MIDWEST ISO CO-OPTIMIZATION BASED REAL-TIME DISPATCH AND PRICING OF ENERGY AND ANCILLARY SERVICES

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ABSTRACT – Midwest ISO's real-time market design with energy and ancillary service co-optimization is reported in this paper. The key components of Midwest ISO's real-time market are described including intra-day reliability commitment, transmission security management, real-time dispatch and pricing. The RT SCED formulation at the core of the real-time dispatch and pricing market is presented. Numerical examples are included to illustrate the primary features of the real-time market.

Key words – Real-time dispatch and pricing, LMP, Energy and ancillary service co-optimization, Intra-day reliability commitment, and Reserve demand curves

I. INTRODUCTION

As the Regional Transmission Operator, Midwest ISO is responsible for reliable grid operation serving the electric energy needs of consumers in 15 U.S. states and the Canadian province of Manitoba (Figure 1) and has a peak load of ~110,000MW. In its existing *energy* market, the energy offer based, security-constrained economic dispatch is utilized in real-time operations to determine base-point dispatch instructions with reserve requirements scheduled outside the energy market in the form of ancillary service self-schedules. In symmetry with its day-ahead counterpart, real-time locational marginal prices (LMP) are calculated every five-minutes after the fact using an ex-post pricing algorithm [1].

For the reasons discussed in [2], the Midwest ISO's electricity market design has recently advanced to include ancillary service (AS, operating reserve) products that are co-optimized with the energy product in its day-ahead (DA) and real-time (RT) markets [4]. Two types of ancillary services are integrated into the co-optimization market design: Regulation (REG) that is utilized to balance load and generation on a moment-to-moment real-time basis, and Contingency Reserves (CR) that can be called on to deliver energy for managing power flows and meeting demand on the grid if a generator trips off-line or a transmission line goes out of service. Midwest ISO's co-optimized energy and AS market is scheduled for operation on January 6, 2009.

With the introduction of the co-optimized energy and AS market, Midwest ISO will be able to commit and dispatch operating reserves and regulation in a co-optimized manner with energy. This co-optimization framework will allow portions of cost-efficient generation that are self-scheduled in the *energy* market for operating reserves to be optimized for energy needs, while shifting the required operating reserves to less cost-efficient generations and still maintain reliability. This will lower overall costs for the Midwest ISO region. To ensure that the regulation dispatches are properly dispersed and contingency reserve dispatches are deliverable for loss of the largest supply resource at any location, locational reserve zones are established where a minimum REG requirement and/or a minimum CR requirement may be defined.

