Invenia's Formulation of MISO DA Market Clearing Process

Power Systems Team

Abstract

As part of *market modelling* mission and *re-create market clearing process history* initiative at Invenia, we would like to set up a pipeline that can approximately simulate the market clearing process in different ISOs. Starting by MISO, we use this document to describe the day-ahead clearing formulation and specify assumptions/approximations and things that can be improved or can be modelled more accurately.

NOMENCLATURE

Parameters

$\Gamma^{flow,0}_{1,m}$ Line/transformer m power flow step-1 slack variable penalty cost in the base-case in $\$/\text{MW}$.
$\Gamma^{flow,0}_{2,m}$ Line/transformer m power flow step-2 slack variable penalty cost in the base-case in $\$/\text{MW}$.
$\Gamma^{flow,c}_{1,m}$ Line/transformer m power flow step-1 slack variable penalty cost in the contingency scenario c in $\$/\text{MW}$.
$\Gamma^{flow,c}_{2,m}$ Line/transformer m power flow step-2 slack variable penalty cost in the contingency scenario c in $\$/\text{MW}$.
$\Gamma^{RS}_{Tot,t}$ Market-wide regulation+spin reserve slack variable penalty cost at time t in $\$/\text{MW}$.
$\Gamma^{RS}_{z,t}$ Zone z regulation+spin reserve slack variable penalty cost at time t in $\$/\text{MW}$.
$\Lambda^{bid}_{d,t,q}$ Bid price of virtual demand d at time t for block q in $\$/\text{MW}$.
$\Lambda^{bid}_{s,t,q}$ Bid price of price-sensitive demand s at time t for block q in $\$/\text{MW}$.
$\Lambda^{offer}_{g,t,q}$ Offer price of generator g at time t for block q in $\$/\text{MW}$.
$\Lambda^{offer}_{i,t,q}$ Offer price of virtual supply i at time t for block q in $\$/\text{MW}$.
$\overline{D}_{d,t,q}$ Maximum energy dispatch of virtual demand d at time t for block q in MW.
$\overline{D}_{s,t,q}$ Maximum energy dispatch of price-sensitive demand s at time t for block q in MW.
$\overline{P}_{g,t,q}$ Maximum energy dispatch of generator g at time t for block q in MW.
$\overline{P}_{i,t,q}$ Maximum energy dispatch of virtual supply i at time t for block q in MW.
$\text{ISF}_{m,n}$ Injection shift factor on line/transformer m for injection at bus n.
$\text{LODF}^{c}_{m,l}$ Line outage distribution factor on line/transformer m in the contingency scenario c for line/transformer l on outage.
$C^{nl}_{g,t}$ No-load cost of generator g at time t in $\$/\text{hour}$.
$C^{off-sup}_{g,t}$ Offline supplemental reserve cost of generator g at time t in $\$/\text{MW}$.
$C^{on-sup}_{g,t}$ Online supplemental reserve cost of generator g at time t in $\$/\text{MW}$.
$C^{reg}_{g,t}$ Regulation reserve cost of generator g at time t in $\$/\text{MW}$.
$C^{spin}_{g,t}$ Spinning reserve cost of generator g at time t in $\$/\text{MW}$.
$C^{st}_{g,t}$ Start-up cost of generator g at time t in $\$$.
$D_{f,t}$ Fixed demand f at time t in MW.
DT^{0}_{g} Number of time periods the unit has been off prior to the first time period of generator g in hours.
DT_{g} Minimum down-time of generator g in hours.
FL^{rate-a}_{m} Rate-A power flow limit on line/transformer m in MW.
FL^{rate-b}_{m} Rate-B power flow limit on line/transformer m in MW.
P^{0}_{g} Initial output power of generator g in MW ($P^0_g \neq 0\ \forall g \in \mathcal{G}^0_{on}, P^0_g = 0\ \forall g \in \mathcal{G}^0_{off}$).
$R^{OR-req}_{Tot,t}$ Market-wide operating reserve requirement at time t in MW.
$R^{OR-req}_{z,t}$ Zone z operating reserve requirement at time t in MW.
$R^{reg-req}_{Tot,t}$ Market-wide regulation reserve requirement at time t in MW.
$R^{reg-req}_{z,t}$ Zone z regulation reserve requirement at time t in MW.
$R^{RS-req}_{Tot,t}$ Market-wide regulation+spin reserve requirement at time t in MW.
$R^{RS-req}_{z,t}$ Zone z regulation+spin reserve requirement at time t in MW.
RR_{g} Ramp-rate of generator g in MW/minute.
SD_{g} Shut-down capability of generator g in MW.
$SI_{n,t}$ Scheduled net interchange at node n at time t in MW.
SU_{g} Start-up capability of generator g in MW.
T Number of intervals (hours) in the DA market solve horizon.

