Invenia's Formulation of MISO RT Market Clearing Process

Power Systems Team

Abstract

As part of *market modelling* 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 Real Time clearing formulation and specify assumptions/approximations and things that can be improved or can be modelled more accurately.

NOMENCLATURE

Parameters

Δt Time difference between two consecutive simulation intervals in minutes.
$\Gamma^{flow,0}_{1,m}$ 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 $\$/\text{MW}$.
$\Gamma^{OR-req}_{Tot,t}$ Market-wide operating reserve requirement slack variable penalty cost at time t in $\$/\text{MW}$.
$\Gamma^{OR-req}_{z,t}$ Zone z operating reserve requirement slack variable penalty cost at time t in $\$/\text{MW}$.
$\Gamma^{reg-req}_{Tot,t}$ Market-wide regulation requirement slack variable penalty cost at time t in $\$/\text{MW}$.
$\Gamma^{reg-req}_{z,t}$ Zone z regulation requirement slack variable penalty cost at time t 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 $\$/\text{MW}$.
$\Lambda^{bid}_{s,t,q}$ 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 $\$/\text{MW}$.
$\overline{D}_{s,t,q}$ 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.
$\text{ISF}_{m,n}$ 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.
$C^{off-sup}_{g,t}$ 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 $\$/\text{MW}$.
$D_{f,t}$ 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.
$NI_{n,t}$ Net interchange at node n at time t in MW.
P^0_g Initial output power of generator g in MW ($P^0_g \neq 0 \ \forall g \in \mathcal{G}^0_{on}, P^0_g = 0 \ \forall g \in \mathcal{G}^0_{off}$).
$P^{max}_{g,t}$ Economic maximum energy dispatch of generator g at time t in MW.
$P^{min}_{g,t}$ Economic minimum energy dispatch of generator g at time t in MW.
$P^{reg-max}_{g,t}$ Maximum energy dispatch of generator g at time t when committed to provide regulations reserve in MW.
$R^{OR-req}_{Tot,t}$ 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^{RT}_g Alternative RT Ramp-rate of generator g in MW/minute.
RR_g Ramp-rate of generator g in MW/minute.
SD_g Shut-down capability of generator g 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 ($U_g^0 = 1\ \forall g \in \mathcal{G}_{on}^0, U_g^0 = 0\ \forall g \in \mathcal{G}_{off}^0$).
$U_{g,t}^{reg}$ Regulation Reserve commitment status of generator g at time t.
$U_{g,t}$ Commitment status of generator g at time t.
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.

Sets

$\mathcal{B}$ Set of Nodes representing the immediate neighbors of MISO.
$\mathcal{C}^{\text{SCED}}$ Set of contingency scenarios considered in the RT SCED.
$\mathcal{F}$ 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.
$\mathcal{L}_c$ Set of lines/transformers on outage in the contingency scenario c of RT SCED.
$\mathcal{M}_0$ Set of monitored lines/transformers in the base-case of RT SCED.
$\mathcal{M}_c$ Set of monitored lines/transformers in the contingency scenario c of RT SCED.
$\mathcal{N}_m$ Set of nodes with non-zero injection shift factor for line/transformer m.
$\mathcal{Q}_{g,t}$ Set of offer curve blocks of generator g at time t.
$\mathcal{T}$ Set of time in hours according with the intervals.
$\mathcal{V}$ Set of electric grid buses including the immediate MISO neighbors.
$\mathcal{Z}$ Set of defined reserve zones in MISO.

Variables

$c_{g,t}(.)$ Variable cost function of generator g at time t in \$.
$fl_{m,t}^0$ 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.
$r_{g,t}^{cont}$ contingency reserve of generator g 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.
$sl1_{m,t}^{flow,c}$ Step-1 slack variable for power flow on line/transformer m at time t in the contingency scenario c in MW.
$sl2_{m,t}^{flow,0}$ Step-2 slack variable for power flow on line/transformer m at time t in the base-case in MW.
$sl2_{m,t}^{flow,c}$ Step-2 slack variable for power flow on line/transformer m at time t in the contingency scenario c in MW.
$sl_{Tot,t}^{OR-req}$ Slack variable for market-wide operating reserve requirement at time t in MW.
$sl_{z,t}^{OR-req}$ Slack variable for zone z operating reserve requirement at time t in MW.
$sl_{Tot,t}^{reg-req}$ Slack variable for market-wide regulation reserve requirement at time t in MW.
$sl_{z,t}^{reg-req}$ Slack variable for zone z regulation reserve requirement at time t in MW.
$sl_{Tot,t}^{RS}$ Slack variable for market-wide regulation+spin reserve requirement at time t in MW.
$sl_{z,t}^{RS}$ Slack variable for zone z regulation+spin reserve requirement at time t in MW.
$V_{g,t}$ 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 Invenia's model for Real Time (RT) market dispatch and clearing, while Invenia's Day Ahead (DA) market clearing process is described in DA MISO Market Formulation. Both of them are used to approximately re-create the historical market outputs of MISO. The purpose of the document is to have a formulation that is as close as possible to our implementation and to avoid abstracting anything. Invenia's RT Formulation is based on the MISO 2009 RT paper. Notice that in the paper, one SCED for operation and one for pricing is described. Before the Extended Locational Marginal Pricing (ELMP), MISO simply re-ran SCED with the same inputs to get the prices. However, ELMP is now used in the pricing run. Thus, the RT market and operation procedure in MISO is illustrated in Figure 1.