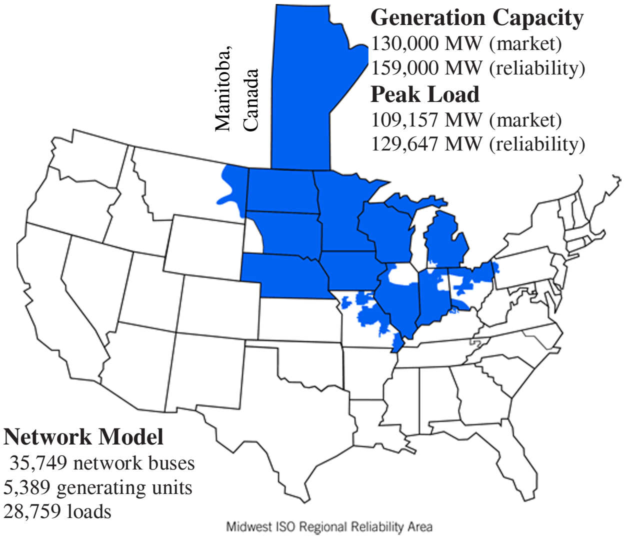

Figure 1 - Midwest ISO reliability and market footprints

Real-time grid reliability is at the center of Midwest ISO's co-optimized energy and AS design. While resource schedules are cleared as financially, not physically binding, the day-ahead market is critically linked to real-time operation through the reliability assessment commitment (RAC) and the two-settlement mechanism that guarantees resource adequacy for reliability and enables participants to arbitrage price differences between day-ahead and real-time markets respectively. The DA market cleared financially binding resource schedules form the basis for the DA RAC by which sufficient resources are committed using the security-constrained unit commitment (SCUC) to meet Midwest ISO's demand forecasts and AS requirements subject to transmission limits. The DA RAC resource commitment schedules make the operating plan for the next day. During the operating day, more accurate information about demand forecasts, net scheduled interchanges (NSI) and transmission limitations is available; the RAC algorithm may be executed several times during the operating day, called intra-day (ID) RAC process, to further update the operating plan. The intra-day operating plan updates allow Midwest ISO operations to prepare sufficient resources at the right locations to manage load-generation-NSI balances and transmission congestions under normal and emergency conditions. With this integrated market-driven scheduling process, Midwest ISO uses the security-constrained economic dispatch (SCED) to achieve real-time reliable grid operation at the lowest costs. Energy deliveries and AS dispatches are priced based on actual system conditions after the fact.

This paper reports upon the Midwest ISO's co-optimization-based real-time dispatch and pricing of energy and ancillary services, while the Midwest ISO's DA co-optimization of energy and AS are reported in [2].

This paper is organized as follows. Midwest ISO's real-time co-optimized energy and AS market rules are highlighted in Section II. In Section IV, the security-constrained economic dispatch formulation for Midwest ISO's real time market is presented with terminology defined in Section III. The real time market solution process is presented in Section V. Numerical results follow in Section VI and the paper is concluded with Section VII.

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II. HIGHLIGHTS OF MIDWEST ISO REAL-TIME CO-OPTIMIZED ENERGY AND AS MARKET

The key market rules of the Midwest ISO's RT market are highlighted below. As the RT market shares some of the key features with the DA market [2], only the business rules peculiar to the RT market are described.

A. Real-Time Market Products

- Energy offers in the form of MW and price ($/MWh) by physical resources.
- Ancillary service offers in $/MW by qualified physical resources.
- Ancillary services include regulating reserve (REG), spinning reserve (SPIN), and supplemental reserve (SUP). Contingency reserve (CR) is made up of both spinning reserve and supplemental reserve from qualified online and offline resources that are fully achievable within the maximum Contingency Reserve Deployment Time (CRDT). Operating reserve (OR) is made up of contingency reserve plus regulating reserve and represents the total short-term operating reserve requirement.
- Regulating reserve in the RT market is a five-minute product consisting of regulating reserve and scheduled regulation service that are fully achievable in the upward or downward direction within the maximum Regulation Response Time (RRT). Regulation may be supplied in the RT market by any online, regulation qualified resource.
- Spinning reserve in the RT market is a ten-minute product and equal to a specified percentage of the Midwest ISO CR requirement that must be supplied by spin qualified online resources.
- Supplemental reserve in the RT market is a ten-minute product defined as a percentage of the Midwest ISO CR requirement that must be supplied by qualified supplemental resources.

B. Real-Time Market Resources

- Internal generation resources: may be qualified to provide energy and ancillary services subject to maximum/minimum emergency/economic/regulation limits, min-run/down times, max-run times, cold/intermediate/hot start/notification times and startup costs, and ramp-rate limits.
- External Asynchronous resources (EAR): may be qualified to provide energy and ancillary services. An available EAR is dispatchable continuously from 0 to its max MW. However, its ramping capability may be restricted by the ramp-rates of its associated external system.
- Type-1 Demand Response Resources (DRR): may be qualified to supply energy at fix target reduction MW (when committed in the Operating Plan), or to provide CR (when not committed, but qualified for CR), subject to shut-down and hourly curtailment costs, minimum interruption/non-interruption times and exclusivity of energy or AS dispatch. The MW amount of Type-1 DRR deployments needs to be discounted from the real-time forecasted demand.
- Type-2 DRRs: may be qualified to provide energy and ancillary services. Type-2 DRRs have the same commitment and dispatch model as generation resources.
- External Bilateral Transactions: are fixed in real time. It includes wheel-in, wheel-out or wheel-through energy schedules.
- Intermittent Renewable Resources (IRR): are qualified to provide energy. They are in general dispatched according to fixed energy self-schedule.
- There are no virtual supplies, virtual demands or demand bids.

