed resources;
    - the minimization of State Transition Cost of MSGs;
    - the minimization of FRU/FRD awards cost; and
    - the minimization of ancillary services (Regulation, Mileage, Spinning and Non-Spinning Reserve, and Corrective Capacity) awards cost.
- All ancillary services procurement constraints are enforced to procure 100% of the relevant requirements. Similarly, FRU/FRD procurement constraints are enforced to procure the upper/lower percentile of the day-ahead uncertainty histogram without demand elasticity.
- Ancillary services and FRU/FRD are procured regionally with nested regions under the system region to satisfy minimum requirements for each region. The procurement

of Corrective Capacity (CC) is locational through corrective contingency constraints using the Contingency Modeling Enhancements (CME) methodology.

- All applicable resource constraints are enforced:
  - resource capacity constraints;
  - unit commitment and state transition inter-temporal constraints; and
  - commodity ramp-sharing constraints.
- All applicable transmission and generation constraints are enforced:
  - network constraints for physical and virtual energy schedules for the base case and preventive transmission and/or generation contingencies;
  - network constraints for physical and virtual energy schedules for corrective transmission contingencies;
  - intertie scheduling limits for energy schedules and ancillary services awards;
  - transmission and generation nomograms, including gas-burn constraints; and
  - Minimum Online Capacity (MOC) constraints.
- Daily energy limit constraints are enforced.
- State of Charge (SOC) constraints are enforced for Limited Energy Storage Resources (LESRs).
- 15min intervals are used for the time horizon spanning the Trading Day.
- Block hourly energy scheduling is available to hourly intertie resources.
- Hourly energy scheduling is available to hourly Proxy Demand Resources (PDRs) and hourly Reliability Demand Response Resources (RDRRs).
- The Day-Ahead MPM functionality is fully preserved; the MPM is essentially a trial pass of the IFM where the established MPM principles apply, namely:
  - the impact of resource commitment and physical and virtual energy schedules on network constraints is quantified;
  - network constraints are classified as competitive or uncompetitive using the Dynamic Competitive Path Assessment (DCPA) method;
  - resources that provide congestion relief on uncompetitive network constraints are flagged for mitigation; and
  - commitment costs and energy bids from resources flagged for mitigation are mitigated for use in the IFM pass.

3 MATHEMATICAL FORMULATION

The focus of the mathematical formulation of the DAME in this technical paper is on the integration of FRU/FRD procurement with the energy scheduling and ancillary services procurement in a single optimization problem with 15min intervals. 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 commitment inter-temporal constraints, MSG modeling, block energy scheduling, contingency constraints, nomograms, energy and SOC limits, and soft constraint penalty relaxation or scarcity treatment, are not included for simplicity and because they do not materially affect the enhancements for the DAM.

3.1 NOTATION

The following notation is used in the problem formulation for the enhanced DAM in this technical paper:

i	Physical Resource index.
j	Virtual Resource index.
r	Region index (zero for system).
im	Import Resource index (used in ITC/ISL constraint formulation).
ex	Export Resource index (used in ITC/ISL constraint formulation).
k	Network constraint index.
t	Time period index (0 for initial condition).
T_{10}	Capacity Ancillary Services time domain (10 min).
T_{15}	Time period duration within the Trading Day (15 min).
T_D	The number of time periods in the Trading Day (92-100), considering the short and long days due to daylight savings changes.
S_r	Set of resources in region *r*.
S_{FSU}	Set of Fast-Start Units ($SUT \leq$ 10min) that can be certified to provide Non-Spinning Reserve from offline status (u = 0).
S_{15}	Set of 15min-start units ($SUT \leq$ 15min) that can provide FRU from offline status (u = 0).
S_k	Set of intertie resources associated with ITC/ISL *k*.
$\forall$	For all…
$\wedge$	Logical and…
$\rightarrow$	Leads to…
Δ	Denotes incremental values.
$\tilde{}$	Denotes initial values from an AC power flow solution.
∂	Partial derivative operator.
$u_{i,t}$	Binary variable indicating commitment status (offline/online) for Resource *i* in time period *t*.
$y_{i,t}$	Binary variable indicating that Resource *i* has a start-up in time period *t*.
$\eta_{i,t}$	Binary variable indicating that online Resource *i* can be shut-down in time period *t*.
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 $UOL_{i,t}$.
$SUC_{i,t}$	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*.
$EN_{i,t}$	Energy schedule of Resource *i* in time period *t*; positive for supply (generation and imports) and negative for demand (demand response and exports).
$L_{i,t}$	Energy schedule of Non-Participating Load Resource *i* in time period *t*.
$FRU_{i,t}$	Flexible Ramping Up capacity of Resource *i* for potential delivery in time period *t*.
$FRD_{i,t}$	Flexible Ramping Down capacity of Resource *i* for potential delivery 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*.
$ASU_{i,t}$	Upward Ancillary Service award (the sum of Regulation Up, and Spinning and Non-Spinning Reserve awards) of Resource *i* in time period *t*.
$RUC_{i,t}$	Regulation Up capacity bid of Resource *i* in time period *t*.
$RDC_{i,t}$	Regulation Down capacity bid of Resource *i* in time period *t*.
$SRC_{i,t}$	Spinning Reserve capacity bid of Resource *i* in time period *t*.
$NRC_{i,t}$	Non-Spinning Reserve capacity bid of Resource *i* in time period *t*.
$ENP_{i,t}$	Energy bid price of Resource *i* in time period *t*.
$FRUP_{i,t}$	Flexible Ramping Up bid price of Resource *i* in time period *t*.
$FRDP_{i,t}$	Flexible Ramping Down bid price of Resource *i* in time period *t*.
$RUP_{i,t}$	Regulation Up bid price of Resource *i* in time period *t*.
$RDP_{i,t}$	Regulation Down bid price of Resource *i* in time period *t*.
SRP_{i}	Spinning Reserve bid price of Resource *i* in time period *t*.
$NRP_{i,t}$	Non-Spinning Reserve bid price of Resource *i* in time period *t*.
$FRUR_{r,t}$	Flexible Ramping Up uncertainty requirement in Region *r* and time period *t*.
$FRDR_{r,t}$	Flexible Ramping Down uncertainty requirement in Region *r* and 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*.
$ASUR_{r,t}$	Upward Ancillary Service requirement (the sum of Regulation Up, and Spinning and Non-Spinning Reserve requirements) in Region *r* and time period *t*.
$RRU_{i,T}(EN_{i,t})$	Piecewise linear ramp up capability function of Resource *i* from its Energy schedule in time period *t* for time domain *T*.
$RRD_{i,T}(EN_{i,t})$	Piecewise linear ramp down capability function of Resource *i* from its Energy schedule in time period *t* for time domain *T*.
$Loss_t$	Transmission losses in time period *t*.
$LPF_{i,t}$	Loss Penalty Factor for Resource *i* in time period *t*.
$SF_{i,k,t}$	Shift Factor for the energy injection schedule of Resource *i* on network constraint *k* in time period *t*.
$F_{k,t}$	Active power flow or scheduled flow on network constraint *k* in time period *t*.
$LFL_{k,t}$	Lower active power flow or scheduling limit (non-positive) on network constraint *k* in time period *t*.
$UFL_{k,t}$	Upper active power flow or scheduling limit on network constraint *k* in time period *t*.
$I_{im,t}$	Energy schedule of Import Resource *im* in time period *t* $\left(I_{im,t} = EN_{i,t}\right)$; used in ITC/ISL constraint formulation.
$E_{ex,t}$	Energy schedule of Export Resource *ex* in time period *t* $\left(E_{ex,t} = -EN_{i,t}\right)$; used in ITC/ISL constraint formulation.
$NEL_{r,t}$	N–1 simultaneous export transfer capability of Region *r* in time period *t*.
$NIL_{r,t}$	N–1 simultaneous import transfer capability of Region *r* in time period *t*.
α_t	Shared ramping coefficient for Regulation in time period *t*.
β_t	Shared ramping coefficient for Spinning Reserve in time period *t*.
γ_t	Shared ramping coefficient for Non-Spinning Reserve in time period *t*.
δ_t	Shared ramping coefficient for Flexible Ramping in time period *t*.