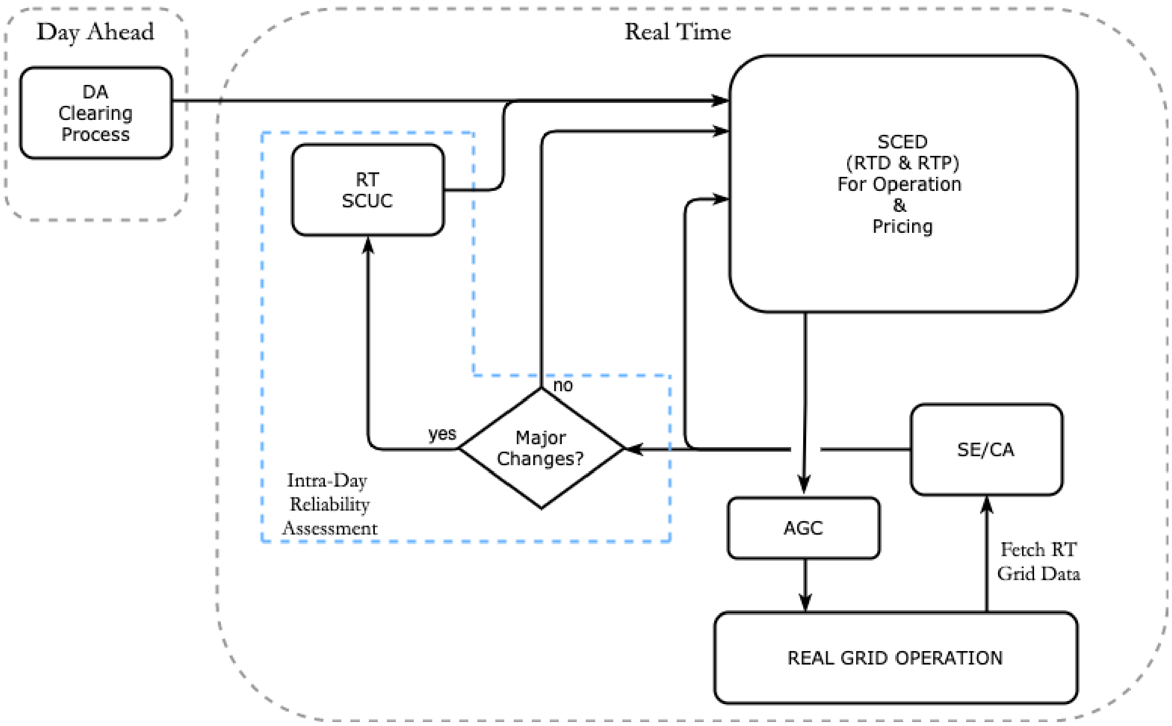

Fig. 1. Real Time Market Clearing & Operation Process in MISO (ISOs' perspective)

Independent System Operators (ISOs) plan the operation of the grid in DA to the best of their knowledge and based on the data provided by the participants. Commitments of units are done in DA and RT. The majority of the resources are committed in DA market, and the remaining ones are committed on the day to supply the energy (still in advance but just a couple of hours/minutes before) These commitments include: Forward RAC, Intra-Day RAC and Look-ahead commitment. There is also commitments of slow long lead units which are committed on the 7-day Forward RAC. The main difference in between each one of these analysis is the uncertainty of the input parameters. Figure 2 shows how the level of uncertainty varies along the processes MISO Overview.