C. Midwest ISO AS Requirements and AS Demand Curves

AS requirements and demand curves are modeled in Midwest ISO's RT market in a similar manner to the DA market process. Market-wide and local reserve zone AS requirements are enforced.

Under normal system operating conditions, the real-time SCED solves periodically every five minutes to meet 100% of the AS requirements, while balancing generation, demand forecasts and NSI changes and managing transmission congestion.

Under emergency system operating conditions that are projected in the ID RAC process, on-line committed resources may be allowed to provide energy above its economic maximum (or minimum for excess generation emergency) limits, and resources that are designated for operation only under emergency conditions may be committed and called online in order to meet 100% of AS requirements. However, energy dispatches for designated regulation resources must continue to observe their regulation maximum and minimum limits.

Under contingency events that occur in the real-time operation, Midwest ISO operations will start deploying the contingency reserves from resources whose CR offers have been awarded in the last real-time market and that are therefore obligated to provide such services. The amount of CR deployment and selection of CR deployment resources are dependent of the size of the contingency events and their locations.

From the start of the CR deployment to the time when additional resources may be dispatched to fully replenish the deployed amount of CR capacities, the market-wide CR requirement to be cleared in the real-time SCED solution will be decreased as necessary to avoid premature occurrence of scarcity prices, which is a result of the CR deployment event rather than a true scarcity condition. Therefore, the market-wide OR requirement is decreased by the amount of CR deployment during the deployment and replenishment period and then restored (or gradually) to the normal requirements as the reserve capacities are replenished. The OR requirement during CR deployment and replenishment is depicted in Figure 2.

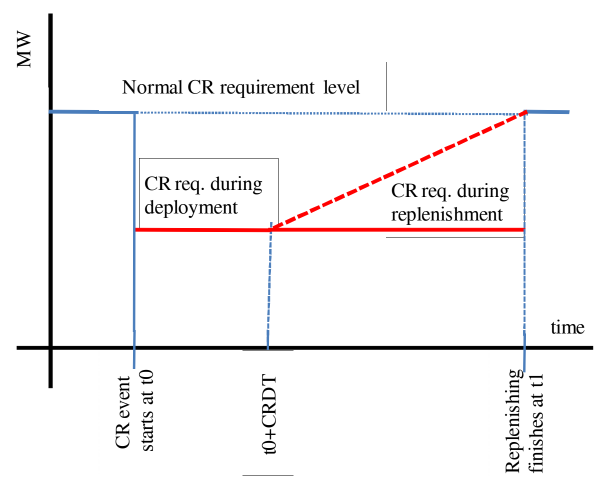

Figure 2 – CR Requirement during CR deployment and replenishment

D. Transmission Constraints in Real-Time Market

In real-time operations, 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 in every 5-minute periodically. Dynamic security over pre-defined major transmission interfaces is analyzed. In addition, the Midwest ISO also monitors the flows over flowgates that are impacted by, and congestion relief over which requires coordination with external RTOs. In the real-time market dispatch, the following constraints are included in the dispatch and pricing solutions:

- Actual thermal constraints: They consist of actual flows over a transmission line or transformer branch.
- Contingency thermal constraints: These constraints result from likely transmission or generation outages that may cause over-loadings of certain transmission elements.
- Surrogate voltage/var or stability constraints: The loadings over pre-defined transfer interfaces must be maintained below a MW level to avoid voltage or stability problems.
- Flowgate constraints: The Midwest ISO grid is part of the Eastern interconnection. Midwest ISO and PJM RTO has reached joint operating agreement that both RTOs will coordinate the congestion relief actions over a pre-defined list of transmission elements, called Reciprocal Coordinated Flowgates (RCF). The objective of the RCF congestion relief approach is to eliminate the seams at the boundary of the two markets taking advantages of the least cost re-dispatch means in both RTO's dispatch systems.

