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Markets Track



Reserve Markets Analysis using Simulator

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Reserve Markets



- *Energy Markets* alone are not able to capture the reliability aspects of power system resources.
- *Reserves Market* are a natural extension to Energy Markets, which inherently model reliability.
- Most electricity markets have or are moving towards having a Reserves Market.



Reserve Markets



- In a *Reserves Market* generators supply bids to sell the *ability* to increase their production if called to do so.
- In order to maximize profit, the producer will determine the best combination of bids to produce energy and provide reserve.
- Energy and reserve should consequently be cleared simultaneously through a *co-optimization* process.

Reserve Markets



- Co-optimization of energy and reserves results in:
 - Optimal generation dispatch set-points and reserve assignments
 - Energy locational marginal prices (LMP)
 - Reserve market clearing prices (RMCP)
- Problem is numerically solved using an OPF that includes resource reserve controls and area or zone reserve constraints.
- PowerWorld: *OPF Reserves*

Reserve Resource Controls

- Generators (and loads) can provide the following types of reserve:
 - *Regulation Reserve (RR)*
 - *Spinning Reserve (SR)*
 - *Non-Spinning or Supplemental Reserve (XR)*



Reserve Resource Controls



- Spinning and supplemental reserve are positive quantities.
- Regulation reserve is a bidirectional control.
 - Two ways to model regulation controls:
 1. As two independent controls: regulation reserve up (RR^+) and regulation reserve down (RR^-).
 2. As a single control. In this case the unit provides the same amount of regulating reserve in both directions.

Reserve Resource Controls



- Spinning and supplemental reserves combined together provide *Contingency Reserve (CR)*
- Contingency reserve plus regulating reserve up is called *Operating Reserve (OR)*

$$\begin{array}{rcl} \text{RR}^+ + \underbrace{\text{SR} + \text{XR}} & = & \text{OR} \\ \text{RR}^+ + \text{CR} & = & \text{OR} \end{array}$$

Reserve Resource Controls



Generators

Generator Information for Current Case

Bus Number: 1
Bus Name: 1
ID: 1
Area Name: Home (1)
Labels: no labels

Fuel Type: Unknown
Unit Type: UN (Unknown)

Status:
☐ Open
☒ Closed

Power and Voltage Control | **Costs** | OPF | Faults | Owners, Area, etc. | Custom | Stability

Output Cost Model | Bid Scale/Shift | **OPF Reserve Bids**

OPF Regulating Reserves		OPF Contingency Reserves	
Up Reserve MW	35.00	Spinning Available	Supplemental Available
Down Reserve MW	25.00	☒ Available	☐ Available
☒ Available for Regulating Reserves		Reserve MW	0.00
Price [\$ /MWh]	8.000	Price [\$ /MWh]	6.000
Maximum MW Increase	55.000	Max MW Increase	120.000
Maximum MW Decrease	40.000		10.000

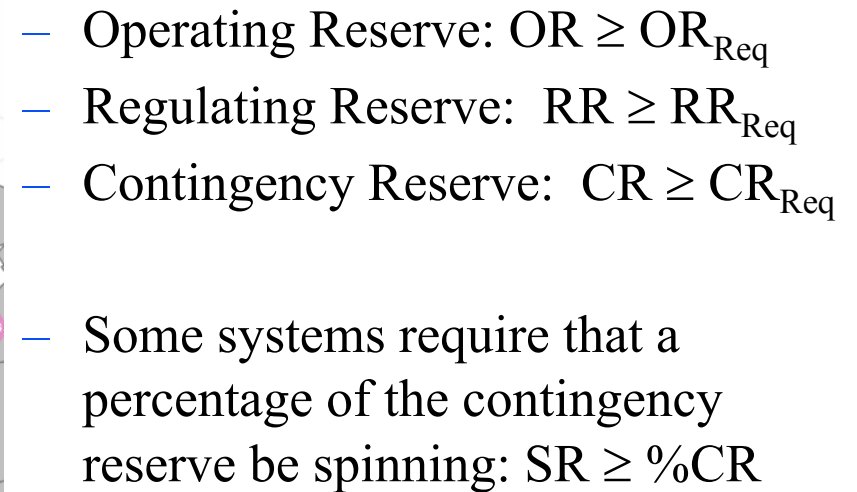
OK Save Cancel Help Print

Spinning and Supplemental Reserve Control Availability

Spinning and Supplemental Limits and Prices

Regulation Reserve Limits and prices

Specified at Area/Zone level.



Reserve Constraints



Reserve Requirements are specified as *Demand Curves*.

Home Area Information for Current Case

Number: 1
Name: Home
Super Area:
Labels: no labels

Area MW Control Options:
☐ No Area Control
☐ Participation Factor Control
☐ Economic Dispatch Control
☐ Area Slack Bus
☐ Injection Group Area Slack
☒ Optimal Power Flow Control

Info / Interchange | Options | Area MW Control Options | **OPF** | Tie Lines | Buses | Gens | Loads | Custom

OPF Results:
Average LMP for Area: 12.00
LMP Standard Deviation: 1.63
Min/Max LMP: 10.00 - 14.01
Total Generator Results:
Production Cost (Scaled) (\$/hr): 1920.65
Unscaled Production Cost (\$/hr): 1920.65
LMP Profit (\$/hr): 0.16

Cost of Energy, Loss, and Congestion Reference:
☒ Existing loss sensitivities directly
☐ Area's Bus' Loads
☐ Injection Group

