California ISO
Shaping a Renewed Future

Integrated Day-Ahead Market

Draft Technical Description

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1 INTRODUCTION

This technical paper describes the integrated Day-Ahead Market (iDAM) optimization problem formulation for discussion purposes. The iDAM combines the functionality of the Integrated Forward Market (IFM) and the Residual Unit Commitment (RUC) into one market application to realize efficiencies in procuring all Day-Ahead Market commodities simultaneously. In that respect, the iDAM is essentially a consolidation of existing and planned market functionality, rather than a market redesign effort. Nevertheless, the Bid Cost Recovery (BCR) allocation of Day-Ahead Market commitment costs, which is currently separate for IFM and RUC, must be changed since these two processes will be fused into iDAM.

1.1 EXISTING DAY-AHEAD MARKET STRUCTURE

Currently the Day-Ahead Market includes two separate market applications that are executed in sequence: IFM and RUC. The IFM commits resources, clears physical and virtual energy schedules, and procures ancillary services. The RUC commits additional resources and schedules additional capacity beyond physical energy schedules to meet the 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 demand forecast. Furthermore, ancillary services awarded in IFM remain constant in RUC.

1.2 PROBLEMS WITH THE EXISTING DAY-AHEAD MARKET

The current Day-Ahead Market structure results in a suboptimal (higher cost) unit commitment solution in the Day-Ahead Market because it is achieved in two stages with different objectives at each stage and because the commitment of the first stage (IFM) is locked in the second stage (RUC). For example, a unit that is committed in IFM may have insufficient capacity to meet the demand forecast leading to additional resource commitment in RUC, which could render the IFM commitment unnecessary. By contrast, the iDAM will commit resources more efficiently in a single process by satisfying both IFM and RUC objectives simultaneously.

Furthermore, the current Day-Ahead Market structure is less efficient for procuring flexible ramp capacity. Flexible ramp is capacity reserved from committed resources for the 5-min ramp between consecutive dispatch intervals in real time; as such, flexible ramp must be procured from all committed resources, whether they are committed in IFM or RUC. However, the existing market structure would only procure flexible ramp in IFM. By contrast, the iDAM will procure flexible ramp more efficiently from all committed resources in a single process.

1.3 MARKET COMMODITIES IN THE INTEGRATED DAY-AHEAD MARKET

Besides resource commitment determination, the commodities procured in iDAM are the following:

- Day-Ahead Energy schedules for physical and virtual resources;
- Day-Ahead Reliability schedules and capacity awards for physical resources;
- Day-Ahead Regulation Up and Down awards;
- Day-Ahead Mileage Up and Down awards;

- Day-Ahead Spinning Reserve awards;
- Day-Ahead Non-Spinning Reserve awards;
- Day-Ahead Flexible Ramp Up and Down awards; and
- Day-Ahead Transmission capacity reservation awards for Dynamic Transfers.

2 ASSUMPTIONS

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

- The unit commitment solution allows both balancing supply and demand bids and meeting the demand forecast. This can be accomplished by enforcing two power balance constraints:
    1) Physical and virtual Energy supply schedules balance physical and virtual Energy demand schedules and transmission losses; and
    2) Physical Reliability supply and dispatchable demand schedules (current RUC schedules) balance the demand forecast including transmission losses.
- The objective function is the maximization of the total merchandizing surplus 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 Multi-State Generators;
    - the minimization of Ancillary Services awards cost;
    - the minimization of Flexible Ramp awards cost;
    - the maximization of Transmission capacity reservation awards benefit; and
    - the minimization of Reliability capacity awards cost.
- The IFM functionality and constraints are fully preserved:
    - physical/virtual Energy supply schedules balance physical/virtual Energy demand schedules and transmission losses;
    - Ancillary Services requirement constraints are enforced;
    - Flexible Ramp requirement constraints are enforced;
    - resource inter-temporal commitment constraints are enforced;
    - resource Energy, Ancillary Services, and Flexible Ramp capacity constraints are enforced;
    - resource Energy, Ancillary Services, and Flexible Ramp ramping constraints are enforced;
    - Ancillary Services and Flexible Ramp time domain constraints are enforced;