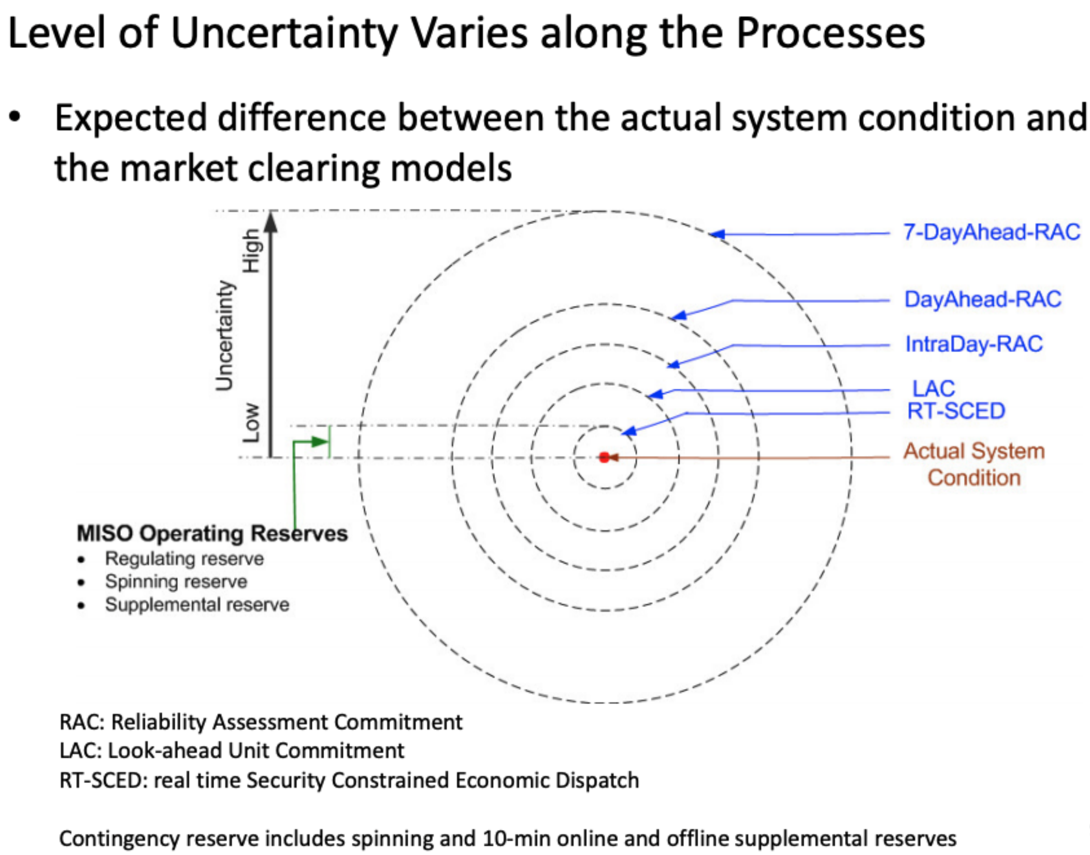

Fig. 2. Uncertainty level for the Commitment of Generation Units

Thus, the full market clearing process can be appreciated in Figure 3

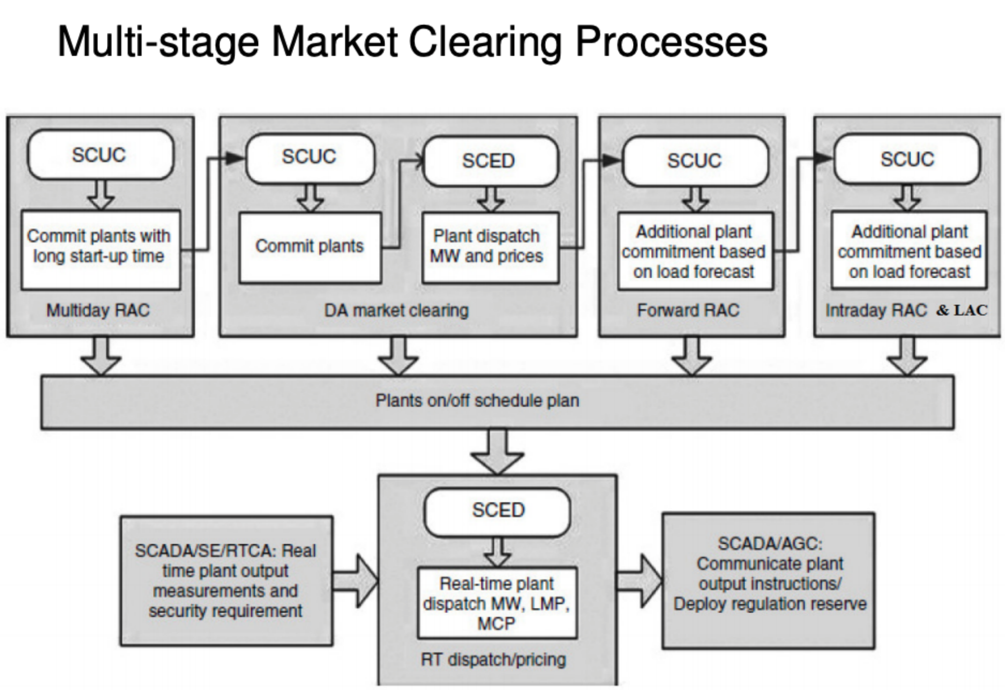

Fig. 3. Multi-stage Market Clearing Processes

However, even with all the analysis that the ISOs preform there are still uncertainties on the grid inputs/parameters that take place in RT. Thus ISOs have automatic controls (AGC, AVR, RAS, etc...) to account for these differences and compensate the real grid.

A. *Invenia's Perspective*

For historical simulations, Invenia fetches the reported information of the actual behaviour of the grid, and for future scenarios this information is forecasted. Thus, Invenia can consider a simplified clearing process for RT as shown in Figure 4.