3.2 GENERAL PROBLEM FORMULATION

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

$$\begin{aligned} \min \quad & C(\mathbf{x}) \\ \text{s.t.} \quad & \mathbf{A}_{eq}\,\mathbf{x} = \mathbf{b}_{eq} \\ & \mathbf{A}\,\mathbf{x} \le \mathbf{b} \end{aligned}$$

3.3 FLEXIBLE RAMPING MODEL

This section gives a brief overview of the Flexible Ramping model without any ancillary services for simplicity. Figure 1 shows the energy and flexible ramping up and down targets in a given time interval.

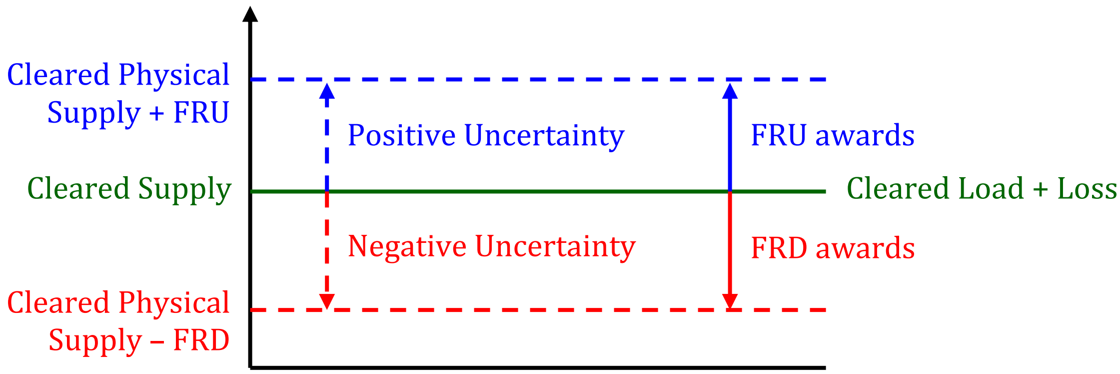

Figure 1. Energy and Flexible Ramping Up/Down targets

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

$$\left.\begin{array}{l}\sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} + Loss_t \\ \sum_i FRU_{i,t} \geq FRUR_t \\ \sum_i FRD_{i,t} \geq FRDR_t \end{array}\right\}, t = 1,2,\dots,T_D$$

FRU/FRD is ramping capacity between intervals reserved to meet uncertainty between the physical supply that clears the IFM and the FMM demand forecast. 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.

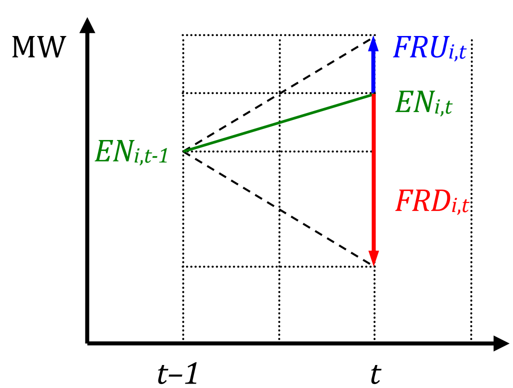

Figure 2. Energy and Flexible Ramping Up/Down ramp constraints

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 and remains available to address any uncertainty that may materialize in FMM.

It is important to note that 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 constraints:

$$\left.\begin{array}{l} LEL_{i,t} + FRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t} - FRU_{i,t} \\ -RRD_{i,T_{15}}\left(EN_{i,t-1}\right) + FRD_{i,t} \leq EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{15}}\left(EN_{i,t-1}\right) - FRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge t = 1,2, \dots, T_D$$

These constraints are more complicated when considering ancillary services awards, as shown in §0 and §3.12.