  - network constraints for physical/virtual Energy schedules (base case and contingencies) are enforced; and
  - scheduling limits for physical/virtual Energy schedules, Ancillary/Ramping Services awards, and Transmission capacity reservation awards, associated with Inter-tie Transmission Corridors (ITCs) are enforced.
- The RUC functionality and constraints are fully preserved:
  - physical Reliability schedules balance the demand forecast including transmission losses;
  - Reliability capacity above the Day-Ahead Energy schedule comes at no cost up to the adjusted Resource Adequacy (RA) capacity (RA capacity minus upward Ancillary Services awards);
  - Reliability capacity in excess of the adjusted RA capacity comes at the cost of the Reliability bid;
  - only Reliability schedules above the Day-Ahead Energy schedules and the adjusted RA capacity receive Reliability capacity awards;
  - the option to use Energy bids in addition to Reliability capacity bids to optimally determine Reliability schedules is preserved;
  - resource Reliability, Ancillary Services, and Flexible Ramp capacity constraints are enforced;
  - resource Reliability, Ancillary Services, and Flexible Ramp ramping constraints are enforced;
  - network constraints for Reliability schedules (base case and contingencies) are enforced;
  - scheduling limits for Reliability schedules, Ancillary/Ramping Service awards, and Transmission capacity reservation awards associated with ITCs are enforced;
  - maximum Energy constraints are enforced; and
  - quick-start capacity constraints are enforced.
- Energy and Reliability schedules are constrained by separate linearized network constraints (for both base case and contingencies) derived from separate AC power flow solutions. These schedules and the Ancillary/Ramping Services awards are also simultaneously constrained by resource capacity and ramping constraints, similarly to the current IFM and RUC.
- The Day-Ahead Market Power Mitigation (MPM) functionality and constraints are fully preserved; the MPM is essentially a “trial” pass of iDAM where the established MPM principles apply, namely:
  - the impact of physical resource Energy schedules on network constraints is quantified;
  - based on Resource Supply Index calculations and metrics, network constraints are classified as competitive or not;
  - resources that provide congestion relief on non-competitive network constraints are flagged for mitigation; and

- Energy bids from resources flagged for mitigation are mitigated and used in the next and final iDAM pass.

- The 72-hr RUC functionality can be achieved by extending the time horizon of iDAM to three Trading Days where only Reliability schedules, Ancillary Services awards, and Flexible Ramp awards for physical supply and dispatchable demand resources are produced for the second and third Trading Day to determine binding start-ups for Extra Long-Start (ELS) Resources.

3 BID COST RECOVERY

As mentioned in the introduction, the current Bid Cost Recovery (BCR) allocation method for the unrecovered Day-Ahead Market commitment costs must be revised with the implementation of iDAM. This is because the current method allocates differently the unrecovered commitment cost from IFM and RUC, whereas these costs cannot be distinguished in iDAM where the resource commitment solution meets both IFM and RUC objectives simultaneously. Consequently, the unrecovered iDAM commitment cost should be allocated to both allocation bases used currently for the allocation of IFM and RUC commitment costs. Therefore, the hourly iDAM bid cost uplift can be allocated to Business Associates as follows:

a) Tier 1: The hourly bid cost uplift would be allocated to Business Associates in proportion to their scheduled demand (load plus exports) in excess of their self-scheduled physical generation and imports, adjusted by any applicable Inter-SC Trades of Load Uplift Obligations, but with a Tier 1 bid cost uplift rate not exceeding the ratio of the hourly bid cost uplift amount divided by the sum of all hourly physical generation schedules and upward ancillary services awards for all Business Associates from CAISO-committed BCR-eligible resources in the relevant Trading Hour. The scheduled demand in the allocation basis would include virtual demand in excess of virtual supply if the total scheduled demand (virtual and physical) exceeds the CAISO Demand forecast in the relevant Trading Hour. This is the current Tier 1 IFM bid cost uplift allocation.