Reserve Requirement Curves:
Operating | **Regulating** | Contingency | Results

☒ Enforce Regulating Reserve Requirements in OPF

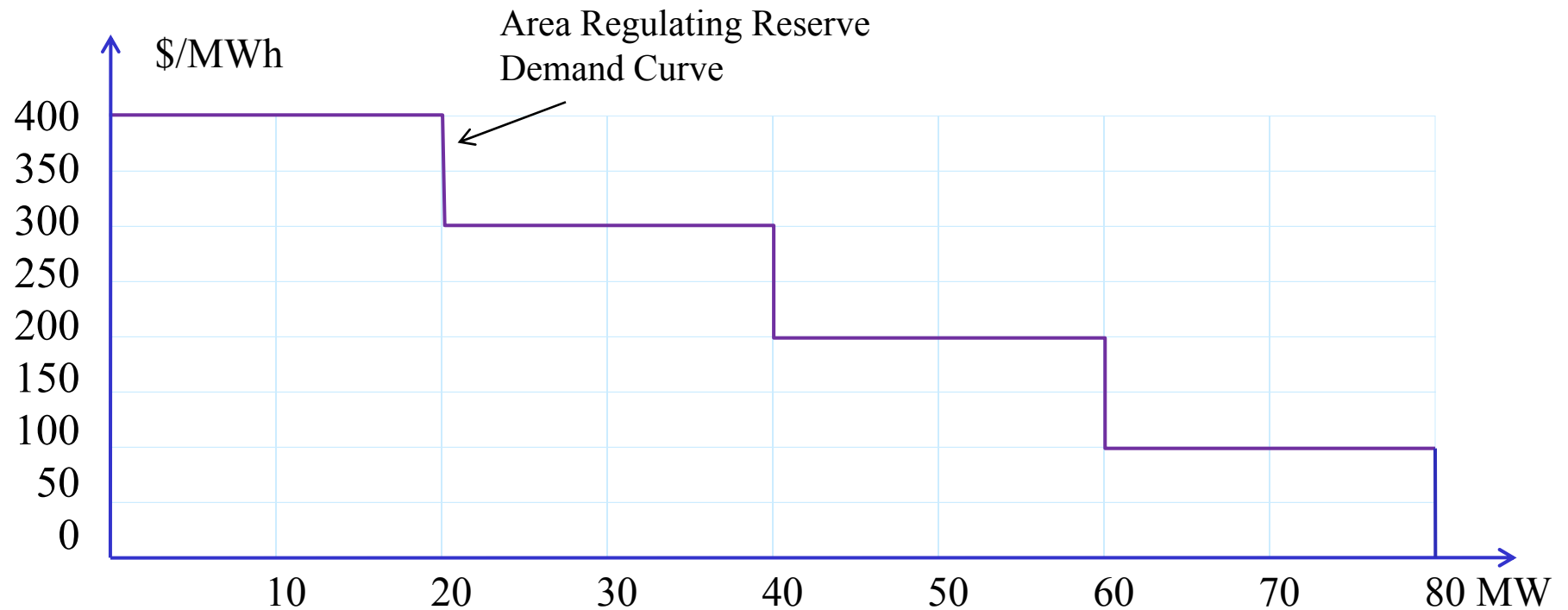
MW	\$/MWh
0.00	400.00
20.00	300.00
40.00	200.00
60.00	100.00
80.00	0.00

OK Save Cancel Help Print

OPF page is used to show OPF results and to define reserve benefit curves

Define demand curves for **Area Reserve**. These are positive, descending values.