3.4 OBJECTIVE FUNCTION

The objective function, ignoring MSG state transitions and regulation mileage, and assuming flat (single segment) energy bids for simplicity, is as follows:

$$\begin{aligned} C = &\sum_{t=1}^{T_D}\sum_i y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T_D}\sum_i u_{i,t}\, MLC_{i,t} + \sum_{t=1}^{T_D}\sum_i \left(EN_{i,t} - LOL_{i,t}\right) ENP_{i,t} - \\ &\sum_{t=1}^{T_D}\sum_i L_{i,t}\, ENP_{i,t} + \sum_{t=1}^{T_D}\sum_j EN_{j,t}\, ENP_{j,t} - \sum_{t=1}^{T_D}\sum_j L_{j,t}\, ENP_{j,t} + \\ &\sum_{t=1}^{T_D}\sum_i RU_{i,t}\, RUP_{i,t} + \sum_{t=1}^{T_D}\sum_i RD_{i,t}\, RDP_{i,t} + \sum_{t=1}^{T_D}\sum_i SR_{i,t}\, SRP_{i,t} + \\ &\sum_{t=1}^{T_D}\sum_i NR_{i,t}\, NRP_{i,t} + \sum_{t=1}^{T_D}\sum_i FRU_{i,t}\, FRUP_{i,t} + \sum_{t=1}^{T_D}\sum_i FRD_{i,t}\, FRDP_{i,t} \end{aligned}$$

All online services are zero when the resource is offline, whereas Non-Spinning Reserve can be provided by offline FSU ($SUT \leq 10$min) and FRU can be provided by offline 15min-start units ($SUT \leq 15$min):

$$u_{i,t} = 0 \rightarrow \left\{\begin{array}{c} EN_{i,t} = RU_{i,t} = RD_{i,t} = SR_{i,t} = FRD_{i,t} = 0, \forall i \\ NR_{i,t} = 0, \forall i \notin S_{FSU} \\ FRU_{i,t} = 0, \forall i \notin S_{15} \end{array}\right\}, t = 1,2, \dots, T_D$$

System Resources (SRs), Non-Generator Resources (NGRs), virtual resources, and non-participating load resources have no discontinuities or inter-temporal constraints and are modeled as always online ($u = 1$). Capacity ancillary services and FRU/FRD can only be awarded to resources certified to provide them, but any physical resource and Import/Export System Resource can be certified to provide FRU/FRD, except for non-participating load resources, hourly intertie resources, and hourly PDR and RDRR. Any resource certified for FRU/FRD with energy bids can be awarded FRU/FRD.

3.5 POWER BALANCE CONSTRAINT

The power balance constraint is as follows:

$$\sum_i EN_{i,t} + \sum_j EN_{j,t} = \sum_i L_{i,t} + \sum_j L_{j,t} + Loss_t, t = 1,2, \dots, T_D$$

The transmission loss is a nonlinear function. In the initial SCUC iteration where there are no network constraints, it is approximated as a percentage of the demand forecast. In the subsequent SCUC iterations the transmission loss is linearized at an AC power flow solution as follows:

$$Loss_t \cong \widetilde{Loss}_t + \sum_i \Delta EN_{i,t} \frac{\partial Loss_t}{\partial EN_{i,t}} + \sum_j \Delta EN_{j,t} \frac{\partial Loss_t}{\partial EN_{j,t}} + \sum_i \Delta L_{i,t} \frac{\partial Loss_t}{\partial L_{i,t}} + \sum_j \Delta L_{j,t} \frac{\partial Loss_t}{\partial L_{j,t}}, t = 1,2, \dots, T_D$$

Where:

$$\widetilde{Loss}_t = \sum_i \widetilde{EN}_{i,t} + \sum_j \widetilde{EN}_{j,t} - \sum_i \tilde{L}_{i,t} - \sum_j \tilde{L}_{j,t}, t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta EN_{i,t} &= EN_{i,t} - \widetilde{EN}_{i,t} \\ \frac{\partial Loss_t}{\partial EN_{i,t}} &= 1 - \frac{1}{LPF_{i,t}} \end{aligned}\right\}, \forall i \land t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta EN_{j,t} &= EN_{j,t} - \widetilde{EN}_{j,t} \\ \frac{\partial Loss_t}{\partial EN_{j,t}} &= 1 - \frac{1}{LPF_{j,t}} \end{aligned}\right\}, \forall j \land t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta L_{i,t} &= L_{i,t} - \tilde{L}_{i,t} \\ \frac{\partial Loss_t}{\partial L_{i,t}} &= \frac{1}{LPF_{i,t}} - 1 \end{aligned}\right\}, \forall i \land t = 1,2, \dots, T_D$$