b) Tier 2: The remaining (after Tier 1 allocation) hourly bid cost uplift would be allocated to Business Associates in proportion to their net negative CAISO Demand deviation in the relevant Trading Hour, with a Tier 2 bid cost uplift rate calculated as the lower of: a) the ratio of the remaining hourly bid cost uplift amount divided by the total net negative CAISO Demand in that Trading Hour; or b) the ratio of the remaining hourly bid cost uplift amount divided by the Reliability Capacity (the positive difference between Reliability and Energy schedules) in that Trading Hour. This is the current Tier 1 RUC bid cost uplift allocation.

c) Tier 3: The remaining (after Tier 2 allocation) hourly bid cost uplift would be allocated to Business Associates in proportion to their metered CAISO Demand in the relevant Trading Hour. MSS entities, regardless of gross or net settlement, that have elected to opt-out of the Reliability scheduling in iDAM, would not be allocated any Tier 3 hourly bid cost uplift. MSS entities that have elected to opt-into the Reliability scheduling in iDAM, regardless of gross or net settlement, would be allocated Tier 3 hourly bid cost uplift in the same manner as other non-MSS SCs. This is the current Tier 2 RUC bid cost uplift allocation.

Note that the current provision to include virtual supply in excess of virtual demand in Tier 1 RUC bid cost allocation is no longer necessary in the iDAM bid cost allocation because that excess virtual supply does not inhibit resource commitment in iDAM to meet the demand forecast.

4 MATHEMATICAL FORMULATION

The focus of the mathematical formulation of iDAM in this technical paper is on the combination of IFM and RUC. Emphasis is given on the particular elements that are required for this combination. Known features that apply in general to the Security Constrained Unit Commitment (SCUC) engine, such as inter-temporal constraints, Multi-State Generator modeling, contingency constraints, nomograms, ITC constraints, soft constraint or scarcity treatment, and new market commodities such as Regulation Mileage and Transmission Capacity Reservation on ITCs, are not included for simplicity and because they do not materially affect the integration of IFM and RUC. On the other hand, Flexible Ramp is part of the formulation because it does have a material impact.

4.1 NOTATION

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

i	Physical Resource index.
j	Virtual Resource index.
k	Network constraint index.
t	Time period index.
T	Time Horizon.
T_{10}	Capacity Ancillary Services time domain (10 min).
T_{60}	Energy schedule and Flexible Ramp time domain (60 min).
S_U	Set of supply and demand response resources (everything except non-participating load).
S_G	Set of Generating resources.
S_Q	Set of quick-start resources.
$S_{E,t}$	Critical network constraint set for Energy schedules in time period *t*.
$S_{R,t}$	Critical network constraint set for Reliability schedules in time period *t*.
$\forall$	For all.
$\rightarrow$	Leads to.
Δ	Denotes incremental values.
$u_{i,t}$	Binary variable indicating that Resource *i* is online in time period *t*.
$y_{i,t}$	Binary variable indicating that Resource *i* has a start-up in time period *t*.
$r_{i,t}$	Binary variable indicating that Resource *i* is on Regulation in time period *t*.
$LOL_{i,t}$	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*; $LOL_{i,t} \leq CL_{i,t} \leq UOL_{i,t}$; 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 and negative for demand).
$REN_{i,t}$	Reliability schedule of Resource *i* in time period *t* (positive for supply and negative for demand).
$RAC_{i,t}$	Resource Adequacy Capacity of Resource *i* in time period *t*; it defaults to zero.
$RAC'_{i,t}$	Adjusted Resource Adequacy Capacity of Resource *i* in time period *t* by subtracting upward AS awards in time period *t*.
$RC_{i,t}$	Reliability award from Resource *i* in time period *t*.
$RD_{i,t}$	Regulation Down award of Resource *i* in time period *t*.
$RU_{i,t}$	Regulation Up 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*.
$FRD_{i,t}$	Flexible Ramp Down award of Resource *i* in time period *t*.
$FRU_{i,t}$	Flexible Ramp Up award of Resource *i* in time period *t*.
$RDC_{i,t}$	Regulation Down capacity bid of Resource *i* in time period *t*.
$RUC_{i,t}$	Regulation Up 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*.
$RENP_{i,t}$	Reliability bid price of Resource *i* in time period *t*.
$RDP_{i,t}$	Regulation Down bid price of Resource *i* in time period *t*.
$RUP_{i,t}$	Regulation Up 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*.
$FRDP_{i,t}$	Flexible Ramp Down bid price of Resource *i* in time period *t*.
$FRUP_{i,t}$	Flexible Ramp Up bid price
RDR_{t}	Regulation Down requirement in time period *t*.
RUR_{t}	Regulation Up requirement in time period *t*.
SRR_{t}	Spinning Reserve requirement in time period *t*.
NRR_{t}	Non-Spinning Reserve requirement in time period *t*.
$FRDD_{t}$	Flexible Ramp Down elastic demand in time period *t*.
$FRUD_{t}$	Flexible Ramp Up elastic demand in time period *t*.
$FRDDP_{t}$	Flexible Ramp Down elastic demand price in time period *t*.
$FRUDP_{t}$	Flexible Ramp Up elastic demand price in time period *t*.
$FRDR_{t}$	Flexible Ramp Down requirement in time period *t*.
$FRUR_{t}$	Flexible Ramp Up requirement in time period *t*.
$RRU_{i,T_s}()$	Piecewise linear ramp up capability function of Resource *i* for time domain T_s (positive).
$RRD_{i,T_s}()$	Piecewise linear ramp down capability function of Resource *i* for time domain T_s (negative).