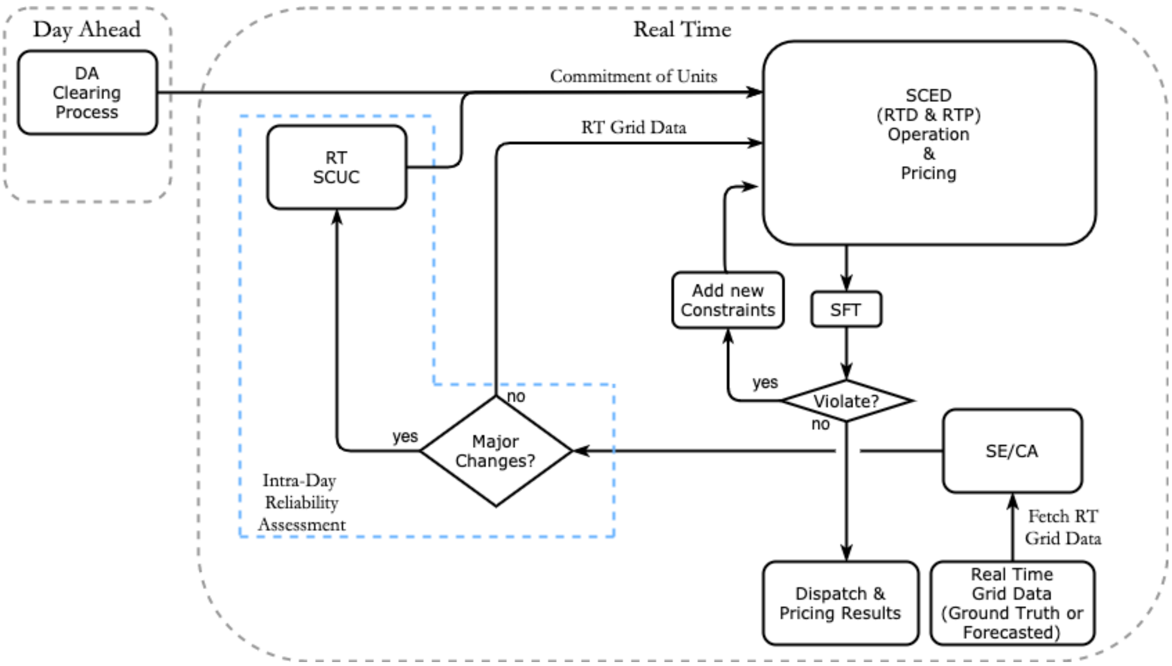

Fig. 4. Real Time Market Clearing & Operation Process in MISO (Invenia's perspective)

To start with a more simplified model, we do not include the Intra-Day Reliability Assessment. For Historical simulations, the mayor changes and contingencies that the grid suffered in RT are already known, so these ones can be considered and included to the SCED from the begining and therefore the current status of the implementation for RT boils down to what is shown in Figure 5.

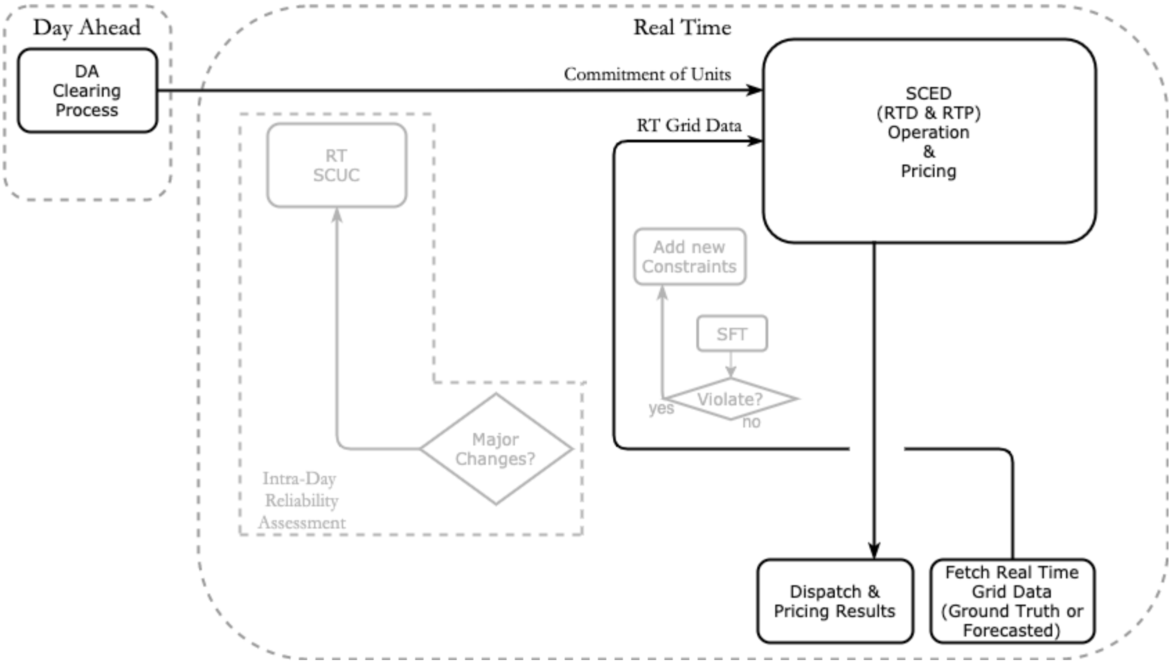

Fig. 5. Real Time Market Clearing & Operation Process in MISO (Invenia's current approximation)