$$\left.\begin{aligned} \Delta L_{j,t} &= L_{j,t} - \tilde{L}_{j,t} \\ \frac{\partial Loss_t}{\partial L_{j,t}} &= \frac{1}{LPF_{j,t}} - 1 \end{aligned}\right\}, \forall j \land t = 1,2, \dots, T_D$$

Performing substitutions, the linearized power balance constraint is as follows:

$$\sum_i \frac{\Delta EN_{i,t}}{LPF_{i,t}} + \sum_j \frac{\Delta EN_{j,t}}{LPF_{j,t}} - \sum_i \frac{\Delta L_{i,t}}{LPF_{i,t}} - \sum_j \frac{\Delta L_{j,t}}{LPF_{j,t}} = 0, t = 1,2, \dots, T_D$$

Where the incremental Energy injections are divided by the corresponding Loss Penalty Factors (LPFs) to account for changes in transmission losses from the previous AC power flow solution.

3.6 ANCILLARY SERVICES PROCUREMENT CONSTRAINTS

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

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

Where the regions are nested under the system 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 capacity ancillary services because they are reserved capacity that can be dispatched or re-procured in real time irrespective of regulation or contingency response needs. The ancillary services and FRU/FRD awards in each region below the system are also constrained by regional deliverability constraints, described in §3.10.

The procurement of Corrective Capacity (CC) is locational through corrective contingency constraints using the Contingency Modeling Enhancements methodology.

3.7 ANCILLARY SERVICES AND FLEXIBLE RAMPING BOUNDS

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

$$\left.\begin{array}{c}0 \leq RD_{i,t} \leq RDC_{i,t} \\ 0 \leq RU_{i,t} \leq RUC_{i,t} \\ 0 \leq SR_{i,t} \leq SRC_{i,t} \\ 0 \leq NR_{i,t} \leq NRC_{i,t} \\ 0 \leq FRU_{i,t} \\ 0 \leq FRD_{i,t}\end{array}\right\}, \forall i \wedge t = 1,2,\ldots,T_D$$

Where the ancillary services capacity bids are limited by the corresponding certified quantities. There are no explicit upper bounds for FRU/FRD since there is no associated capacity bid for them, i.e., all available capacity under the energy bid above/below the energy schedule can be procured as FRU/FRD, except for non-participating load, hourly intertie resources, and hourly PDR and RDRR, which are not eligible for FRU/FRD. Similarly, there are no upper bounds for Corrective Capacity. The ancillary services and FRU/FRD awards are further constrained by capacity and ramp constraints, described in §0 and §3.12.

3.8 ANCILLARY SERVICES TIME DOMAIN CONSTRAINTS

The ancillary services time domain constraints for online resources are as follows:

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

Where all upward ancillary services awards are simultaneously constrained by the 10min upward ramp capability from the energy schedule.

The time domain constraint for offline Non-Spinning Reserve is as follows:

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

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

3.9 FLEXIBLE RAMPING PROCUREMENT CONSTRAINTS

The system-wide FRU/FRD procurement constraints are as follows:

$$\left.\begin{array}{l} \sum_i FRU_{i,t} \geq FRUR_t = FRUR_{0,t} \\ \sum_i FRD_{i,t} \geq FRDR_t = FRDR_{0,t} \end{array}\right\}, t = 1,2, \dots, T_D$$

Where the Flexible Ramping Up/Down uncertainty requirements for the system region ($r = 0$) are derived as an upper/lower percentile of the historical error between the physical supply that clears the IFM and the FMM demand forecast. Unlike the nested regional procurement of capacity ancillary services, described in §3.6, instead of a similar regional FRU/FRD procurement constraints, the regional deliverability constraints described in §3.10 are used without any minimum FRU/FRD requirements in each region below the system.