$LPFE_{i,t}$	Loss Penalty Factor for the Energy injection schedule of Resource *i* in time period *t*.
$LPFR_{i,t}$	Loss Penalty Factor for the Reliability injection schedule of Resource *i* in time period *t*.
L_t	First transmission loss approximation for time period *t*.
D_t	Demand forecast (including transmission losses) for time period *t*.
$SF_{i,k,t}$	Shift Factor for the Energy or Reliability injection schedule of Resource *i* on network constraint *k* in time period *t*.
$F_{k,t}$	Base case active power flow for Energy schedules on network constraint *k* in time period *t*.
$RF_{k,t}$	Base case active power flow for Reliability schedules on network constraint *k* in time period *t*.
$LFL_{k,t}$	Lower active power flow limit on network constraint *k* in time period *t*.
$UFL_{k,t}$	Upper active power flow limit on network constraint *k* in time period *t*.
C	Objective function.
a	Configuration parameter for including Energy cost in Reliability cost: a = 0: Energy cost not included (current approach). a = 1: Energy cost is included.
f	Demand forecast factor used in Maximum Energy constraints.
c	Capacity factor used in quick-start capacity constraints.
α	Ramping coefficient for Regulation.
β	Ramping coefficient for Spinning Reserve.
γ	Ramping coefficient for Non-Spinning Reserve.

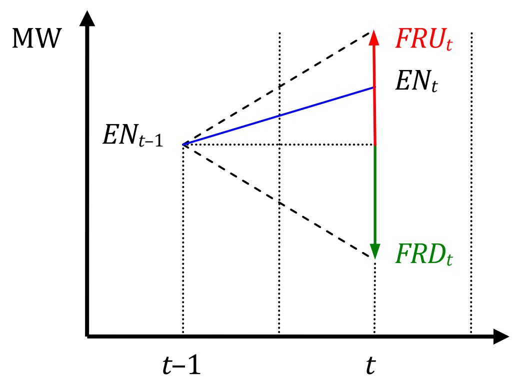
4.2 GENERAL PROBLEM FORMULATION

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

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

4.3 FLEXIBLE RAMP MODELING

This section gives a brief overview of the Flexible Ramp model without any Ancillary Services for simplicity. The following figure shows the potential Flexible Ramp Up and Down awards for a resource in a given time period *t* that can be procured based on the Energy schedule ramp from the previous time period.



The dashed lines represent the upward and downward ramp capability of the resource from the Energy schedule in the previous time period. The Flexible Ramp Up and Down awards are limited by that ramp capability. The Flexible Ramp award may include capacity that is expended in the scheduled ramp from the previous time period to the current time period, consistent with the "real ramp" Flexible Ramp model.