We first start by Real-Time Security-Constrained Economic Dispatch (SCED) and describe how different components would appear in this formulation. It is worth to highlight that Invenia's formulation of the RT market largely follows DA MISO Market Formulation. Therefore, only the contrasting variations and rules peculiar to the RT market formulation are described in detail, however the full formulation for the RT market is contained in this document.

Since Invenia's DA MISO Market Formulation assumes that (i) line outages are considered to be active for the whole day, and (ii) the network models and small islands are excluded from the grid, the RT Market Formulation presented in this paper also considers one grid topology for a given RT run.

II. Security-Constrained Economic Dispatch (SCED)

A. Generators

1) Objective function:

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

The energy cost $c_{g,t}(p_{g,t})$ is calculated using (2) following the same formulation described in DA MISO Market Formulation. The rest of the terms $C^{reg}_{g,t} r^{reg}_{g,t}$, $C^{spin}_{g,t} r^{spin}_{g,t}$, $C^{on-sup}_{g,t} r^{on-sup}_{g,t}$ and $C^{off-sup}_{g,t} r^{off-sup}_{g,t}$ correspond to the AS for: regulation, spinning and on/off supplemental reserve.

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

2) Operational Constraints: DA Security Constrained Unit Commitment (DA-SCUC) in combination with the DA Reliability Assessment (DA-RAC) selects the generation resources/units to be committed for RT Energy Dispatch ($U_{g,t}$, binary) and Ancillary Services (AS). AS include regulating reserve (($U^{reg}_{g,t}$, binary) and Contingency Reserve (CR), the latter, is made out of spinning reserve ($spin$) and/or online/offline supplemental reserve of resources/units ($on - sup$ and $off - sup$). The selected units for CR must achieve the reserve requirement within the maximum Contingency Reserve Deployment Time (CRDT), which corresponds to 10 minutes as shown in Figure 6 (taken from MISO STCR Evaluation). Note that spinning reserve needs to be fully deployed within 10 min, whereas supplemental reserve needs to start deploying within 10 min and arrive to maximum reserve by 30 min.

In comparison with the DA, generators' RT operational constraints related to minimum/maximum energy and ancillary service dispatch have only slight variations. Limits for the energy dispatch in Eq. (3)-(5) take into account the $\mathcal{Q}_{g,t}$ set of q segments of the cost functions for each generator.

ANCILLARY SERVICE PRODUCT	OPERATING ISSUE ADDRESSED	TIME HORIZON	REQUIREMENT SOURCE
Regulating Reserves	Continuous imbalance due to normal generation/load variation	Seconds	NERC BAL-001-2
Contingency (Spin and Supplemental) Reserves	Disturbance triggered by a contingency that meets the Disturbance Control Standard (DCS) threshold	10 min.	NERC BAL-002-2(i)
Ramp Products	Uncertainty due to normal energy supply and demand variation	10 min. after target dispatch interval	Good Utility Practice

Fig. 6. MISO Ancillary Service Products

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

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

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

The binary parameter $U^{reg}_{g,t}$ is an input to the RT from DA clearing process, and it is defined to capture the change of the dispatch limit when the unit is supposed to provide regulation reserve. The market resource maximum and minimum limit constraints are shown in Eq. (6) and (7) respectively. However, in RT the 50% conservative regulation limit shown in Eq. (8) in DA MISO Market Formulation is replaced by Eq. (8) since in RT regulation units can provide full regulation within their limits.

$$p_{g,t} + r^{reg}_{g,t} + r^{spin}_{g,t} + r^{on-sup}_{g,t} \leq P^{max}_{g,t}(U_{g,t} - U^{reg}_{g,t}) + P^{reg-max}_{g,t} U^{reg}_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{6}$$

$$p_{g,t} - r^{reg}_{g,t} \geq P^{min}_{g,t}(U_{g,t} - U^{reg}_{g,t}) + P^{reg-min}_{g,t} U^{reg}_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{7}$$

$$0 \leq r^{reg}_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{8}$$

$$r^{spin}_{g,t} \geq 0 \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{9}$$

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

While limits for the spinning and supplemental reserve for online units are shown in Eq. (11), the offline supplemental reserve dispatch constraint is shown in Eq. (12)

$$r^{spin}_{g,t} + r^{on-sup}_{g,t} \leq (P^{max}_{g,t} - P^{min}_{g,t}) U_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{11}$$

$$0 \leq r^{off-sup}_{g,t} \leq (P^{max}_{g,t} - P^{min}_{g,t})(1 - U_{g,t}) \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \tag{12}$$