E. Intra-Day Reliability Assessment Commitment

As is described in [2], the DA RA commitment serves to assure resource adequacy required to achieve real-time reliable grid operations. Entering the operating day, more accurate information on system operational needs is available. Taking advantage of this up-to-date system information, the ID RAC process is implemented to further improve the DA RAC schedules for energy and AS. The ID RAC may be executed several times during the day of operation as major system conditions change. The ID RAC produces the resource operating plans for the next few hours including the following information:

- Fast-responsive resource startup and shut-down schedules
- Designation of resources to provide regulation

F. Ex-Post Pricing of Energy and Ancillary Services

Real-time prices for energy and ancillary services are calculated every five minutes after the fact based on actual energy and ancillary service dispatches and transmission constraints. The ex-post pricing of energy and ancillary services utilizes the same RT SCED algorithm.

III. TERMINOLOGY

Prior to describing the RT SCED algorithms, the used terminology is given below for ease of reference.

$ECost_t$: Total energy dispatch cost for generation supplying resources for dispatch interval *t (minute)*. It is summation of energy dispatch costs of the RT market resources.

$ASCost_t$: Total AS dispatch cost for AS offers for dispatch interval *t*. It is summation of hourly AS dispatch cost of the RT market resources.

$ASValue_t$: Total AS value for dispatch interval *t*. It equals summation of products of cleared MW quantities and prices on the market-wide and reserve zone OR and REG demand curves.

i and *Nr*: Index and number of physical RT market resources.

ES_{rt} : Energy dispatch of energy supplying resource *r* at interval *t*.

FD_t : Forecasted RTO demand for dispatch interval *t*.

L_t : Transmission loss at time *t*, nodal transmission loss sensitivity based linear function of nodal net injections.

k and *Nps:* Index and number of phase angle regulators *(PAR).*

θ_{kt} : Angle of PAR *k* at interval *t,* bounded with its min and max regulating limits in radian.

d_j : Nodal distribution factors for transmission losses.

S_{lrt} : Shift factors of constraint *l* with respect to the dispatch of resource *r* or the angle of PAR *k*.

LF_{lt} : Flow component resulting from external loop flows.

Pf_l : Actual active flow in MW over constraint *l*.

Qf_l : Actual reactive flow in MVar over constraint *l*.

ES_r^0 : Actual output of energy supplying resource *r*.

θ_k^0 : Actual initial angle of PAR *k*.

REG_{rt} : REG dispatch of committed resource *r* and interval *t*.

CR_{rt} : CR dispatch of qualified resource *i* and interval *t*.

RF_{it} : Binary parameter indicating whether resource *r* is assigned to provide regulation for dispatch interval *t* in the latest operating plan. This flag is pre-determined in the ID RAC process and is fixed over one specific operating hour in the real-time dispatch.

RHL_{rt} : Regulation max limit of resource *r* and interval *t*.

$EcHL_{rt}$: Economic max limit of resource *r* and interval *t*.

CF_{rt} : Binary parameter indicating whether resource *r* is online to provide energy. It is pre-determined based on the actual real-time status or the commitment status in the current operating plan.

RLL_{rt} : Regulation min limit of resource *r* and interval *t*.

$EcLL_{rt}$: Economic min limit of resource *r* and interval *t*.

RRL_{rt} : Ramp-rate limit (MW/hour) of resource *r* and interval *t*.

α_t : CR sharing of ramp-rate limit, a configurable option to manage ramp-rate dispatches.

Q_t^{GOR} : Equal to a given percentage of OR requirement that is to be supplied by generation resources (excluding Type-1 DRRs).

Q_t^{REG} (Q_{zt}^{REG}), Q_t^{OR} (Q_{zt}^{OR}) and Q_t^{RS} (Q_{zt}^{RS}): Market-wide (zonal) REG, OR, and REG+SPIN requirements at interval *t*.