U_g^0 Initial commitment status of generator g ($U_g^0 = 1\ \forall g \in \mathcal{G}_{on}^0, U_g^0 = 0\ \forall g \in \mathcal{G}_{off}^0$).
UT_g^0 Number of time periods the unit has been on prior to the first time period of generator g in hours.
UT_g Minimum up-time of generator g in hours.
$P_{g,t}^{max}$ Economic maximum energy dispatch of generator g at time t in MW.
$P_{g,t}^{min}$ Economic minimum energy dispatch of generator g at time t in MW.
$P_{g,t}^{reg-max}$ Maximum energy dispatch of generator g at time t when committed to provide regulations reserve in MW.
dispat Minimum energy dispatch of generator g at time t when committed to provide regulations reserve in MW.

Sets

$\mathcal{B}$ Set of Nodes representing the immediate neighbors of MISO.
$\mathcal{C}^{\text{SCUC}}$ Set of contingency scenarios considered in the DA SCUC.
$\mathcal{D}$ Set of virtual demands.
$\mathcal{D}_n$ Set of virtual demands at node n.
$\mathcal{F}$ Set of fixed demands.
$\mathcal{F}_n$ Set of fixed demands at node n.
$\mathcal{G}$ Set of generators excluding demand response resources type-I.
$\mathcal{G}_{off}^0$ Set of generators which are not initially committed.
$\mathcal{G}_{on}^0$ Set of generators which are initially committed.
$\mathcal{G}_n$ Set of generators excluding demand response resources type-I at node n.
$\mathcal{G}_z$ Set of generators in MISO zone z for reserve procurement.
$\mathcal{G}_{av,t}$ Set of generators with enabled availability flag at time t.
$\mathcal{G}_{mr,t}$ Set of generators with enabled must-run flag at time t.
$\mathcal{I}$ Set of virtual supplies.
$\mathcal{I}_n$ Set of virtual supplies at node n.
$\mathcal{L}_c$ Set of lines/transformers on outage in the contingency scenario c of DA SCUC.
$\mathcal{M}_0$ Set of monitored lines/transformers in the base-case of DA SCUC.
$\mathcal{M}_c$ Set of monitored lines/transformers in the contingency scenario c of DA SCUC.
$\mathcal{N}_m$ Set of nodes with non-zero injection shift factor for line/transformer m.
$\mathcal{Q}_{d,t}$ Set of bid curve blocks of virtual demand d at time t.
$\mathcal{Q}_{g,t}$ Set of offer curve blocks of generator g at time t.
$\mathcal{Q}_{i,t}$ Set of offer curve blocks of virtual supply i at time t.
$\mathcal{Q}_{s,t}$ Set of bid curve blocks of price-sensitive demand bid s at time t.
$\mathcal{S}$ Set of price-sensitive demands.
$\mathcal{S}_n$ Set of price-sensitive demands at node n.
$\mathcal{T}$ Set of time epochs.
$\mathcal{V}$ Set of electric grid buses including the immediate MISO neighbors.
$\mathcal{Z}$ Set of defined reserve zones in MISO.

Variables

$c_{d,t}(.)$ Variable cost function of virtual demand d at time t in \$.
$c_{g,t}(.)$ Variable cost function of generator g at time t in \$.
$c_{i,t}(.)$ Variable cost function of virtual supply i at time t in \$.
$c_{s,t}(.)$ Variable cost function of price-sensitive demand s at time t in \$.
$d_{d,t,q}$ Energy dispatch of virtual demand d at time t for block q in MW.
$d_{d,t}$ Energy dispatch of virtual demand d at time t in MW.
$d_{s,t,q}$ Energy dispatch of price-sensitive demand s at time t for block q in MW.
$d_{s,t}$ Energy dispatch of price-sensitive demand s at time t in MW.
$fl_{m,t}^0$ Power flow on line/transformer m at time t in the base-case in MW.
$fl_{m,t}^c$ Power flow on line/transformer m at time t in the contingency scenario c in MW.
$p_{n,t}^{net}$ Net power injection at node n at time t in MW.
$p_{g,t,q}$ Energy dispatch of generator g at time t for block q in MW.
$p_{g,t}$ Energy dispatch of generator g at time t in MW.
$p_{i,t,q}$ Energy dispatch of virtual supply i at time t for block q in MW.
$p_{i,t}$ Energy dispatch of virtual supply i at time t in MW.
$r_{g,t}^{off-sup}$ Offline supplemental reserve of generator g at time t in MW.
$r_{g,t}^{on-sup}$ Online supplemental reserve of generator g at time t in MW.
$r_{g,t}^{reg}$ Regulation reserve of generator g at time t in MW.
$r_{g,t}^{spin}$ Spinning reserve of generator g at time t in MW.
$sl1_{m,t}^{flow,0}$ Step-1 slack variable for power flow on line/transformer m at time t in the base-case in MW.