Reserve Constraints



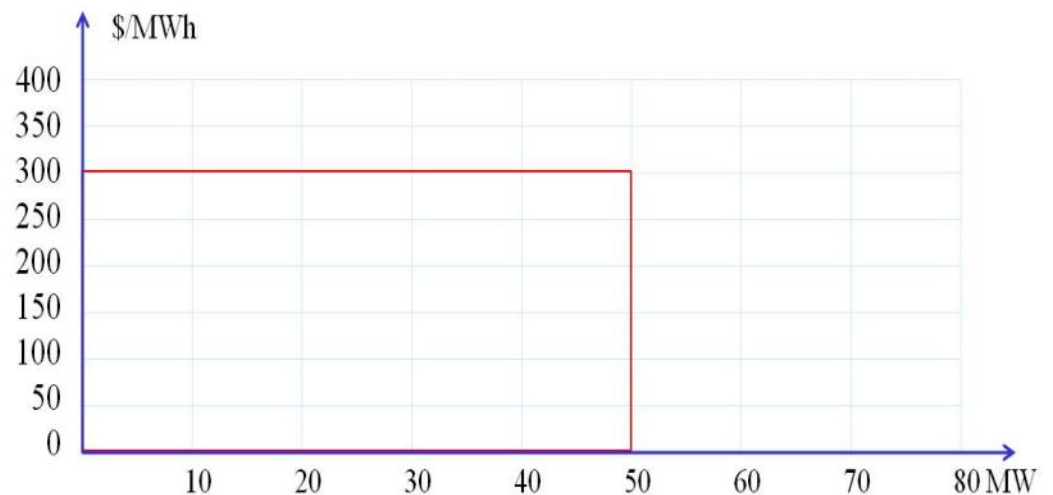
- Reserve Requirement Curves

Operating Regulating Contingency Results

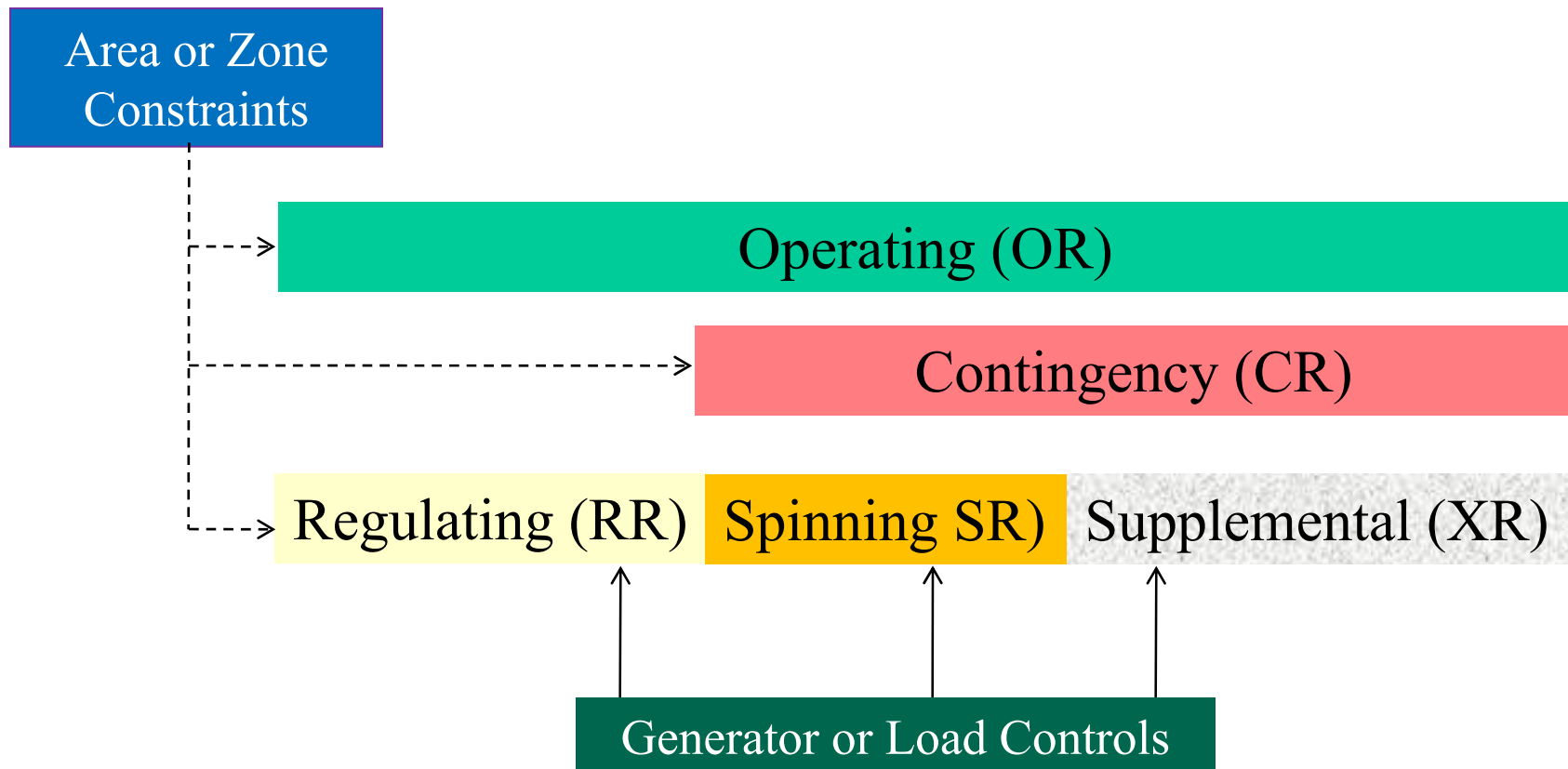
Records ▾ Set ▾ >>

☒ Enforce Regulating Reserve Requirements in OPF

MW	\$/MWh
0.00	300.00
50.00	0.00



Reserve Controls and Constraints



Objective Function



- The LP problem consists in maximizing total surplus:

$$\text{Total Surplus} = \text{Benefit} - \text{Costs}$$



- Up Regulation Reserve Surplus
- Down Regulation Reserve Surplus
- Contingency Reserve Surplus
- Operating Reserve Surplus



- Up Regulation Reserve Cost
- Down Regulation Reserve Cost
- Spinning Reserve Cost
- Supplemental Reserve Cost

OPF Main Dialog



Check OPF
Reserves Option.
This solves the
LP-OPF including
reserve controls
and constraints

Solve LP OPF
Including
Reserves

The image shows a software dialog box titled "LP OPF Dialog". It has four tabs: "Options", "Results", "LP Solution Details", and "Advanced Options". The "Options" tab is active and contains three sub-sections: "Common Options", "Constraint Options", and "Control Options". In the "Common Options" section, the "Objective Function" has two radio buttons: "Minimum Cost" (selected) and "Minimum Control Change". Below this, there is a checked checkbox for "Include OPF Reserve Requirements" and an unchecked checkbox for "Use a Single Control for Up/Down Regulation". The "LP Control Variables" section has five checkboxes: "Disable All Phase Shifter Controls" (unchecked), "Disable All Generator MW Controls" (unchecked), "Disable All Load MW Controls" (checked), "Disable Area-to-Area MW Transaction Controls" (unchecked), and "Disable DC Transmission Line MW Controls" (unchecked). The "LP Options" section on the right has a "Maximum Number of LP Iterations" set to 30, a checkbox for "Treat Maximum LP Iteration Solutions as Valid" (unchecked), a "Phase Shifter Cost (\$ / degree)" set to 0.1000, and three checked checkboxes: "Calculate Bus Marginal Cost of Reactive Power", "Save Full OPF Results in PWB File", and "Do Detailed LP Logging (i.e., Each Pivot)". There is also an unchecked checkbox for "Start with Last Valid OPF Solution". At the bottom of the dialog, there are several buttons: "OK" (with a green checkmark), "Solve LP OPF", "Single Outer Loop", "Initialize LP OPF", "Save As", "Help" (with a question mark), and "Cancel" (with a red X).

Example: Single Area System



3-bus case with 3 generators

Generators																				
Loads				Areas				Zones				Super Areas								
	Number of Bus	Name of Bus	ID	REG Avail.	SPN Avail.	SUP Avail.	Min MW	Gen MW	REG MW Up	REG MW Down	SPN MW Up	SUP MW Up	Max MW	REG Max Up	REG Max Down	SPN Max	SUP Max	REG Price	SPN Price	SUP Price
1	1	1	1	YES	YES	NO	0.00	119.67	5.00	20.00	0.00	0.00	400.00	55.00	40.00	120.00	10.00	8.00	6.00	4.00
2	2	2	1	YES	YES	YES	0.00	60.35	75.00	60.00	0.00	0.00	400.00	75.00	60.00	50.00	48.00	7.50	4.00	5.20
3	3	3	1	NO	YES	YES	0.00	0.00	0.00	0.00	0.00	0.00	400.00	10.00	10.00	50.00	36.00	5.00	4.50	3.70