It is important to note that both Energy schedules (EN_{t-1}, EN_t) and Flexible Ramp awards (FRU_t, FRD_t) are calculated simultaneously by the optimization engine, i.e., they are *control variables*. The only exception is the initial point (EN_0), which is a fixed input for the ramp to the Energy schedule of the first time period. These control variables are constrained by the following set of capacity and ramp constraints:

$$\max(EN_{t-1} + FRU_t, EN_t) \leq UEL_t$$

$$\min(EN_{t-1} - FRD_t, EN_t) \geq LEL_t$$

$$FRU_t \leq RRU(EN_{t-1})$$

$$FRD_t \leq -RRD(EN_{t-1})$$

$$RRD(EN_{t-1}) \leq EN_t - EN_{t-1} \leq RRU(EN_{t-1})$$

These constraints are more complicated when considering Ancillary Services awards and Reliability schedules, as shown in the following sections.

4.4 OBJECTIVE FUNCTION

The objective function, assuming flat (single segment) Energy bid and elastic Flexible Ramp demand prices for simplicity, is as follows:

$$C = \sum_{t=1}^{T}\sum_{i} y_{i,t}\, SUC_{i,t} + \sum_{t=1}^{T}\sum_{i} u_{i,t}\, MLC_{i,t} + \sum_{t=1}^{T}\sum_{i}\left(EN_{i,t} - LOL_{i,t}\right) ENP_{i,t}$$
$$+ \sum_{t=1}^{T}\sum_{j} EN_{j,t}\, ENP_{j,t} + \sum_{t=1}^{T}\sum_{i} RD_{i,t}\, RDP_{i,t} + \sum_{t=1}^{T}\sum_{i} RU_{i,t}\, RUP_{i,t}$$
$$+ \sum_{t=1}^{T}\sum_{i} SR_{i,t}\, SRP_{i,t} + \sum_{t=1}^{T}\sum_{i} NR_{i,t}\, NRP_{i,t} + \sum_{t=1}^{T}\sum_{i} FRD_{i,t}\, FRDP_{i,t}$$
$$+ \sum_{t=1}^{T}\sum_{i} FRU_{i,t}\, FRUP_{i,t} - \sum_{t=1}^{T} FRDD_{t}\, FRDDP_{t} - \sum_{t=1}^{T} FRUD_{t}\, FRUDP_{t}$$
$$+ a \sum_{t=1}^{T}\sum_{i \in S_U} \max\left(0, REN_{i,t} - EN_{i,t}\right) ENP_{i,t} + \sum_{t=1}^{T}\sum_{i \in S_U} RC_{i,t}\, RENP_{i,t}$$

Where the Reliability award is determined as follows:

$$RC_{i,t} = \max\left(0, REN_{i,t} - \max\left(EN_{i,t}, RAC'_{i,t}\right)\right), \qquad \forall i \in S_U, \forall t$$

And the Adjusted Resource Adequacy capacity is given by:

$$RAC'_{i,t} = RAC_{i,t} - RU_{i,t} - SR_{i,t} - NR_{i,t}, \qquad \forall i \in S_U, \forall t$$

The binary variables and constraints required to linearize the last two terms in the objective function are not shown here for simplicity. Furthermore, all online services are zero when the resource is offline, and Regulation services are zero when the resource is not regulating:

$$u_{i,t} = 0 \rightarrow EN_{i,t} = REN_{i,t} = SR_{i,t} = FRD_{i,t} = FRU_{i,t} = 0, \qquad \forall i \in S_U, t$$

$$u_{i,t} = 0 \rightarrow r_{i,t} = 0 \rightarrow RU_{i,t} = RD_{i,t} = 0, \qquad \forall i \in S_U, t$$