$sl1^{flow,c}_{m,t}$ Step-1 slack variable for power flow on line/transformer m at time t in the contingency scenario c in MW.
$sl2^{flow,0}_{m,t}$ Step-2 slack variable for power flow on line/transformer m at time t in the base-case in MW.
$sl2^{flow,c}_{m,t}$ Step-2 slack variable for power flow on line/transformer m at time t in the contingency scenario c in MW.
$sl^{RS}_{Tot,t}$ Slack variable for market-wide regulation+spin reserve requirement at time t in MW.
$sl^{RS}_{z,t}$ Slack variable for zone z regulation+spin reserve requirement at time t in MW.
$u^{reg}_{g,t}$ Regulation commitment status of generator g at time t.
$u_{g,t}$ Commitment status of generator g at time t.
$v_{g,t}$ Start-up status of generator g at time t.
$w_{g,t}$ Shut-down status of generator g at time t.

I. Introduction

In this document, we will be describing our model for day-ahead (DA) market clearing process in MISO that is used to approximately re-create the historical market outputs. The purpose of the document is to have a formulation that is as close as possible to our implementation and to avoid abstracting anything.

The DA market procedure in MISO is illustrated in Figure 1.

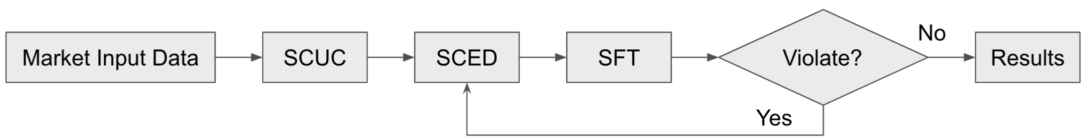

Fig. 1. Day-ahead Market Clearing Process in MISO

We first start by Security-Constrained Unit Commitment (SCUC) and describe how different components would appear in this formulation.

It is also assumed that line outages are incorporated in the network models and small islands are excluded from the grid. Also, for simplicity, we have only considered one grid topology for a given DA run meaning that we consider the line outages that are active for the whole day and for outages that are partially active over a day, we set a threshold for the number of hours the device is on outage and set disable/enable the device for the whole day depending on that.

II. Security-Constrained Unit Commitment (SCUC)

A. Generators

1) Objective function:

$$\sum_{\forall t\in\mathcal{T}}\sum_{\forall g\in\mathcal{G}}\Big[c_{g,t}(p_{g,t})+C^{nl}_{g,t}u_{g,t}+C^{st}_{g,t}v_{g,t}+ \\ C^{reg}_{g,t}r^{reg}_{g,t}+C^{spin}_{g,t}r^{spin}_{g,t}+C^{on-sup}_{g,t}r^{on-sup}_{g,t}+C^{off-sup}_{g,t}r^{off-sup}_{g,t}\Big] \tag{1}$$

According to MISO, the offer curve of a generator can be piece-wise constant (slope = 0 flag in MISO indicator) or piece-wise linear (slope = 1 flag)[1]. For the case of piece-wise linear, they make a piece-wise constant approximation by breaking each segment of the offer curve into multiple blocks. After this treatment, all offer curves become piece-wise constant and $c_{g,t}(p_{g,t})$ can be computed as:

$$c_{g,t}(p_{g,t})=\sum_{\forall q\in\mathcal{Q}_{g,t}}p_{g,t,q}\Lambda^{offer}_{g,t,q} \qquad \forall g\in\mathcal{G},t\in\mathcal{T} \tag{2}$$

where q indexes the blocks, $\Lambda^{offer}_{g,t,q}$ is the price of the q-th block, and $p_{g,t}=\sum_{\forall q\in\mathcal{Q}_{g,t}}p_{g,t,q}$. As a consequence, the operational cost functions will always be piece-wise linear with functions with monotonically increasing slopes and therefore convex.