REG Avail.	SPN Avail.	SUP Avail.
YES	YES	NO
YES	YES	YES
NO	YES	YES

Reserve Control Availability



REG Max Up	REG Max Down	SPN Max	SUP Max	REG Price	SPN Price	SUP Price
55.00	40.00	120.00	0.00	8.00	6.00	5.00
75.00	60.00	50.00	48.00	7.50	4.00	5.20
10.00	10.00	50.00	36.00	5.00	4.50	3.70

Available MW and
prices of reserve controls

Example: Single Area System



- Control variables:
 - P_1, P_2, P_3 (Generator MW Output)
 - P_1^{RR+}, P_2^{RR+} (Gen Up Regulation Reserve)
 - P_1^{RR-}, P_2^{RR-} (Gen Down Regulation Reserve)
 - P_1^{SR}, P_2^{SR} (Gen Spinning Reserve)
 - P_2^{XR}, P_3^{XR} (Gen Supplemental Reserve)
 - A_1^{RR+} (Area Up Regulation Reserve)
 - A_1^{RR-} (Area Down Regulation Reserve)
 - A_1^{CR} (Area Contingency Reserve)
 - A_1^{OR} (Area Operation Reserve)

Example: Single Area System



- Constraints:

$$P_1 + P_2 + P_3 = P_{\text{LOAD}}$$

(Power Balance)

$$S_{jk} \leq S_{jk}^{\text{max}}$$

(Line Limits)

$$P_1^{RR+} + P_2^{RR+} = A_1^{RR+}$$

(RR+ Balance)

$$P_1^{RR-} + P_2^{RR-} = A_1^{RR-}$$

(RR- Balance)

$$P_1^{SR} + P_2^{SR} + P_2^{XR} + P_3^{SR} + P_3^{XR} = A_1^{CR}$$

(CR Balance)

$$P_1^{RR+} + P_1^{SR} + P_2^{RR+} + P_2^{SR} + P_2^{XR} + P_3^{SR} + P_3^{XR} = A_1^{OR}$$

(OR Balance)

$$P_i + P_i^{RR+} + P_i^{SR} + P_i^{XR} \leq P_i^{\text{max}}$$

(Gen Max Limits)

$$P_i^{\text{min}} \leq P_i - P_i^{RR-}$$

(Gen Min Limits)

OPF Reserves Solution



ID	Org. Value	Value
Gen 1 #1 MW Control	119.691	119.691
Gen 1 #1 REG MW Up Control	5.000	0.000
Gen 1 #1 REG MW Down Contr	20.000	20.000
Gen 1 #1 SPN MW Control	0.000	0.000
Gen 2 #1 MW Control	60.316	60.316
Gen 2 #1 REG MW Up Control	75.000	60.000
Gen 2 #1 REG MW Down Contr	60.000	60.000
Gen 2 #1 SPN MW Control	50.000	4.000
Gen 2 #1 SUP MW Control	0.000	0.000
Gen 3 #1 MW Control	0.000	0.000
Gen 3 #1 SPN MW Control	14.000	0.000
Gen 3 #1 SUP MW Control	36.000	36.000
Area Home OPR MW Control	0.000	100.000
Area Home REG MW Up Contr	80.000	60.000
Area Home REG MW Down Cor	80.000	80.000
Area Home CTG MW Control	100.000	40.000
Slack-Area Home	0.000	0.000
Slack-Area Home OPR	-180.000	0.000
Slack-Area Home REG Up	0.000	0.000
Slack-Area Home REG Down	0.000	0.000
Slack-Area Home CTG	0.000	0.000
Slack-Line 1 TO 3 CKT 1	0.000	0.000

Generator Energy, RR^+ , RR^- , SR
and XR control LP variables

Area Reserve LP Variables

Area Reserve Slack
Variables

Spinning Percent Constraint



- Some markets require the spinning reserve of a zone to be at least a certain percentage of the contingency reserve of that zone.
 - This ensures that enough “local” spinning reserve is available to respond to unexpected events.
- In example, the spinning percent constraint is:

$$P_1^{SR} + P_2^{SR} + P_3^{SR} \geq SR\% \times Z_1^{CR}$$

Spinning Percent Example



- Consider the 3-bus case with contingency reserves only.
- Since this case has only one area and one zone, which are the same, let us apply a 40% percent requirement to the Area Spinning Reserve.
- Assume the following generator data:

Gen Records						
	Spn Avail.	Sup Avail	SPN Max	SUP Max	SPN Price	SUP Price
Gen1	NO	NO	120	10	6	5
Gen2	YES	YES	30	48	4	3.2
Gen3	YES	YES	30	36	4.5	3.7

Spinning Percent Example

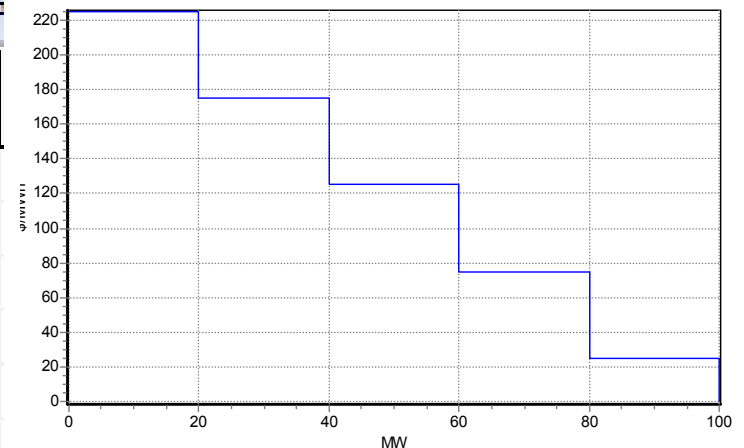


Solution
w/o SPN%
Enforced

Solution
with SPN%
Enforced

All LP Variables			
LP Basic Variables			
LP Basis Matrix			
Inverse of LP Basis Matrix			
Records			
Set			
Columns			
ID	Org. Value	Value	
1 Gen 1 #1 MW Control	119.729	119.729	
2 Gen 2 #1 MW Control	60.263	60.263	
3 Gen 2 #1 SPN MW Control	16.000	30.000	
4 Gen 2 #1 SUP MW Control	48.000	48.000	
5 Gen 3 #1 MW Control	0.000	0.000	
6 Gen 3 #1 SPN MW Control	0.000	10.000	
7 Gen 3 #1 SUP MW Control	36.000	12.000	
8 Area Home CTG MW Control	100.000	100.000	
9 Slack-Area Home	0.000	0.000	
10 Slack-Area Home CTG	0.000	0.000	
11 Slack-Line 1 TO 3 CKT 1	0.000	0.000	
12 Slack-Area Home SPN %	-24.000	0.000	