3.10 NETWORK CONSTRAINTS

The linearized physical network constraints at an AC power flow solution are as follows:

$$LFL_{k,t} \leq F_{k,t} \cong \tilde{F}_{k,t} + \sum_i \Delta EN_{i,t}\, SF_{i,k,t} + \sum_j \Delta EN_{j,t}\, SF_{j,k,t} - \sum_i \Delta L_{i,t}\, SF_{i,k,t} - \sum_j \Delta L_{j,t}\, SF_{j,k,t} \leq UFL_{k,t}, \forall k \wedge\ t = 1,2, \dots, T_D$$

Where the incremental energy injections are multiplied by the corresponding shift factor for the relevant network constraint to account for changes in the active power flow from the AC power flow solution. Additional nodal constraints limit virtual and physical energy schedules when the power flow solution reverts to DC.

The FRU/FRD awards from intertie resources associated with Intertie Transmission Corridor (ITC) or Intertie Scheduling Limit (ISL) constraints are constrained by these constraints along with all other relevant commodities. The ITC/ISL constraint is a set of four constraints, two in each import/export direction, one for energy schedules and capacity awards, and the other for capacity awards alone. This formulation allows energy schedules in opposite directions to net, but prevents netting of capacity awards with energy schedules or with capacity awards in the opposite direction:

$$\left.\begin{array}{c}\sum_{im \in S_k}\left(I_{im,t} + RU_{im,t} + SR_{im,t} + NR_{im,t} + FRU_{im,t}\right) - \sum_{ex \in S_k}\left(E_{ex,t} - FRU_{ex,t}\right) \leq UFL_{k,t} \\ \sum_{im \in S_k}\left(RU_{im,t} + SR_{im,t} + NR_{im,t} + FRU_{im,t}\right) + \sum_{ex \in S_k} FRU_{ex,t} \leq UFL_{k,t} \\ LFL_{k,t} \leq \sum_{im \in S_k}\left(I_{im,t} - RD_{im,t} - FRD_{im,t}\right) - \sum_{ex \in S_k}\left(E_{ex,t} + FRD_{ex,t}\right) \\ LFL_{k,t} \leq -\sum_{im \in S_k}\left(RD_{im,t} + FRD_{im,t}\right) - \sum_{ex \in S_k} FRD_{ex,t}\end{array}\right\},$$

$$\forall k \wedge t = 1, \ldots, T_D$$

Where in the case of ITC constraints, the set S_k includes all intertie resources bound by the ITC k, and in the case of ISL constraints, the set S_k includes all intertie resources associated with (tagged at) the corresponding intertie of the ISL k. 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 into the associated BAA, and the import direction in ISL constraints is into the "from" BAA of the associated intertie. Virtual bids are not allowed on intertie resources and capacity ancillary services can only be provided by certified import resources, whereas FRU/FRD can be provided by both import and export resources, except for hourly intertie resources.

To prevent procuring AS/FRP in regions below the system in excess of the N–1 simultaneous export/import transfer capability of these regions, the energy schedules, ancillary services, and FRU/FRD awards in each region below the system are constrained by regional deliverability constraints. These constraints reserve transmission capacity on the regional transmission interface for energy and capacity export/import, as follows:

$$\left.\begin{array}{l}\max\left(0, \sum_{i \in S_r}\left(EN_{i,t} - L_{i,t}\right) + \sum_{j \in S_r}\left(EN_{j,t} - L_{j,t}\right) - Loss_{r,t}\right) + \max\left(0, \sum_{i \in S_r} ASU_{i,t} - ASUR_{r,t}\right) + \\ \quad \max\left(0, \sum_{i \in S_r}\left(FRU_{i,t}\right) - FRUR_{r,t}\right) + \max\left(0, FRDR_{r,t} - \sum_{i \in S_r}\left(FRD_{i,t}\right)\right) \le NEL_{r,t} \\ \max\left(0, \sum_{i \in S_r}\left(L_{i,t} - EN\right) + \sum_{j \in S_r}\left(L_{j,t} - EN_{j,t}\right) + Loss_{r,t}\right) + \max\left(0, \sum_{i \in S_r} RD_{i,t} - RDR_{r,t}\right) + \\ \quad \max\left(0, \sum_{i \in S_r}\left(FRD_{i,t}\right) - FRDR_{r,t}\right) + \max\left(0, FRUR_{r,t} - \sum_{i \in S_r}\left(FRU_{i,t}\right)\right) \le NIL_{r,t}\end{array}\right\},$$