According to the Exhibit 4-8 in (BPM-002-r20), the offer curves submitted by units (other than DRR-II and some examples of run of river) start from 0 and not the P^{min}. It means that the additional cost to the no-load cost for running the unit at P^{min} can be calculated by obtaining the area under the offer curve from 0 to P^{min}. This cost term is included in $c_{g,t}(p_{g,t})$. Figure 2 shows an example of a piecewise linear cost curve of a generator. Note that for the sake of no-load cost description clarity, we have switched to cost curve rather than the offer curve in this figure. The area under the offer curve from 0 to P^{min} would give the $C^{Pmin}-C^{nl}$. For DRR type-II and external asynchronous resources that can start from negative MW values, we set both the variable cost from 0 to P^{min} and the no-load cost to 0.

[1]In our terminology, the offer curve is the derivative of the cost curve of the generator that indicates the unit's marginal cost.

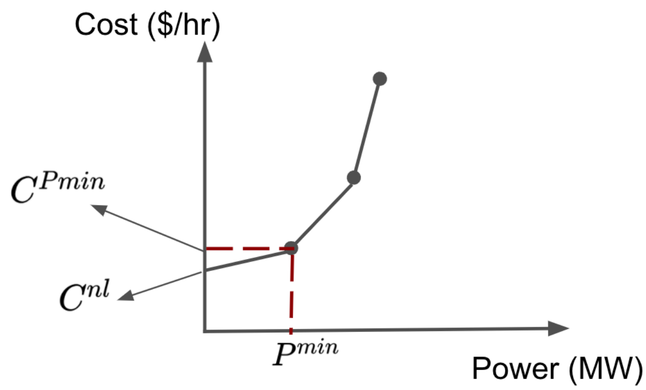

Fig. 2. Piece-wise Linear Cost Curve of a Generator

2) Operational Constraints: Below, we go through the operational constraints of the generator and add constraints related to minimum/maximum energy and ancillary service dispatch.

According to MISO business practice manual (BPM-002-r20), if a generator is set to provide regulation reserve, the minimum/maximum dispatch limit of the unit shrinks from "economic minimum/maximum" to "regulation minimum/maximum" as shown Figure 3.

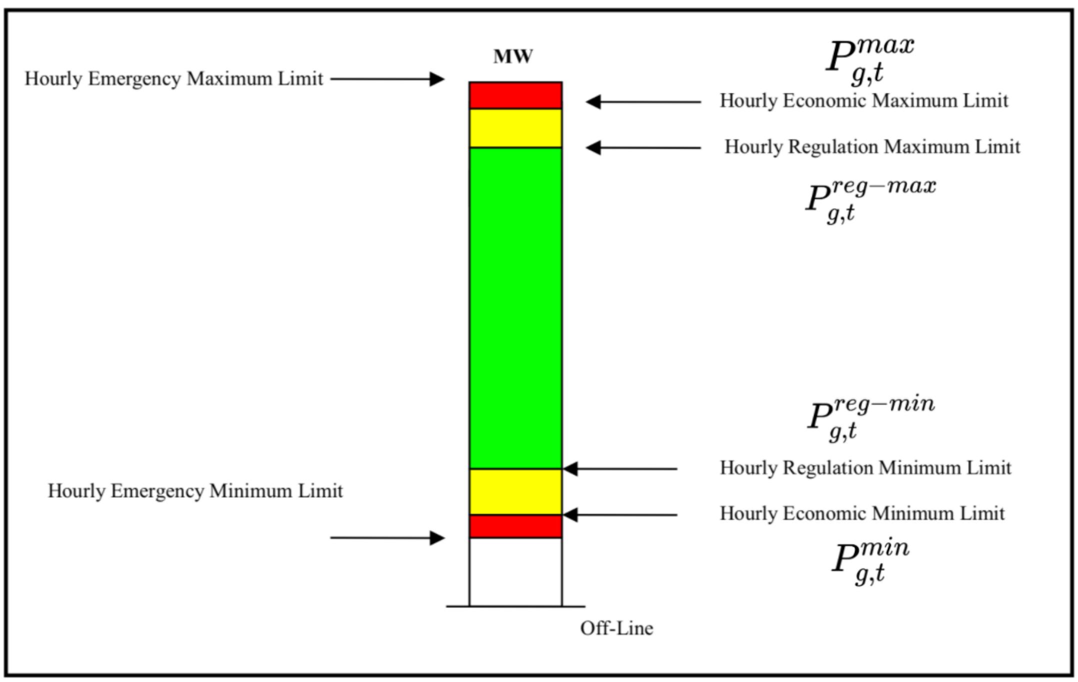

Fig. 3. Dispatch Limits of a Generator in MISO

A binary variable $u_{g,t}^{reg}$ is defined for this purpose to capture the change of the dispatch limit when the unit is supposed to provide regulation reserve following the formulation in MISO 2009 DA paper, which can be seen in Eq. (6)-(8).