3) Ramp Constraints: Since the RT formulation presented is designed to work for different time intervals, the parameter Δt represent the frequency of the simulations in minutes (Traditionally 5 min intervals, but it could be used for 60min or 10 min). Furthermore, In the RT market, resources are allowed to specify an up or down ramp-rate (RR^{RT}_g) limit separately when they are not providing regulation. When they are on-regulation, a bi-directional ramp rate limit may be defined. Details about Midwest ISO's ramp rate models are described in MISO Ramp Rate Models. Note: equations (13) to (19) can be modelled as soft constraints or hard constraints as the user needs. Penalties for ramp constraints and capacity constraints are very high. Ramp constraint penalty is slightly lower than capacity penalty. But MISO applies LMP cap at VOLL = $\$3500/MWh$. When ramp or capacity constraints are violated, prices will be capped at VOLL. Transmission constraint demand curve can be found on tariff schedule 28A MISO-Tariff

$$p_{g,t} + \alpha_t r^{cont}_{g,t} - p_{g,t-1} \leq \Delta t RR_g U^{reg}_{g,t-1} + \Delta t RR^{RT}_g (1 - U^{reg}_{g,t-1}) U_{g,t-1} + SU_g V_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{13}$$

$$p_{g,t-1} - p_{g,t} \leq \Delta t RR_g U^{reg}_{g,t} + \Delta t RR^{RT}_g (1 - U^{reg}_{g,t}) U_{g,t} + SD_g W_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{14}$$

$$p_{g,1} + \alpha_t r^{cont}_{g,1} - P^0_g \le \Delta t RR_g U^0_g + SU_g V_{g,1} \qquad \forall g \in \mathcal{G} \tag{15}$$
$$P^0_g - p_{g,1} \le \Delta t RR_g U_{g,1} + SD_g W_{g,1} \qquad \forall g \in \mathcal{G} \tag{16}$$
$$\text{where:} \quad r^{cont}_{g,t} = r^{spin}_{g,t} + r^{on-sup}_{g,t} + r^{off-sup}_{g,t} \tag{17}$$

Since the current approximation of the ramp rates at Invenia are the same for DA and RT, Eq. (13) and (14) are simplified to Eq. (18) and (19), however once better ramp rates are available Eq. (13) and (14) can be used.

$$p_{g,t} + \alpha_t r^{cont}_{g,t} - p_{g,t-1} \le \Delta t RR_g U_{g,t-1} + SU_g V_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{18}$$
$$p_{g,t-1} - p_{g,t} \le \Delta t RR_g U_{g,t} + SD_g W_{g,t} \qquad \forall g \in \mathcal{G}, t \in \mathcal{T} \backslash \{1\} \tag{19}$$

4) Items that can be Improved:

- 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.
- Ramp Rates constraints may only be relevant during short periods of time. Our current guess is that with an hourly resolution these ramp rates will not be violating, however this need further research. However, even if contingency reserve and regulating reserve are not actually deployed, across an hour their effect would be to reduce the allowed range of ramping for energy.
- As mentioned in the text, the timeline of deploying supplemental reserve is different from the spinning reserve. This has not been distinguished in the current formulation and might be a point for future improvement.

B. Modelling the Borders

Border Modelling Formulation for the RT will be consider exactly as it is done for the DA. However, for historical simulations instead of a scheduled interchange at node n at a time t, the real time hourly power interchange between MISO and its external control areas will be used. Simulation of future scenarios where no real time data is available will continue to use the scheduled interchanged data. For simulations every 10 minutes and/or 5 minutes, the data will be extrapolated.In this document, the net interchange between MISO and its external control areas will be defined as $NI_{n,t}$, and it will take the value of the scheduled interchange or the RT interchange depending on the simulation and/or the available data.

According to Invenia's DA MISO Market Formulation, external areas aggregated and represented with a single node while keeping all the lines/transformers that go from these areas to MISO's internal control areas. Also, only the external areas that are immediate neighbor of MISO are represented. The hourly profile of MWs to these nodes is considered positive to indicate export to MISO internal control areas, while negative MWs indicate import from MISO internal control areas.

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.

C. Energy Balance Constraint

Since RT uses the actual values of the demand as a fixed parameter for a time t, energy dispatch of price sensitive demands is already represented within the fixed real demand. Again, for historical simulations, the demand will be fetched and interpolated (for every hour, 10 min or 5 min as needed). In the case of future scenarios, forecasted load could be used instead. For simplifications, transmission losses for Invenia's RT formulation are ignored. As a result of this, the energy balance constraint is as follows:

$$\sum_{\forall g \in \mathcal{G}} p_{g,t} + \sum_{\forall n \in \mathcal{B}} NI_{n,t} = \sum_{\forall f \in \mathcal{F}} D_{f,t} \qquad \forall t \in \mathcal{T} \tag{20}$$

Note: Energy balance constraint can be also expressed as a soft constraint with two slack variables one for up and one for down. This is optional depending on the user needs.

1) Items that can be Improved:

- Including losses in the energy balance constraints.