$r \in rz$: Denote resource *r* is located in reserve zone *rz*.

$r \in SPIN$: Denote resource *r* is a SPIN qualified resource.

$r \in GEN$: Denote resource *r* is a qualified generation resource.

RMx^{REG} (RMx^{CR}): Max single resource dispatch for REG (CR).

$DRR1TargetMW_{rt}$: Target curtailment MW for Type DRR *r*.

$MaxOfflineCT_{rt}$: Max CR MW of quick-start offline resource *r*.

IV. THE SECURITY-CONSTRAINED ECONOMIC DISPATCH ALGORITHM

The RT SCED algorithm is designed to carry out RT dispatch and the ex-post RT pricing in compliance with Midwest ISO's energy and AS market business rules. For simplicity and convenience of reference, Greek symbols are used to index the pertinent constraints and denote their shadow prices as needed.

- Objective function

$$\min\left[ECost_t + ASCost_t - ASValue_t\right]$$

- Power balance Constraint

$$(\lambda_t) \quad \sum_{r=1}^{Nr} ES_{rt} = FD_t + L_t$$

- Transmission limit constraint

$$(\mu_t) \left\{ \Delta Tf_{lt} + \sum_{r=1}^{Nr}[S_{lrt} * ES_{rt}] + \sum_{k=1}^{Nps}[S_{lkt} * \theta_{kt}] \right\} \begin{matrix} \le \\ = \\ \ge \end{matrix} TSL_{lt}$$

The term, ΔTf_{lt}, accounts for the impacts of native loads, external loop flows, NSI changes and reactive flows on transmission constraint flows:

$$\Delta Tf_{lt} = \sqrt{Pf_l^2 + Qf_l^2} - \sum_{r=1}^{Nr}[S_{lrt} * ES_r^0] - \sum_{k=1}^{Nps}[S_{lkt} * \theta_k^0]$$

Transmission constraints, as good utility practice (GUP), are modeled as soft constraints in the RT SCED algorithm.

- Market resource maximum limit constraint

$$(\tau_{rt}^{\max}) \quad ES_{rt} + REG_{rt} + CR_{rt} \le RF_{rt} * RHL_{rt} + (1 - RF_{rt})EcHL_{rt}$$

- Market resource minimum limit constraint

$$(\tau_{rt}^{mn}) \quad ES_{rt} - REG_{rt} \ge \left\{ \begin{matrix} RF_{rt} \times RLL_{rt} + \\ (1 - RF_{rt})EcLL_{rt} - (1 - CF_{rt})EcLL_{rt} \end{matrix} \right\}$$

- Ramp-rate limit constraint

$$(\tau_{rt}^{RR}) \begin{cases} Up-ramp: ES_{rt} + \alpha_t \times CR_{rt} \le ES_{r,t-5} + RRL_{rt} * 5/60 \\ Down-ramp: -ES_{rt} + ES_{r,t-5} \le RRL_{rt} * 5/60 \end{cases}$$

In the real-time market, resources are allowed to specify an up or down ramp-rate 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 ram rate models are described in [3].

- Market-wide/zonal REG requirement constraint

$$(\gamma_t^{REG}): \quad \sum REG_{rt} \ge Q_t^{REG}$$

$$(\gamma_{zt}^{REG}): \quad \sum_{r \in rz} REG_{rt} \ge Q_{zt}^{REG}$$

For the RT market SCED, Q_t^{REG} and Q_{zt}^{REG} are based on the REG MW on the REG demand curve.

- Market-wide/zonal OR requirement constraint

$$(\gamma_t^{OR}): \quad \sum REG_{rt} + \sum CR_{rt} \ge Q_t^{OR}$$

$$(\gamma_{zt}^{OR}): \quad \sum_{r \in rz} REG_{rt} + \sum_{r \in rz} CR_{rt} \ge Q_{zt}^{OR}$$

To ensure sufficient capacity be committed for reliability, Q_t^{OR} (Q_{zt}^{OR}) equals 100% OR requirement in the ID RA SCUC. For the RT SCED, they are equal to the OR MW cleared on the OR demand curve.