$$0 \leq p_{g,t,q} \leq \overline{P}_{g,t,q} u_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T}, q \in \mathcal{Q}_{g,t} \tag{3}$$

$$p_{g,t} = \sum_{\forall q \in \mathcal{Q}_{g,t}} p_{g,t,q} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{4}$$

$$P_{g,t}^{min} u_{g,t} \leq p_{g,t} \leq P_{g,t}^{max} u_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{5}$$

$$p_{g,t} + r_{g,t}^{reg} + r_{g,t}^{spin} + r_{g,t}^{on-sup} \leq P_{g,t}^{max}(u_{g,t} - u_{g,t}^{reg}) + P_{g,t}^{reg-max} u_{g,t}^{reg} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{6}$$

$$p_{g,t} - r_{g,t}^{reg} \geq P_{g,t}^{min}(u_{g,t} - u_{g,t}^{reg}) + P_{g,t}^{reg-min} u_{g,t}^{reg} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{7}$$

$$0 \leq r_{g,t}^{reg} \leq 0.5(P_{g,t}^{reg-max} - P_{g,t}^{reg-min}) u_{g,t}^{reg} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{8}$$

$$r_{g,t}^{spin} \geq 0 \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{9}$$

$$r_{g,t}^{on-sup} \geq 0 \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{10}$$

$$r_{g,t}^{spin} + r_{g,t}^{on-sup} \leq (P_{g,t}^{max} - P_{g,t}^{min}) u_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{11}$$

$$0 \leq r_{g,t}^{off-sup} \leq (P_{g,t}^{max} - P_{g,t}^{min})(1 - u_{g,t}) \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{12}$$

3) Unit Availability & Must-run Constraints:

$$u_{g,t} \leq 0 \quad \forall g \in \mathcal{G} \backslash \mathcal{G}_{av,t}, t \in \mathcal{T} \tag{13}$$

$$u_{g,t} \geq 1 \quad \forall g \in \mathcal{G}_{mr,t}, t \in \mathcal{T} \tag{14}$$

4) Ramp Constraints:

$$r_{g,t}^{reg} \leq 5RR_g \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{15}$$

$$r_{g,t}^{spin} + r_{g,t}^{on-sup} + r_{g,t}^{off-sup} \leq 10RR_g \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{16}$$

$$p_{g,t} - p_{g,t-1} \leq 60RR_g u_{g,t-1} + SU_g v_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{17}$$

$$p_{g,t-1} - p_{g,t} \leq 60RR_g u_{g,t} + SD_g w_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{18}$$

$$p_{g,1} - P_g^0 \leq 60RR_g U_g^0 + SU_g v_{g,1} \quad \forall g \in \mathcal{G} \tag{19}$$

$$P_g^0 - p_{g,1} \leq 60RR_g u_{g,1} + SD_g w_{g,1} \quad \forall g \in \mathcal{G} \tag{20}$$

5) Commitment Status Constraints: In the constraints below, $v_{g,t}$ and $w_{g,t}$ that are supposed to capture the startup and shutdown of a generator, respectively, are **not** binary variables but are defined in such a way that will only take values $\{0, 1\}$ given the constraints Eq. (22), (23), (24), (25) and the positive cost associated with starting up the generator in the objective function.

$$u_{g,t} \in \{0, 1\} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{21}$$

$$0 \leq v_{g,t} \leq 1 \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{22}$$

$$0 \leq w_{g,t} \leq 1 \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{23}$$

$$u_{g,t} - u_{g,t-1} = v_{g,t} - w_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{24}$$

$$u_{g,1} - U_g^0 = v_{g,1} - w_{g,1} \quad \forall g \in \mathcal{G} \tag{25}$$

$$u_{g,t}^{reg} \in \{0, 1\} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{26}$$

$$u_{g,t}^{reg} \leq u_{g,t} \quad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{27}$$