D. Net Nodal Injection Constraint

$$p_{n,t}^{net} = \sum_{\forall g \in \mathcal{G}_n} p_{g,t} + NI_{n,t} - \sum_{\forall f \in \mathcal{F}_n} D_{f,t} \qquad \forall n \in \mathcal{V}, t \in \mathcal{T} \tag{21}$$

E. Group Reserve Constraints

For the RT Market SCED, $R_{Tot,t}^{reg-req}$ and $R_{z,t}^{reg-req}$ are based on the Operating Reserve Demand Curve (ORDC) for regulation reserve requirement and the operating reserve (OR) requirement. These group constraints are treated as soft constraints through adding slack variables $sl_{Tot,t}^{reg-req}$ and $sl_{z,t}^{reg-req}$ for the wide market reserve and the zonal reserve. Then, the non-zero slack variables are penalized in the objective function in Eq (22).

- Objective function:

$$\sum_{\forall t \in \mathcal{T}} \left[\Gamma_{Tot,t}^{reg-req} sl_{Tot,t}^{reg-req}\right] + \sum_{\forall z \in \mathcal{Z}} \left[\Gamma_{z,t}^{reg-req} sl_{z,t}^{reg-req}\right] + \sum_{\forall t \in \mathcal{T}} \left[\Gamma_{Tot,t}^{OR-req} sl_{Tot,t}^{OR-req}\right] + \sum_{\forall z \in \mathcal{Z}} \left[\Gamma_{z,t}^{OR-req} sl_{z,t}^{OR-req}\right] \tag{22}$$

- Market-wide/zonal Regulation Reserve Requirement Constraints

$$\sum_{\forall g \in \mathcal{G}} r_{g,t}^{reg} \geq R_{Tot,t}^{reg-req} - sl_{Tot,t}^{reg-req} \qquad \forall t \in \mathcal{T} \tag{23}$$

$$\sum_{\forall g \in \mathcal{G}_z} r_{g,t}^{reg} \geq R_{z,t}^{reg-req} - sl_{z,t}^{reg-req} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{24}$$

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

$$\sum_{\forall g \in \mathcal{G}} \left[r_{g,t}^{reg} + r_{g,t}^{spin} + r_{g,t}^{on-sup} + r_{g,t}^{off-sup}\right] \geq R_{Tot,t}^{OR-req} - sl_{Tot,t}^{OR-req} \qquad \forall t \in \mathcal{T} \tag{25}$$

$$\sum_{\forall g \in \mathcal{G}_z} \left[r_{g,t}^{reg} + r_{g,t}^{spin} + r_{g,t}^{on-sup} + r_{g,t}^{off-sup}\right] \geq R_{z,t}^{OR-req} - sl_{z,t}^{OR-req} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{26}$$

1) Good Utility Practice (GUP) Reserve Requirement: The good utility practice (GUP) constraints are enforced as soft constraints for both the DA SCUC and the RT SCED, however in contrast to DA, RT GUP constraint is prioritized with lower violation penalties to avoid infeasibilities (as stated in MISO 2009 RT paper). DA SCED requires special handling, to make sure the prices are not contaminated by the violation penalties, decontamination policy varies by ISO. For MISO, when GUP constraints are violated in the DA market SCED solution, a second SCED solve is required with these violated constraints relaxed. The general logic is to relax the limits of the violated constraints by the amounts of violation determined in the 1st SCED solution with a user-defined margin (e.g., 5%). This is elaborated in Section V.B of MISO 2009 DA paper. Table I shows a comparison of the penalties for GUP for SCED for DA and RT.

Type	Penalty
DA SCED (First solve)	High Penalty
DA SCED (Second solve)	User Defined Relaxed High Penalty (e.g. Relaxed by 5%)
RT SCED	Low Penalty (e.g., 10^{-6})

TABLE I
GUP SCED PENALTY COMPARISON FOR DA AND RT

- Objective function:

$$\sum_{\forall t \in \mathcal{T}} \left[\Gamma_{Tot,t}^{RS} sl_{Tot,t}^{RS} + \sum_{\forall z \in \mathcal{Z}} \Gamma_{z,t}^{RS} sl_{z,t}^{RS}\right] \tag{27}$$

- Constraints:

$$\sum_{\forall g \in \mathcal{G}} \left[r_{g,t}^{reg} + r_{g,t}^{spin}\right] \geq R_{Tot,t}^{RS-req} - sl_{Tot,t}^{RS} \qquad \forall t \in \mathcal{T} \tag{28}$$

$$\sum_{\forall g \in \mathcal{G}_z} \left[r_{g,t}^{reg} + r_{g,t}^{spin}\right] \geq R_{z,t}^{RS-req} - sl_{z,t}^{RS} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{29}$$

$$sl_{Tot,t}^{RS} \geq 0 \qquad \forall t \in \mathcal{T} \tag{30}$$

$$sl_{z,t}^{RS} \geq 0 \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \tag{31}$$

2) Items that can be Improved:

- Updating the group reserve constraints to account for SOL and IROL constraints.
- Market-wide min generation-based OR requirement.
- Max single regulating resource or CR dispatch (GUP).