$\forall r > 0 \wedge t = 1, \dots, T_D$

Where the upward ancillary services are bundled together because of their cascaded procurement:

$$ASU_{i,t} = RU_{i,t} + SR_{i,t} + NR_{i,t}, \forall i \wedge t = 1,2, \dots, T_D$$

$$ASUR_{r,t} = RUR_{r,t} + SRR_{r,t} + NRR_{r,t}, \forall r \wedge t = 1,2, \dots, T_D$$

The Flexible Ramping Up/Down uncertainty requirements for a region are derived as an upper/lower percentile of the historical error between the physical supply that clears the IFM and the FMM demand forecast for that region. The nested regional deliverability constraints permit a flexible procurement of FRU/FRD where there is no minimum regional requirement, unlike the procurement of capacity ancillary services; however, transmission capacity is reserved as needed on the regional transmission interface to import FRU/FRD to satisfy the regional requirement or to export surplus FRU/FRD in excess of the regional requirement. This approach results in the most efficient overall procurement of FRU/FRD.

There is no reason for accurate loss modeling in these constraints; hence, a simple average loss factor would be sufficient. When such a regional constraint is binding in the optimal solution, its shadow price will affect the marginal prices of the commodities in the region, namely the energy, capacity ancillary services, and flexible ramping.

The positive difference terms in the regional deliverability constraints allows energy schedules in opposite directions to net, but prevent netting of capacity awards with energy schedules or with capacity awards in the opposite direction. These terms must be linearized in the MILP optimization engine. The general approach for linearizing a sum of positive differences without using binary variables is to write the constraint in all possible combinations where the positive differences can take a positive value. For example, for two positive difference terms:

$$\max(0, a) + \max(0, b) \le c \ge 0 \Leftrightarrow \begin{cases} a \le c \\ b \le c \\ a + b \le c \end{cases}$$

In general, n terms result in $2^n - 1$ linear constraints. Therefore, the four terms the regional deliverability constraints will result in 15 linear constraints per direction, per region, per interval. A large number of constraints does not impose a large performance requirement on a MILP solver because only the critical constraints are enforced.

3.11 SHARED RAMPING CONSTRAINTS

All resource commodities, i.e., energy, ancillary services, and FRU/FRD, are simultaneously constrained by the shared ramping constraints. For resources that remain online across time intervals, the shared ramping constraints are as follows:

$$\left.\begin{array}{l} EN_{i,t} - EN_{i,t-1} \geq -RRD_{i,T_{15}}\left(EN_{i,t-1}\right) + \alpha_t \dfrac{RD_{i,t-1} + RD_{i,t}}{2} + \delta_t \, FRD_{i,t} \\ EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{15}}\left(EN_{i,t-1}\right) - \alpha_t \dfrac{RU_{i,t-1} + RU_{i,t}}{2} - \\ \quad \beta_t \dfrac{SR_{i,t-1} + SR_{i,t}}{2} - \gamma_t \dfrac{NR_{i,t-1} + NR_{i,t}}{2} - \delta_t \, FRU_{i,t} \end{array}\right\},$$
$$\forall i \wedge u_{i,t-1} = u_{i,t} = 1 \wedge t = 1,2,\ldots,T_D$$

For resources that start up, the shared ramping constraints are as follows:

$$EN_{i,t} \leq LOL_{i,t} + RRU_{i,T_{15}/2}\left(LOL_{i,t}\right) - \alpha_t \, RU_{i,t} - \beta_t \, SR_{i,t} - \gamma_t \, NR_{i,t} - \delta_t \, FRU_{i,t},$$
$$\forall i \wedge u_{i,t-1} = 0 \wedge u_{i,t} = 1 \wedge t = 1,2,\ldots,T_D$$

Where half of the interval ramp is used to ramp up from LOL.