6) Minimum Up-time/Down-time Constraints:

$$\sum_{t=1}^{\min(UT_g - UT_g^0, T)} (u_{g,t} - 1) = 0 \quad \forall g \in \mathcal{G}_{on}^0 \tag{28}$$

$$\sum_{t=1}^{\min(DT_g - DT_g^0, T)} u_{g,t} = 0 \quad \forall g \in \mathcal{G}_{off}^0 \tag{29}$$

$$\sum_{i=t-\min(UT_g, T)+1}^{t} v_{g,i} \leq u_{g,t} \quad \forall g \in \mathcal{G}, t \in \{\min(UT_g, T), ..., T\} \tag{30}$$

$$\sum_{i=t-\min(DT_g, T)+1}^{t} w_{g,i} \leq 1 - u_{g,t} \quad \forall g \in \mathcal{G}, t \in \{\min(DT_g, T), ..., T\} \tag{31}$$

7) Items that can be Improved:

- MISO's new ramp product (flexiramp).
- Modelling cold, warm and hot states for start-up and shut-down.
- Modelling the start-up time and shut-down time constraints.
- Modelling the shut-down cost in the objective function.
- Proper modelling of units when the emergency flag is on.
- Considering constraints specific to hydro units.
- Looking at the generator offer curves, it looks like the modelling of Demand response resources type-I is different from the rest of the units. However, it seems this type of resources are not major and they usually do not clear so we will be skipping modelling them for now.
- Relaxing the integers to reduce the computational complexity of the SCUC.

B. Demands and Virtual Transactions

Demands and virtual transactions appear in the bid data published by MISO. There are two demand types that is fixed and price-sensitive and there are two virtual transaction types that are supply and demand.

The fixed demands are price takers and would only be introduced in the energy balance constraints so we just give the formulation of price-sensitive demand bids and virtual supply offers and demand bids and describe how they appear in the objective function.

The price-sensitive demands and virtual demands (decrements) are represented in piece-wise constant blocks in descending order with respect to the associated bid price of each block. The virtual supply (increments) offers are represented in piece-wise constant blocks in ascending order with respect to the associated offer price of each block.

1) Objective function:

$$\sum_{\forall t\in\mathcal{T}}\Big[\sum_{\forall s\in\mathcal{S}} c_{s,t}(d_{s,t}) + \sum_{\forall d\in\mathcal{D}} c_{d,t}(d_{d,t}) + \sum_{\forall i\in\mathcal{I}} c_{i,t}(p_{i,t})\Big] \tag{32}$$

where

$$c_{s,t}(d_{s,t}) = -\sum_{\forall q\in\mathcal{Q}_{s,t}} d_{s,t,q}\Lambda^{bid}_{s,t,q} \qquad \forall s\in\mathcal{S}, t\in\mathcal{T} \tag{33}$$

$$c_{d,t}(d_{d,t}) = -\sum_{\forall q\in\mathcal{Q}_{d,t}} d_{d,t,q}\Lambda^{bid}_{d,t,q} \qquad \forall d\in\mathcal{D}, t\in\mathcal{T} \tag{34}$$

$$c_{i,t}(p_{i,t}) = \sum_{\forall q\in\mathcal{Q}_{i,t}} p_{i,t,q}\Lambda^{offer}_{i,t,q} \qquad \forall i\in\mathcal{I}, t\in\mathcal{T} \tag{35}$$

2) Operational Constraints:

$$0 \le d_{s,t,q} \le \overline{D}_{s,t,q} \qquad \forall s\in\mathcal{S}, t\in\mathcal{T}, q\in\mathcal{Q}_{s,t} \tag{36}$$

$$d_{s,t} = \sum_{\forall q\in\mathcal{Q}_{s,t}} d_{s,t,q} \qquad \forall s\in\mathcal{S}, t\in\mathcal{T} \tag{37}$$

$$0 \le d_{d,t,q} \le \overline{D}_{d,t,q} \qquad \forall d\in\mathcal{D}, t\in\mathcal{T}, q\in\mathcal{Q}_{d,t} \tag{38}$$

$$d_{d,t} = \sum_{\forall q\in\mathcal{Q}_{d,t}} d_{d,t,q} \qquad \forall d\in\mathcal{D}, t\in\mathcal{T} \tag{39}$$

$$0 \le p_{i,t,q} \le \overline{P}_{i,t,q} \qquad \forall i\in\mathcal{I}, t\in\mathcal{T}, q\in\mathcal{Q}_{i,t} \tag{40}$$

$$p_{i,t} = \sum_{\forall q\in\mathcal{Q}_{i,t}} p_{i,t,q} \qquad \forall i\in\mathcal{I}, t\in\mathcal{T} \tag{41}$$

C. Modelling the Borders

The hourly scheduled interchange between MISO and its external control areas such as SPP and PJM is published and is publicly available. Some parts of these external areas are modelled in details while some other parts are aggregated. In our first attempt, we would like to aggregate these external areas and represent them with a single node while keeping all the lines/transformers that go from these areas to MISO's internal control areas. Also, we would only keep and represent the external areas that are immediate neighbor of MISO. We then assign an hourly profile of MWs to these nodes where positive MWs indicate export to MISO internal control areas, while negative MWs indicate import from MISO internal control areas. In this document, we refer to the scheduled interchange at node n at time t with $SI_{n,t}$.