- Market-wide min generation-based OR requirement (GUP)

$$(\gamma_t^{GOR}): \quad \sum REG_{rt} + \sum_{r \in GEN} CR_{rt} \ge Q_t^{GOR}$$

This GUP constraint is prioritized with lower violation penalty for the RT SCED.

- Market-wide/zonal REG+SPIN requirement (GUP)

$$(\gamma_t^{RS}): \quad \sum REG_{rt} + \sum_{r \in SPIN} CR_{rt} \ge Q_t^{RS}$$

$$(\gamma_{zt}^{RS}): \quad \sum_{r \in rz} REG_{rt} + \sum_{r \in rz, r \in SPIN} CR_{rt} \ge Q_{zt}^{RS}$$

The GUP constraints are prioritized with lower violation penalty for the RT market SCED.

- Max single resource REG or CR dispatch (GUP)

$$(\tau_{rt}^{REG}): \quad REG_{rt} \le RMx^{REG}$$

$$(\tau_{rt}^{CR}): \quad CR_{rt} \le RMx^{CR}$$

These GUP constraints are prioritized with lower violation penalty for the RT market SCED.

- Energy, REG and CR Self-schedule constraint (GUP)

$$(\tau_{rt}^{SS}) \begin{cases} ES_{rt} \ge CF_{rt} \times ESS_{rt} \\ REG_{rt} \ge RF_{rt} \times REGSS_{rt} \\ CR_{rt} \ge CRSS_{rt} \end{cases}$$

The self-schedule constraints are prioritized with low violation penalties.

- CR Deployment constraint (GUP)

$$(\tau_{rt}^{CRD}) \quad \begin{matrix} CR_{rt} \ge \beta \times CR_{r,t-1} \\ CR_{rt} \ge CR_r^{deployed} \end{matrix}$$

This pair of constraints is to ensure compliance with required reliability standards. Because CR is a ten-minute product, the first constraint is enforced for the first interval after the initiation of a CR event so that the same resource will be awarded CR for at least 10 minute duration. The second constraint is enforced when a resource has CR deployed. These constraints are allowed to violate with low penalties.

- Offline supplemental CR cleared from qualified offline quick-start resources must observe their min-down time constraints.
- Type-1 DRRs that have been called on and are providing energy in real-time are not qualified to provide CR:

$$(\delta_{rt}^{DRR1e}) \quad CR_{rt} \le (1 - CF_{rt}) \times DRR1TargetMW_{rt}$$

- Offline supplemental reserve dispatch constraint

$$(\delta_{rt}^{SUP}) \quad CR_{rt} \le (1 - CF_{rt}) * MaxOffline\ CT_{rt}$$

- Tie-breaking constraints for price-tied energy and AS offers (GUP) are enforced with low penalty (e.g., 10^{-6}).

V. RT MARKET CLEARING SOLUTION

The Midwest ISO real-time market based operation includes several cohesive business processes (Figure 3):

- Intra-day reliability assessment: The ID RAC takes advantage of the latest system information to update the resource operating plans (OP) to better meet the needs of real-time operation. The main goal of the ID RAC process is to determine whether the current operating plan can meet forecasted loads, anticipated NSI changes, transmission security and AS requirements. When needed to resolve likely operating concerns, the ID RAC recommends commitment of fast-responsive resources, such as Combustion Turbines. The ID RAC also makes sure that appropriate resources are selected to meet market-wide as well as local reserve zone AS requirements. The ID RAC process may be executed several times during the day of operation.
- EMS transmission security analysis: The SE and CA functions in the EMS perform periodic analysis of transmission system security under the normal and likely contingency conditions. Actual transmission element congestions or those to be anticipated under contingencies are identified; their sensitivities with respect to nodal net injections are calculated and transferred to the RT SCED for enforcements. In addition, transmission loss sensitivities are updated in each SE cycle.
- Automatic generation control (AGC): The AGC system implements the base-point dispatches calculated in the RT

Dispatch and deploys the regulation to maintain moment-to-moment generation-load-NSI balances. Under contingency events, it also deploys contingency reserves.