For resources that shut down, the shared ramping constraints are as follows:

$$EN_{i,t} \leq LOL_{i,t} + RRU_{i,T_{15}/2}\left(LOL_{i,t}\right) - \alpha_t \, RD_{i,t} - \delta_t \, FRD_{i,t}\},$$
$$\forall i \wedge u_{i,t} = 1 \wedge u_{i,t+1} = 0 \wedge t = 1,2,\ldots,T_D$$

Where half of the interval ramp is used to ramp down to LOL.

For resources that remain offline across time intervals, the shared ramping constraints are as follows:

$$\gamma_t \frac{NR_{i,t-1} + NR_{i,t}}{2} + \delta_t \, FRU_{i,t} \leq LOL_{i,t} + RRU_{i,T_{15}-SUT_{i,t}}\left(LOL_{i,t}\right),$$
$$\forall i \in S_{15} \wedge u_{i,t-1} = u_{i,t} = 0 \wedge t = 1,2,\ldots,T_D$$

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

The shared ramping coefficients specify how the various commodities share the resource ramp capability. The shared ramping constraint reserves ramp capability for the average ancillary services awards over the ramp between the time interval midpoints, whereas FRU/FRD align exactly with that ramp. 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.

3.12 RESOURCE CAPACITY CONSTRAINTS

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

$$\left.\begin{array}{l} RU_{i,t} + RD_{i,t} > 0 \rightarrow \begin{cases} UOL'_{i,t} = \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) \\ LOL'_{i,t} = \max\left(LOL_{i,t}, LRL_{i,t}\right) \end{cases} \\ \left.\begin{array}{l} RU_{i,t} + RD_{i,t} = 0 \\ SR_{i,t} + NR_{i,t} > 0 \end{array}\right\} \rightarrow \begin{cases} UOL'_{i,t} = \min\left(UOL_{i,t}, CL_{i,t}\right) \\ LOL'_{i,t} = LOL_{i,t} \end{cases} \\ RU_{i,t} + RD_{i,t} + SR_{i,t} + NR_{i,t} = 0 \rightarrow \begin{cases} UOL'_{i,t} = UOL_{i,t} \\ LOL'_{i,t} = LOL_{i,t} \end{cases} \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{array}{l} UEL'_{i,t} = \min\left(UOL'_{i,t}, UEL_{i,t}\right) \\ LEL'_{i,t} = \left(1 - \eta_{i,t}\right) \max\left(LOL'_{i,t}, LEL_{i,t}\right) \end{array}\right\}, \forall i \wedge t = 1,2, \dots, T_D$$

Where zero is used instead of the LEL if the resource can be shut down, which is possible when there is no energy self-schedule (LEL is equal to LOL), no online ancillary services, and the inter-temporal constraints allow it. In this case, the FRD can span the LOL.

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

$$\left.\begin{array}{l} EN_{i,t} \le UOL'_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LOL'_{i,t} + RD_{i,t} + FRD_{i,t} \le EN_{i,t} \\ LEL'_{i,t} + FRD_{i,t} \le EN_{i,t} \le UEL'_{i,t} - FRU_{i,t} \end{array}\right\}, \forall i \wedge u_{i,t} = 1 \wedge t = 1,2, \dots, T_D$$

And for offline resources:

$$NR_{i,t} \le UOL'_{i,t}, \forall i \in S_{FSU} \wedge u_{i,t} = 0 \wedge t = 1,2, \dots, T_D$$

$$\left.\begin{array}{l} NR_{i,t} + FRU_{i,t} \le UOL'_{i,t} \\ FRU_{i,t} \le UEL'_{i,t} \end{array}\right\}, \forall i \in S_{15} \wedge u_{i,t} = 0 \wedge t = 1,2, \dots, T_D$$