Contingency Reserve Requirement Curve



Spinning Percent Example

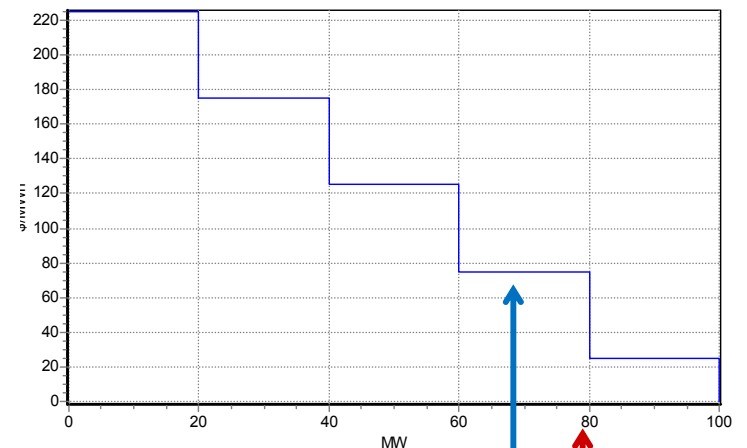


75%
Solution

90%
Solution

All LP Variables			
LP Basic Variables			
LP Basic Matrix			
Inverse of LP Ba			
Records Set Columns			
	ID	Org. Value	Value
1	Gen 1 #1 MW Control	119.729	119.729
2	Gen 2 #1 MW Control	60.263	60.263
3	Gen 2 #1 SPN MW Control	30.000	30.000
4	Gen 2 #1 SUP MW Control	20.000	6.667
5	Gen 3 #1 MW Control	0.000	0.000
6	Gen 3 #1 SPN MW Control	30.000	30.000
7	Gen 3 #1 SUP MW Control	0.000	0.000
8	Area Home CTG MW Control	80.000	66.667
9	Slack-Area Home	0.000	0.000
10	Slack-Area Home CTG	0.000	0.000
11	Slack-Line 1 TO 3 CKT 1	0.000	0.000
12	Slack-Area Home SPN %	-12.000	0.000

Contingency Reserve Requirement Curve





Multiple Area/Zone Case



- 2 Areas and 3 Zones
- 10-bus, 6-gen case
- Assume the following reserve constraint requirements:

	Enforce			Requirement		
	OPR	REG	CTG	OPR	REG	CTG
Area A	YES	YES		150 @ 400	80 @ 300	
Area B	YES	YES		90 @ 250	60 @ 150	
Zone 1			YES			65 @ 300
Zone 2			YES			45 @ 140
Zone 3			YES			35 @ 120

Area Results



Reserve Requirement Curves						
Operating	Regulating	Contingency	Results			
	REG +	REG--	SPN	SUP	CTG	OPR
Enforce	YES	YES	NO	NO	NO	YES
Cleared MW	80.00	80.00	65.00	5.00	70.00	150.00
Max Reserve MW	110.00	100.00	235.00	39.00	274.00	384.00
Hourly Cost \$/hr	860.00	860.00	845.00	42.50	887.50	1747.50
Price \$/MWh	143.00	12.00			-201.00	-131.00
Hourly Benefit \$/hr	24000.00	24000.00			0.00	60000.00

AREA A

Area A enforces Operation and Regulation Reserve. Prices are obtained for each one of these constraints. There is scarcity pricing so the price is given by the demand curve.

Reserve Requirement Curves						
Operating	Regulating	Contingency	Results			
	REG +	REG--	SPN	SUP	CTG	OPR
Enforce	YES	YES	NO	NO	NO	YES
Cleared MW	43.00	60.00	0.00	47.00	47.00	90.00
Max Reserve MW	170.00	100.00	295.00	157.00	452.00	622.00
Hourly Cost \$/hr	774.00	1140.00	0.00	331.50	331.50	1105.50
Price \$/MWh	150.00	24.00			0.00	-132.00
Hourly Benefit \$/hr	6450.00	9000.00			0.00	22500.00

AREA B

Area B enforces Operation and Contingency reserve. There is scarcity pricing.

Zone Results



Reserve Requirement Curves

Operating	Regulating	Contingency	Results				ZONE 1
	REG +	REG--	SPN	SUP	CTG	OPR	
Enforce	NO	NO	NO	NO	YES	NO	
Cleared MW	80.00	80.00	65.00	0.00	65.00	145.00	
Max Reserve MW	110.00	100.00	112.50	0.00	112.50	222.50	
Hourly Cost \$/hr	860.00	860.00	845.00	0.00	845.00	1705.00	
Price \$/MWh	0.00	0.00			144.00	0.00	
Hourly Benefit \$/hr	0.00	0.00			19500.00	0.00	