- RT Dispatch (RTD): The RT Dispatch process determines the base-point dispatches and AS assignments for individual resources to meet real-time generation and AS requirements subject to the transmission constraints from the EMS. The RT Dispatch algorithm executes every five minutes.
- Ex-Post Pricing (RTP): The ex-post pricing process determines the real-time energy LMPs and AS MCPs. The Ex-Post Pricing algorithm executes every five minutes.

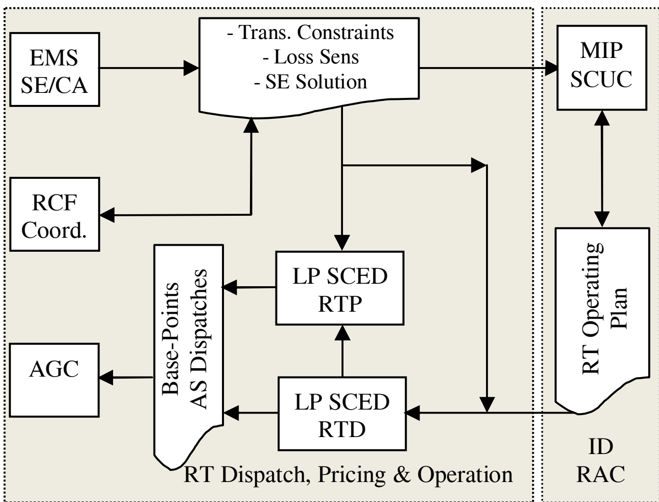

Figure 1 - RT Market

LMPs at commercial pricing nodes (*cp*) and AS MCPs for reserve zones, calculated ever five minute periods, are integrated over each hour. The hourly integrated LMPs and MCPs are used as real-time market settlement determinants. The definitions for LMPs and MCPs are given in [2].

VI. NUMERICAL ILLUSTRATIONS

For clarity and simplicity, numerical cases based on a 5-bus example with 5 generation resources and one local reserve zone (Appendix A includes input data) are used to illustrate the primary features of RT Energy and AS co-optimization market.

A. Security Constrained Energy-Only Dispatch

In this case, the AS requirements are not enforced and the RT SCED model solves for an energy-only dispatch to meet the 669ME load subject to a 240MW limit transmission constraint. The dispatch results are given in Table 1. The transmission constraint is binding with a shadow price of $22.21/MW. The two resources, G3 and G5, are marginal with LMPs equal to their offer prices. The other two resources, G1 and G2, are fully loaded as the LMPs are higher their energy offer prices. With one binding transmission constraints and two marginal resources, the market dispatch and clearing results are intuitively quite understandable.

B. Security-Constrained Energy and AS Co-Optimization

On top of the above case, the market-wide and reserve zone AS requirements are enforced in the current case. Table 2 shows the market clearing results for this case.

Table 1 – Energy-Only Dispatch

Resource Name	CF	Dispatch Limit		ES (MW)	Price ($/MWh)	
		Min	Max		Offer	LMP
G1	1	11.0	110.0	110.0	14.00	27.32
G2	1	10.0	100.0	100.0	15.00	27.32
G3	1	52.0	520.0	195.8	30.00	30.00
G4	0	0.0	200.0	0.0	30.00	30.20
G5	1	60.0	600.0	280.3	10.00	10.00

Table 2 – Energy and AS Co-Optimization Dispatch

Resource Name	CF	RF	Dispatch (MW)			Market Prices			Offer Prices		
			Energy	Reg	CR	LMP	REG	CR	Energy	REG	CR
G1	1	1	110.0	0.0	0.0	27.32	20.57	9.90	14.00	7.70	4.62
G2	1	1	80.0	20.0	0.0	27.32	20.57	9.90	15.00	8.25	4.95
G3	1	0	213.2	0.0	50.0	30.00	20.57	9.90	30.00	16.50	9.90
G4	0	0	0.0	0.0	16.0	30.20	5.50	3.00	30.00	16.50	3.00
G5	1	1	282.8	50.0	14.0	10.00	5.50	3.30	10.00	5.50	3.00