1) Items that can be Improved:

- Not aggregating the buses appearing in the immediate neighbours and include those that are already included in the MISO models.
- Modelling the borders at the owner level (i.e. the described approach) might have issues that are likely to be due to: 1) the non-contiguous part of PJM that is embedded in MISO and 2) loop flows around the north of the great lakes.

D. Energy Balance Constraint

For simplifications, we ignore the losses in the formulations. As a result of this, the energy balance constraint is as follows:

$$\sum_{\forall g\in\mathcal{G}} p_{g,t} + \sum_{\forall i\in\mathcal{I}} p_{i,t} + \sum_{\forall n\in\mathcal{B}} SI_{n,t} = \sum_{\forall f\in\mathcal{F}} D_{f,t} + \sum_{\forall s\in\mathcal{S}} d_{s,t} + \sum_{\forall d\in\mathcal{D}} d_{d,t} \qquad \forall t\in\mathcal{T} \tag{42}$$

1) Items that can be Improved:

- Including losses in the energy balance constraints.

E. Net Nodal Injection Constraint

$$p_{n,t}^{net} = \sum_{\forall g \in \mathcal{G}_n} p_{g,t} + \sum_{\forall i \in \mathcal{I}_n} p_{i,t} + SI_{n,t} - \sum_{\forall f \in \mathcal{F}_n} D_{f,t} - \sum_{\forall s \in \mathcal{S}_n} d_{s,t} - \sum_{\forall d \in \mathcal{D}_n} d_{d,t} \qquad \forall n \in \mathcal{V}, t \in \mathcal{T} \tag{43}$$

F. Group Reserve Constraints

Note that the Operating Reserve Demand Curve (ORDC) for regulation reserve requirement and operating reserve (OR) requirement is only used in the SCED to treat these group reserve constraints as soft constraints (through adding slack variables to the constraint and penalizing non-zero slack variables in the objective using ORDC) and are not used in the DA SCUC where these constraints are modelled as hard constraints to ensure sufficient resources are committed to meet MISO's reliability requirements. MISO 2009 DA paper

1) Market-wide/zonal Regulation Reserve Requirement Constraints:

$$\sum_{\forall g \in \mathcal{G}} r_{g,t}^{reg} \geq R_{Tot,t}^{reg-req} \qquad \forall t \in \mathcal{T} \tag{44}$$

$$\sum_{\forall g \in \mathcal{G}_z} r_{g,t}^{reg} \geq R_{z,t}^{reg-req} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{45}$$

2) Market-wide/zonal Operating Reserve (OR) Requirement Constraints:

$$\sum_{\forall g \in \mathcal{G}} \left[r_{g,t}^{reg} + r_{g,t}^{spin} + r_{g,t}^{on-sup} + r_{g,t}^{off-sup} \right] \geq R_{Tot,t}^{OR-req} \qquad \forall t \in \mathcal{T} \tag{46}$$

$$\sum_{\forall g \in \mathcal{G}_z} \left[r_{g,t}^{reg} + r_{g,t}^{spin} + r_{g,t}^{on-sup} + r_{g,t}^{off-sup} \right] \geq R_{z,t}^{OR-req} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{47}$$

3) Good Utility Practice (GUP) Reserve Requirement: The good utility practice (GUP) constraints are enforced as soft constraints in SCUC and SCED through adding high violation penalties to the constraints. However, in DA SCUC, they can be violated and if they get violated, they would not need any special handling. However, their violation in SCED requires special handling to make sure the prices are not contaminated by the violation penalties. This is elaborated in Section V.B of MISO 2009 DA paper.