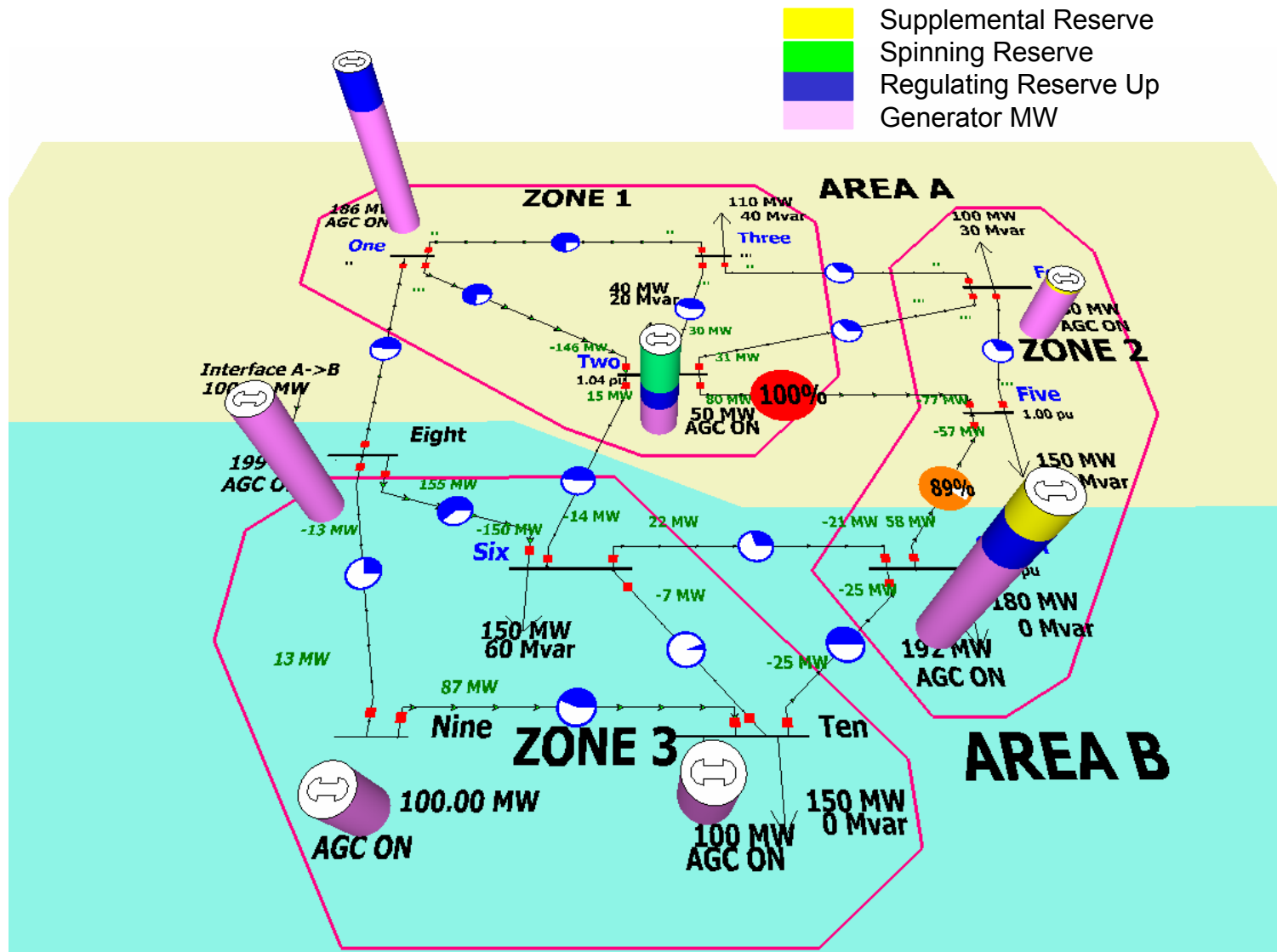
Reserve Requirement Curves

Operating	Regulating	Contingency	Results				ZONE 3
	REG +	REG--	SPN	SUP	CTG	OPR	
Enforce	NO	NO	NO	NO	YES	NO	
Cleared MW	0.00	10.00	0.00	7.00	7.00	7.00	
Max Reserve MW	90.00	50.00	295.00	113.00	408.00	498.00	
Hourly Cost \$/hr	0.00	240.00	0.00	31.50	31.50	31.50	
Price \$/MWh	0.00	0.00			136.50	0.00	
Hourly Benefit \$/hr	0.00	0.00			840.00	0.00	