For the simple cases shown in Tables 1 and 2, the energy dispatches and LMPs are the same, since the one single-price energy offers are used for the resources and the redispatch costs of resolving the constraints are the same (so the shadow prices of the binding transmission constraints are also the same). For the resources (G1, G2 and G3) that are in the local reserve zone, the REG MCP is $20.57/MW, which is higher than the REG offer price of $8.25/MW by G2. This seemingly higher REG MCP results from the energy on G2 being dispatched down in order for the resource to provide REG to meet the reserve zone AS requirement. This product substitution cost by G2 is determined by the difference between energy LMP and its energy offer price. As a result, the REG MCP is equal to REG offer price plus the energy product substitution cost (also called marginal lost opportunity cost).

In general, the AS MCPs are the corresponding AS offer prices plus the associated product substitution costs. When energy and AS dispatches are not coupled by resource capacities, then AS MCPs will be equal to the AS offer prices of the marginally cleared AS offers. When energy and AS dispatches are coupled, meaning the dispatch of one product is backed down in order to make room for the dispatch of a different product, then product substitution occurs and such re-dispatch costs will be reflected in the AS MCPs. This pricing effect is important to ensure that resources comply with real-time dispatch instructions, indifferent to whether it is dispatched to provider energy or AS.

The consistency between MW dispatch instructions and pricing incentives is true when the energy and AS dispatches are analyzed along with market prices for a single dispatch interval. However, it is important to realize that, when evaluated in a longer time horizon, the “optimal” single-interval dispatch may not be “globally optimal”, due to the phenomenon of energy trapping issue [3].

In this current case, the CR dispatch is not coupled with REG or energy dispatches. As a result, the CR MCPs are determined by the offer prices of the marginally dispatched CR offers from G3 (in the local reserve zone) and G4.

VII. CONCLUSIONS

This paper reports on Midwest ISO's co-optimized RT energy and AS market design and its implementation. The key components of Midwest ISO's real-time market, including real-time dispatch, real-time pricing, and the intra-day RAC, are described. The co-optimization of energy and AS is expected to not only reduce the overall energy costs of serving the loads, but also provide efficient price signals for ancillary services that may be self-scheduled by generators. Numerical examples are included to illustrate the primary features of the real-time co-optimized energy and AS market design.

VIII. APPENDIX

- Resource dispatch parameters

Resource	Minimum Limits			Maximum Limits			Qualified			Ramp	Actual
Name	Eme	Eco	REG	REG	Eco	Eme	REG	SPIN	SUP	Limit	Gen
G1	11	11	11	110	110	120	1	1	0	240	100
G2	10	10	10	100	100	110	1	1	0	240	90
G3	52	52	52	520	520	550			0	480	200
G4	0	0	0	200	200	220			1	600	
G5	60	60	60	600	600	660	1	1	0	660	350

- Resource energy and AS offers

Resource	Band 1 Energy		AS Offer Price			Loss	Shift
Name	MW	Price	REG	SPIN	SUP	Sens	Factors
G1	90	14.00	7.70	4.62		0.01088	0.08439
G2	95	15.00	8.25	4.95		0.01088	0.08439
G3	300	30.00	16.50	9.90	0	-0.00506	-0.01527
G4	120	30.00	16.50	9.90	3.00	0.00782	-0.04145
G5	400	10.00	5.50	3.30		0.05641	0.80358

Note: The transmission constraint has 240MW limit.

- Market-wide AS requirement data

  REG Req = 70MW; CR Req=80MW; SPIN Req = 64MW

- Local reserve zone AS requirement data

  G1, G2 and G3 are inside the reserve zones.

  REG Req = 20MW; CR Req=50MW; SPIN Req=40MW

IX. ACKNOWLEDGMENT

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XI. BIOGRAPHIES

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