Note that Ancillary Services and Reliability awards apply only to resources certified to provide them. For Resources not certified for Reliability awards:

$$REN_{i,t} \leq EN_{i,t}, \qquad \forall i \in S_U, \forall t$$

4.5 POWER BALANCE CONSTRAINTS

There are two power balance constraints for each time period: one for Energy schedules, and another one for Reliability schedules. In the first SCUC iteration where a power flow solution is not yet available from Network Analysis (NA), the Energy power balance constraints are as follows:

$$\sum_{i} EN_{i,t} + \sum_{j} EN_{j,t} = L_t, \qquad \forall t$$

Where L is a first approximation of the transmission loss, typically a percentage of the demand forecast. In the subsequent SCUC iterations, the linearized Energy power balance constraints from the Energy base case power flow solutions from NA are as follows:

$$\sum_i \frac{\Delta EN_{i,t}}{LPFE_{i,t}} + \sum_j \frac{\Delta EN_{j,t}}{LPFE_{j,t}} = 0, \qquad \forall t$$

Where the incremental Energy injections are divided by the corresponding Loss Penalty Factors to account for changes in transmission losses from the Energy base case solution.

Similarly, in the first SCUC iteration, the Reliability power balance constraints are as follows:

$$\sum_{i \in S_U} REN_{i,t} = D_t, \qquad \forall t$$

Where D is the demand forecast inclusive of transmission losses, but exclusive of demand response. In the subsequent SCUC iterations, the linearized Reliability power balance constraints from the Reliability base case power flow solutions from NA are as follows:

$$\sum_{i \in S_U} \frac{\Delta REN_{i,t}}{LPFR_{i,t}} = 0, \qquad \forall t$$

Where the incremental Reliability injections are divided by the corresponding Loss Penalty Factors to account for changes in transmission losses from the Reliability base case solution.

Note that NA must solve the power flow equations and must calculate Loss Penalty Factors separately for Energy and Reliability schedules, a total of $2 \times T$ power flow solutions. Similarly, contingency analysis must be performed separately for Energy and Reliability schedules and the critical network constraint set must also be determined separately for Energy and Reliability schedules. Nevertheless, because there are no network differences for the Energy and Reliability schedules (they both flow on the same network), the Shift Factors are the same for both. However, the critical constraint set and ultimately the binding constraints may be different for Energy and Reliability schedules.

4.6 NETWORK CONSTRAINTS

The linearized network constraints at a power flow solution for Energy schedules are as follows:

$$LFL_{k,t} \leq F_{k,t} + \sum_i \Delta EN_{i,t}\, SF_{i,k,t} + \sum_j \Delta EN_{j,t}\, SF_{j,k,t} \leq UFL_{k,t}, \qquad \forall k \in S_{E,t}, \forall t$$

Where the incremental Energy schedules are multiplied by the corresponding Shift Factor for the relevant network constraint to account for changes in the power flow from the Energy base case solution. Additional nodal constraints limiting virtual and physical Energy schedules at virtual Energy schedule locations are formulated when the power flow solution reverts to DC.

The linearized network constraints at a power flow solution for Reliability schedules are as follows:

$$LFL_{k,t} \leq RF_{k,t} + \sum_{i \in S_U} \Delta REN_{i,t}\, SF_{i,k,t} \leq UFL_{k,t}, \qquad \forall k \in S_{R,t}, \forall t$$

Where the incremental Reliability schedules are multiplied by the corresponding Shift Factor for the relevant network constraint to account for changes in the power flow from the Reliability base case solution.

4.7 MAXIMUM ENERGY CONSTRAINTS

These soft constraints limit the Energy from committed physical supply resources to a high percentage of the demand forecast, as follows:

$$\sum_{i \in S_U} EN_{i,t} \leq f\, D_t, \qquad \forall t$$

4.8 QUICK-START CAPACITY CONSTRAINTS

These soft constraints limit the Reliability schedules from quick-start resources, as follows:

$$\sum_{i \in S_Q} REN_{i,t} \leq c \sum_{i \in S_Q} UOL_{i,t}\,, \qquad \forall t$$

4.9 ANCILLARY/RAMPING SERVICES REQUIREMENTS

Assuming a single AS Region for simplicity, the AS requirement constraints are as follows:

$$\left.\begin{array}{c}
\sum_i RD_{i,t} \geq RDR_t \\
\sum_i RU_{i,t} \geq RUR_t \\
\sum_i RU_{i,t} + \sum_i SR_{i,t} \geq RUR_t + SRR_t \\
\sum_i RU_{i,t} + \sum_i SR_{i,t} + \sum_i NR_{i,t} \geq RUR_t + SRR_t + NRR_t \\
\sum_i FRD_{i,t} = FRDD_t \leq FRDR_t \\
\sum_i FRU_{i,t} = FRUD_t \leq FRUR_t
\end{array}\right\}, \qquad \forall t$$

Note that there is cascaded procurement for the Ancillary Services, but it does not include Flexible Ramp, which is a ramping service on a different time domain. Furthermore, the Flexible Ramp demands are elastic (control variables) and bounded from above by the Flexible Ramp requirements.