- Objective function:

$$\sum_{\forall t \in \mathcal{T}} \left[\Gamma_{Tot,t}^{RS} sl_{Tot,t}^{RS} + \sum_{\forall z \in \mathcal{Z}} \Gamma_{z,t}^{RS} sl_{z,t}^{RS} \right] \tag{48}$$

- Constraints:

$$\sum_{\forall g \in \mathcal{G}} \left[r_{g,t}^{reg} + r_{g,t}^{spin} \right] \geq R_{Tot,t}^{RS-req} - sl_{Tot,t}^{RS} \qquad \forall t \in \mathcal{T} \tag{49}$$

$$\sum_{\forall g \in \mathcal{G}_z} \left[r_{g,t}^{reg} + r_{g,t}^{spin} \right] \geq R_{z,t}^{RS-req} - sl_{z,t}^{RS} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{50}$$

$$sl_{Tot,t}^{RS} \geq 0 \qquad \forall t \in \mathcal{T} \tag{51}$$

$$sl_{z,t}^{RS} \geq 0 \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{52}$$

4) Items that can be Improved:

- Updating the group reserve constraints to account for SOL and IROL constraints.
- Market-wide min generation-based OR requirement.

G. Thermal Branch Constraints

In the DA SCUC, MISO uses a pre-defined constraint list for base-case and line contingency cases to be imposed. These constraints are treated as soft constraints with 2-step violation penalties referred to as marginal value limit (MVL) which is defined through Transmission Cost Demand Curve (cf this paper and FERC schedule 28A for more info). Assuming that we have come up with a good heuristic to obtain the pre-defined constraint list, the constraints and the effect on the objective function are as follows:

1) Objective Function:

$$\sum_{\forall t \in \mathcal{T}} \Big[\sum_{\forall m \in \mathcal{M}_0} \Gamma_{1,m}^{flow,0} sl1_{m,t}^{flow,0} + \Gamma_{2,m}^{flow,0} sl2_{m,t}^{flow,0} + \big[\sum_{\forall c \in \mathcal{C}^{\text{SCUC}}} \sum_{\forall m \in \mathcal{M}_c} \Gamma_{1,m}^{flow,c} sl1_{m,t}^{flow,c} + \Gamma_{2,m}^{flow,c} sl2_{m,t}^{flow,c} \big] \Big] \tag{53}$$

2) Base-Case Constraints:

$$fl^0_{m,t} = \sum_{\forall n \in \mathcal{N}_m} \mathrm{ISF}_{m,n} p^{net}_{n,t} \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{54}$$

$$-(FL^{rate-a}_m + sl1^{flow,0}_{m,t} + sl2^{flow,0}_{m,t}) \leq fl^0_{m,t} \leq (FL^{rate-a}_m + sl1^{flow,0}_{m,t} + sl2^{flow,0}_{m,t}) \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{55}$$

$$0 \leq sl1^{flow,0}_{m,t} \leq \overline{SL1}^{flow,0}_m \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{56}$$

$$sl2^{flow,0}_{m,t} \geq 0 \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{57}$$

3) Contingency Constraints:

$$fl^c_{m,t} = \sum_{\forall n \in \mathcal{N}_m} \mathrm{ISF}_{m,n} p^{net}_{n,t} + \sum_{\forall l \in \mathcal{L}_c} \mathrm{LODF}^c_{m,l} fl^0_{l,t} \qquad \forall c \in \mathcal{C}^{\mathrm{SCUC}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{58}$$

$$-(FL^{rate-b}_m + sl1^{flow,c}_{m,t} + sl2^{flow,c}_{m,t}) \leq fl^c_{m,t} \leq (FL^{rate-b}_m + sl1^{flow,c}_{m,t} + sl2^{flow,c}_{m,t}) \qquad \forall c \in \mathcal{C}^{\mathrm{SCUC}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{59}$$

$$0 \leq sl1^{flow,c}_{m,t} \leq \overline{SL1}^{flow,c}_m \qquad \forall c \in \mathcal{C}^{\mathrm{SCUC}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{60}$$

$$sl2^{flow,c}_{m,t} \geq 0 \qquad \forall c \in \mathcal{C}^{\mathrm{SCUC}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{61}$$

4) Items that can be Improved:

- Model IROL and SOL constraints to be respected after reserve deployment.
- Include the contingencies for flowgates and better market-to-market flowgate modelling.
- Include contingencies that have a set of lines/transformers coming in-service while a set of lines go out-of-service.
- Create an hourly grid topology resolution given that line outage data have hourly resolutions and we can have 24 grid topologies (24 ISFs) for a certain day.

H. Final SCUC Formulation

The final objective function for SCUC is:

$$\min (1) + (32) + (48) + (53) \tag{62}$$

subject to all the constraints listed in Section II for different devices, services and network formulations.