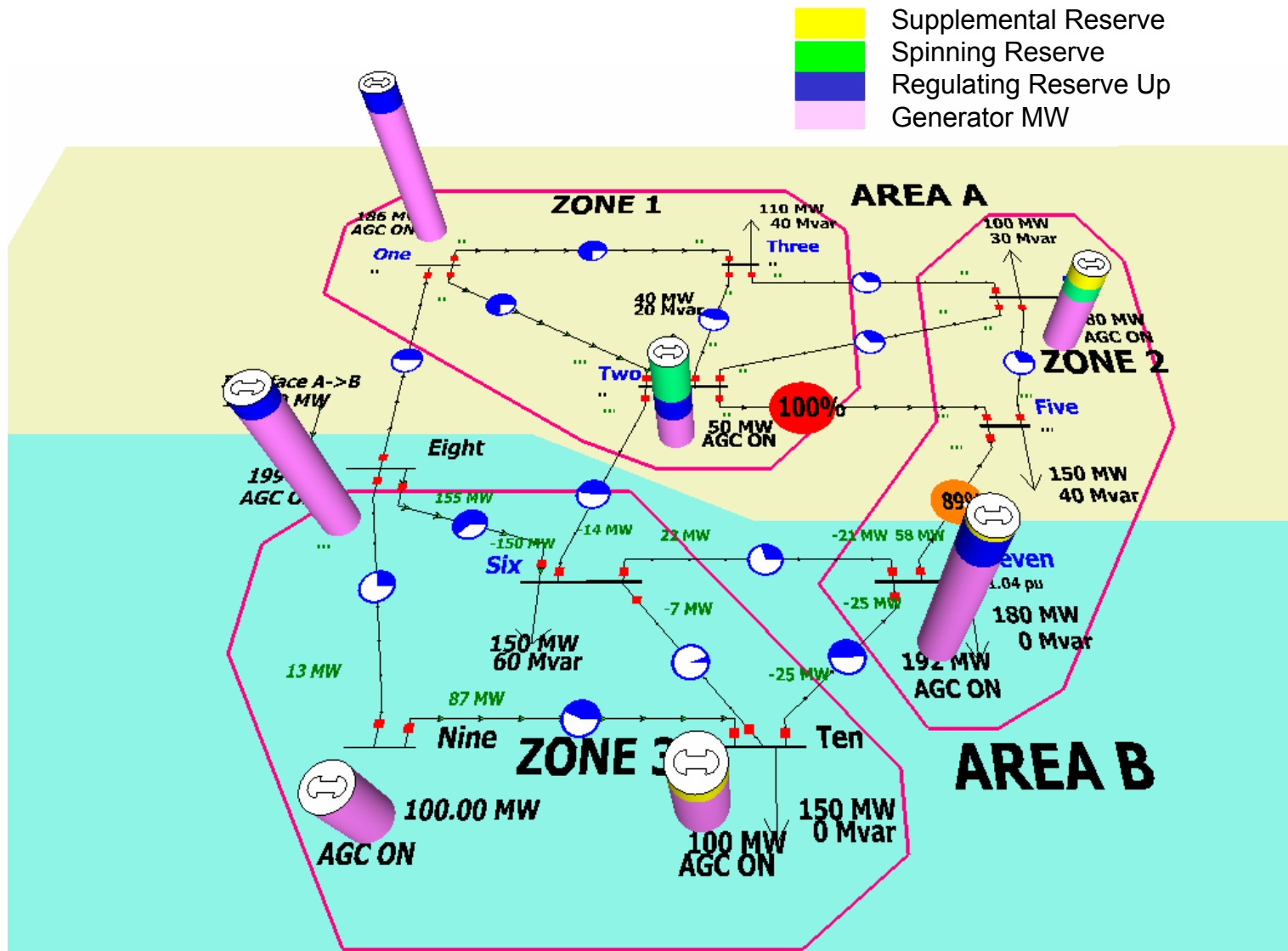
Reserve Requirement Curves

Operating	Regulating	Contingency	Results				ZONE 2
	REG +	REG--	SPN	SUP	CTG	OPR	
Enforce	NO	NO	NO	NO	YES	NO	
Cleared MW	43.00	50.00	0.00	45.00	45.00	88.00	
Max Reserve MW	80.00	50.00	122.50	83.00	205.50	285.50	
Hourly Cost \$/hr	774.00	900.00	0.00	342.50	342.50	1116.50	
Price \$/MWh	300.00	300.00			139.50	500.00	
Hourly Benefit \$/hr	0.00	0.00			6300.00	0.00	

Reserves 3-D Visualization



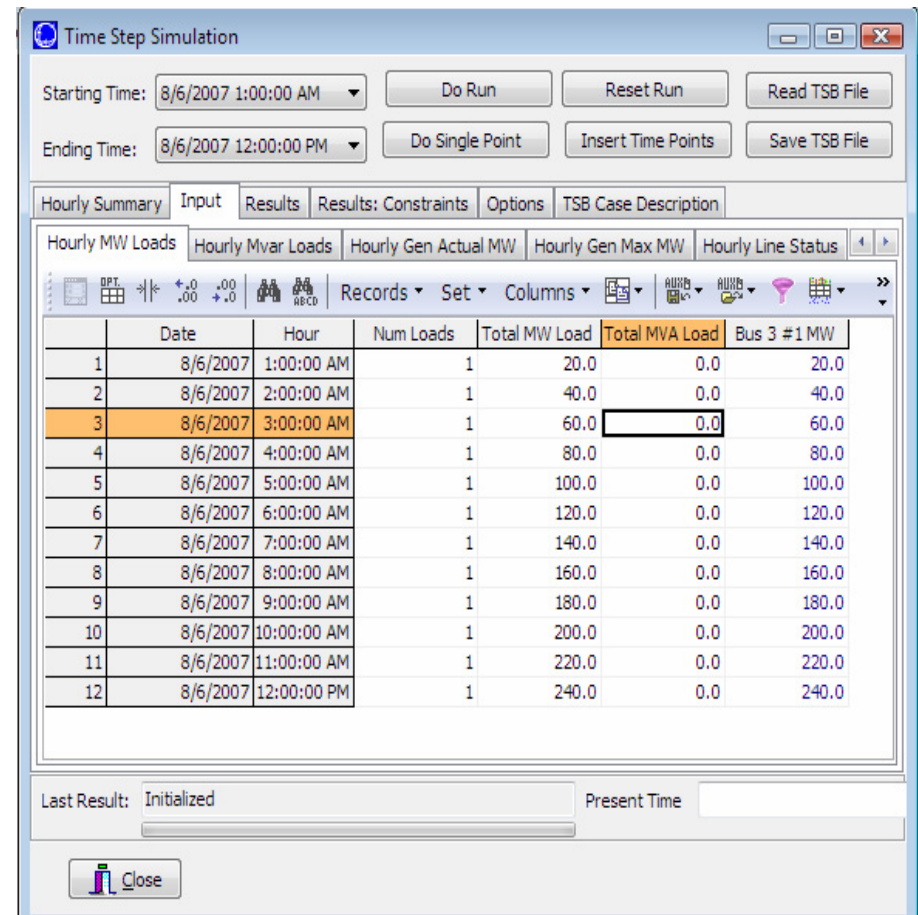
Impact of Available Reserve



Time Step Simulations



- Simulator can obtain hour-by-hour power flow and OPF solutions using the Time Step Simulation (TSS) Tool.
- TSS supports simulation of reserve markets



Time Step Simulations



- Generator Results:

Areas Buses Generators Injection Groups Interfaces Lines Owners Superareas Transformers Zones																		
	Date	Hour	Skip	1 #1 SPN	2 #1 SPN	3 #1 SPN	1 #1 Gen	2 #1 Gen	3 #1 Gen	1 #1 REG	2 #1 REG	3 #1 REG	1 #1 SPN	2 #1 SPN	3 #1 SPN	1 #1 SUP	2 #1 SUP	3 #1 SUP
				Price	Price	Price	MW	MW	MW	MW Up	MW Up	MW Up	MW Up	MW Up	MW Up	MW Up	MW Up	MW Up
1	8/6/2007	1:00:00 AM	NO	10.0	15.0	18.0	20.0	0.0	0.0	5.0	75.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
2	8/6/2007	2:00:00 AM	NO	10.0	15.0	18.0	40.0	0.0	0.0	40.0	0.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
3	8/6/2007	3:00:00 AM	NO	10.0	15.0	18.0	55.0	5.0	0.0	55.0	5.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
4	8/6/2007	4:00:00 AM	NO	10.0	15.0	18.0	55.0	25.0	0.0	55.0	25.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
5	8/6/2007	5:00:00 AM	NO	10.0	15.0	18.0	75.0	25.0	0.0	55.0	25.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
6	8/6/2007	6:00:00 AM	NO	10.0	15.0	18.0	95.0	25.0	0.0	55.0	25.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
7	8/6/2007	7:00:00 AM	NO	20.0	30.0	36.0	115.0	25.0	0.0	55.0	25.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
8	8/6/2007	8:00:00 AM	NO	20.0	30.0	36.0	135.0	25.0	0.0	55.0	25.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
9	8/6/2007	9:00:00 AM	NO	20.0	30.0	36.0	119.7	60.2	0.0	19.8	60.2	0.0	16.0	0.0	0.0	0.0	48.0	36.0
10	8/6/2007	10:00:00 AM	NO	20.0	30.0	36.0	99.9	99.9	0.3	5.0	75.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
11	8/6/2007	11:00:00 AM	NO	20.0	30.0	36.0	99.9	99.9	20.3	5.0	75.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0
12	8/6/2007	12:00:00 PM	NO	20.0	30.0	36.0	99.9	99.9	40.3	5.0	75.0	0.0	16.0	0.0	0.0	0.0	48.0	36.0

Verify
change in
Reserve Bid
Prices

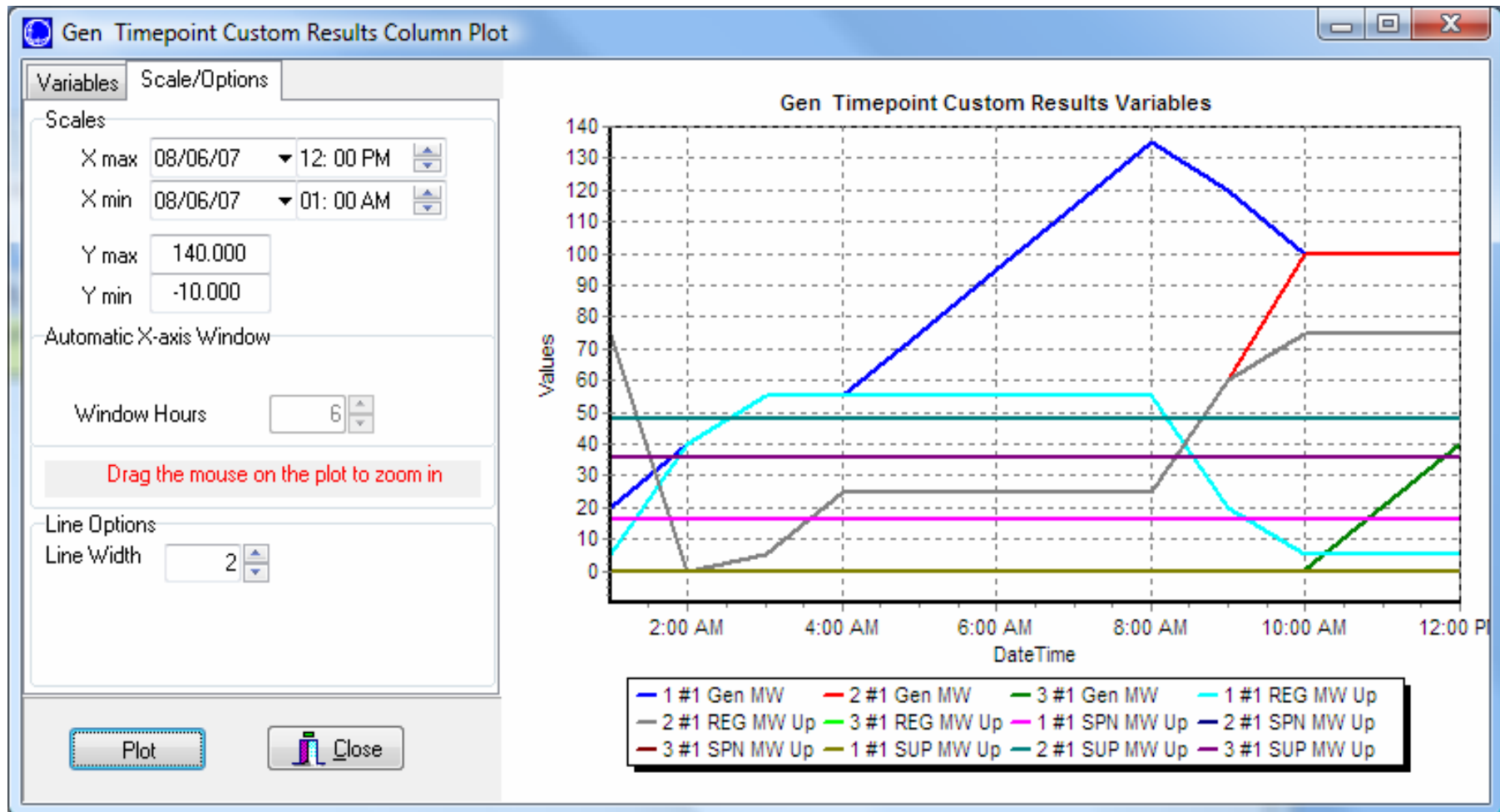
Generator
hourly cleared
energy output

Generator hourly
regulating reserve

Generator hourly
spinning reserve

Generator hourly
supplemental reserve

Time Step Simulations



Conclusions



- Reserve Markets capture the reliability aspects of power system resources by co-optimizing energy and reserve.
- Price signals determined in a Reserves Market capture the reliability requirements.
- Future enhancements include:
 - Detailed reserve price resolution
 - Tight integration with SCOPF
 - Detailed modeling of ramp constraints