4.10 ANCILLARY/RAMPING SERVICES BOUNDS

The Ancillary/Ramping Services upper/lower bound constraints are as follows:

$$\left.\begin{array}{c} 0 \leq RD_{i,t} \leq RDC_{i,t} \\ 0 \leq RU_{i,t} \leq RUC_{i,t} \\ 0 \leq SR_{i,t} \leq SRC_{i,t} \\ 0 \leq NR_{i,t} \leq NRC_{i,t} \\ 0 \leq FRD_{i,t} \\ 0 \leq FRU_{i,t} \end{array}\right\}, \quad \forall i,t$$

There are no upper bound constraints for Flexible Ramp since there is no associated capacity quantity bid, i.e., all available capacity under the Energy bid can be procured as Flexible Ramp Up or Down.

4.11 ANCILLARY/RAMPING SERVICES TIME DOMAIN CONSTRAINTS

The Ancillary/Ramping Services time domain constraints are as follows:

$$\left.\begin{array}{c} RD_{i,t} \leq -RRD_{i,T_{10}}\left(EN_{i,t-1}\right) \\ RU_{i,t} + SR_{i,t} + NR_{i,t} \leq RRU_{i,T_{10}}\left(EN_{i,t-1}\right) \\ FRD_{i,t} \leq -RRD_{i,T_{60}}\left(EN_{i,t-1}\right) \\ FRU_{i,t} \leq RRU_{i,T_{60}}\left(EN_{i,t-1}\right) \\ RD_{i,t} \leq -RRD_{i,T_{10}}\left(REN_{i,t-1}\right) \\ RU_{i,t} + SR_{i,t} + NR_{i,t} \leq RRU_{i,T_{10}}\left(REN_{i,t-1}\right) \\ FRD_{i,t} \leq -RRD_{i,T_{60}}\left(REN_{i,t-1}\right) \\ FRU_{i,t} \leq RRU_{i,T_{60}}\left(REN_{i,t-1}\right) \end{array}\right\}, \quad \forall i,t$$

Note that Ancillary Services are simultaneously constrained in a 10min domain from the Energy and Reliability schedules, whereas Flexible Ramp is constrained separately in a 60min domain from the Energy and Reliability schedules. This is because Flexible Ramp is not a capacity service for a given interval, but a ramping service across intervals.

4.12 RESOURCE CAPACITY CONSTRAINTS

The Generating Resource capacity constraints are as follows:

For $r_{i,t} = 1$:

$$\left.\begin{array}{c}\max\left(LOL_{i,t}, LRL_{i,t}\right) + RD_{i,t} \le EN_{i,t} \\ EN_{i,t} \le \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) - RU_{i,t} - SR_{i,t} - NR_{i,t} \\ LEL_{i,t} \le EN_{i,t} \le UEL_{i,t} \\ \max\left(LOL_{i,t}, LRL_{i,t}\right) + RD_{i,t} + FRD_{i,t} \le EN_{i,t-1} \\ EN_{i,t-1} \le \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LEL_{i,t} + FRD_{i,t} \le EN_{i,t-1} \le UEL_{i,t} - FRU_{i,t} \\ \max\left(LOL_{i,t}, LRL_{i,t}\right) + RD_{i,t} \le REN_{i,t} \\ REN_{i,t} \le \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) - RU_{i,t} - SR_{i,t} - NR_{i,t} \\ LEL_{i,t} \le REN_{i,t} \le UEL_{i,t} \\ \max\left(LOL_{i,t}, LRL_{i,t}\right) + RD_{i,t} + FRD_{i,t} \le REN_{i,t-1} \\ REN_{i,t-1} \le \min\left(UOL_{i,t}, URL_{i,t}, CL_{i,t}\right) - RU_{i,t} - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LEL_{i,t} + FRD_{i,t} \le REN_{i,t-1} \le UEL_{i,t} - FRU_{i,t}\end{array}\right\}, \forall i \in S_G, \forall t$$