F. Thermal Branch Constraints

Transmission 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).

1) ISOs Contingencies Perspective: In the RT SCED, the state estimator (SE) and contingency analysis (CA) functions in the Energy Management System (EMS) are utilized to monitor actual transmission thermal loadings and detect potential contingency flow violations. The EMS SE is executed every minute and the EMS CA is every 5-minute periodically. In addition, the Midwest ISO also monitors the flows over flowgates that are impacted by, and congestion relief over which requires coordination with external Regional Transmission Operators (RTOs). With all the available data from the real grid in combination with the SE, the CA tool constantly lists a set for base-case and line contingency cases to be imposed for the next SCED interval.

2) INVENIAs Contingencies Perspective: Invenia does not have access to data of the Real Grid each minute. While some data is reported hourly, the SE data is reported every six hours. Therefore Invenia's approach is to assume that line outages are incorporated in the network models and only one grid topology is considered for a given DA and or RT run. There are two main types of simulations to be run using the SCED, (i) Historical Simulations, where we have all the available data beforehand, and (ii) Future Scenarios, for which future grid data has to be estimated/forecasted. For historical RT simulations, the actual list of contingencies that took place can be used as a fictitious output of the CA and remove them from the base-case if their status remains off within a set threshold (under contingency for more than 12 hrs). On the other hand for Future Scenarios, the list of contingencies to be used could be set as the same set provided by DA. 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:

3) Objective Function:

$$\sum_{\forall t \in \mathcal{T}} \Big[\sum_{\forall m \in \mathcal{M}_0} \Gamma^{flow,0}_{1,m} sl1^{flow,0}_{m,t} + \Gamma^{flow,0}_{2,m} sl2^{flow,0}_{m,t} + \big[\sum_{\forall c \in \mathcal{C}^{\text{SCED}}} \sum_{\forall m \in \mathcal{M}_c} \Gamma^{flow,c}_{1,m} sl1^{flow,c}_{m,t} + \Gamma^{flow,c}_{2,m} sl2^{flow,c}_{m,t} \big] \Big] \tag{32}$$

4) Base-Case Constraints: For RT, the reactive power flow trough the lines is required to calculate the term $\Delta T f_{l,t}$, which accounts for the impacts of native loads, external loop flows, NSI changes and reactive flows on transmission constraint flows as expressed in the MISO 2009 RT paper. However, as a first approximation of the case base transmission constraints this term is ignored. Therefore case base constraints are:

$$fl^0_{m,t} = \sum_{\forall n \in \mathcal{N}_m} \text{ISF}_{m,n} p^{net}_{n,t} \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{33}$$

$$-(FL^{rate-a}_m + sl1^{flow,0}_{m,t} + sl2^{flow,0}_{m,t}) \le fl^0_{m,t} \le (FL^{rate-a}_m + sl1^{flow,0}_{m,t} + sl2^{flow,0}_{m,t}) \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{34}$$

$$0 \le sl1^{flow,0}_{m,t} \le \overline{SL1}^{flow,0}_m \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{35}$$

$$sl2^{flow,0}_{m,t} \ge 0 \qquad \forall m \in \mathcal{M}_0, t \in \mathcal{T} \tag{36}$$

5) Contingency Constraints:

$$fl^c_{m,t} = \sum_{\forall n \in \mathcal{N}_m} \text{ISF}_{m,n} p^{net}_{n,t} + \sum_{\forall l \in \mathcal{L}_c} \text{LODF}^c_{m,l} fl^0_{l,t} \qquad \forall c \in \mathcal{C}^{\text{SCED}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{37}$$

$$-(FL^{rate-b}_m + sl1^{flow,c}_{m,t} + sl2^{flow,c}_{m,t}) \le fl^c_{m,t} \le (FL^{rate-b}_m + sl1^{flow,c}_{m,t} + sl2^{flow,c}_{m,t}) \qquad \forall c \in \mathcal{C}^{\text{SCED}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{38}$$

$$0 \le sl1^{flow,c}_{m,t} \le \overline{SL1}^{flow,c}_m \qquad \forall c \in \mathcal{C}^{\text{SCED}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{39}$$

$$sl2^{flow,c}_{m,t} \ge 0 \qquad \forall c \in \mathcal{C}^{\text{SCED}}, m \in \mathcal{M}_c, t \in \mathcal{T} \tag{40}$$

Note: Transmission constraints slack variables could be set up at 10000 dollars. There could be a different penalty for different amounts of violations for transmission constraints. For minimum violations the penalty should be small, but if the violation is considerably high, the penalty should be high too (Rate A and Rate B could be used for this).

6) Items that can be Improved:

- Obtain the reactive power Qf_l and calculate the actual $\Delta T f_{l,t}$
- 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.

G. Final SCUC Formulation

The final objective function for SCUC is:

$$\min\,(1) + (22) + +(27) + (32) \tag{41}$$

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