For $u_{i,t} = 1 \wedge r_{i,t} = 0$:

$$\left.\begin{array}{c}LOL_{i,t} \le EN_{i,t} \le \min\left(UOL_{i,t}, CL_{i,t}\right) - SR_{i,t} - NR_{i,t} \\ LEL_{i,t} \le EN_{i,t} \le UEL_{i,t} \\ LOL_{i,t} + FRD_{i,t} \le EN_{i,t-1} \le \min\left(UOL_{i,t}, CL_{i,t}\right) - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LEL_{i,t} + FRD_{i,t} \le EN_{i,t-1} \le UEL_{i,t} - FRU_{i,t} \\ LOL_{i,t} \le REN_{i,t} \le \min\left(UOL_{i,t}, CL_{i,t}\right) - SR_{i,t} - NR_{i,t} \\ LEL_{i,t} \le REN_{i,t} \le UEL_{i,t} \\ LOL_{i,t} + FRD_{i,t} \le REN_{i,t-1} \le \min\left(UOL_{i,t}, CL_{i,t}\right) - SR_{i,t} - NR_{i,t} - FRU_{i,t} \\ LEL_{i,t} + FRD_{i,t} \le REN_{i,t-1} \le UEL_{i,t} - FRU_{i,t}\end{array}\right\}, \forall i \in S_G, \forall t$$

And for the special case of offline Non-Spinning Reserve ($u_{i,t} = 0 \wedge SUT_{i,t} \le T_{10}$):

$$\left.\begin{array}{c}EN_{i,t} = REN_{i,t} = 0 \\ NR_{i,t} \le \min\left(UOL_{i,t}, CL_{i,t}\right)\end{array}\right\}, \qquad \forall i \in S_G, \forall t$$

The time domain constraint is also different in this case, as follows:

$$NR_{i,t} \le LOL_{i,t} + RRU_{i,T_{10}-SUT_{i,t}}\left(LOL_{i,t}\right), \qquad \forall i, t$$

Note that although an economic Energy bid is not required for Regulation and Spinning or Non-Spinning Reserve awards, it is required for Flexible Ramp awards because they are used for ramping across intervals.

4.13 RESOURCE RAMPING CONSTRAINTS

The Generating Resource Energy and Ancillary Services ramping constraints are as follows:

$$\left.\begin{array}{c} EN_{i,t} - EN_{i,t-1} \geq RRD_{i,T_{60}}\left(EN_{i,t-1}\right) + \alpha\left(RD_{i,t-1} + RD_{i,t}\right) \\ EN_{i,t} - EN_{i,t-1} \leq RRU_{i,T_{60}}\left(EN_{i,t-1}\right) - \alpha\left(RU_{i,t-1} + RU_{i,t}\right) - \\ -\beta\left(SR_{i,t-1} + SR_{i,t}\right) - \gamma\left(NR_{i,t-1} + NR_{i,t}\right) \\ REN_{i,t} - REN_{i,t-1} \geq RRD_{i,T_{60}}\left(REN_{i,t-1}\right) + \alpha\left(RD_{i,t-1} + RD_{i,t}\right) \\ REN_{i,t} - REN_{i,t-1} \leq RRU_{i,T_{60}}\left(REN_{i,t-1}\right) - \alpha\left(RU_{i,t-1} + RU_{i,t}\right) - \\ -\beta\left(SR_{i,t-1} + SR_{i,t}\right) - \gamma\left(NR_{i,t-1} + NR_{i,t}\right) \end{array}\right\}, \qquad \forall i \in S_G, \forall t$$

Note that Flexible Ramp is not included in the resource ramping constraints; it is reserved in the resource capacity constraints along with the Ancillary Services, but it is released for ramping across intervals.