Managing Voltage/stability Constraints at PJM

(FERC RTO/ISO Meeting on future market design and software enhancements)

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Transmission Operations Manual (M-03) Stability Criteria

- PJM RTO established stability limits for preventing electrical separation of a generating unit or a portion of the PJM RTO.
- PJM recognizes three types of stability:
  - **Steady State (voltage) Stability** - A gradual slow change to generation that is balanced by load.
  - **Transient Stability** - The ability of a generating unit or a group of generating units to maintain synchronism following a relatively severe and sudden system disturbance. The first few cycles are the most critical time period.
  - **Dynamic Stability** - The ability of a generating unit or a group of generating units to damp oscillations caused by relatively minor disturbances through the action of properly tuned control systems.
- ***PJM will operate the facilities that are under PJM operational control such that the PJM system will maintain stability following any single facility malfunction or failure.***

Today's operation/markets

PJM Voltage monitoring and control

- PJM operation utilizes the PJM EMS System to perform real-time contingency analysis as the primary operator decision tool to determine when and where reactive resources should be committed.
- PJM models reactive interfaces to address potential system-wide voltage problems due to power transfers.
  - Reactive Interfaces ensure sufficient wide-area reactive reserves to permit transfers.
- PJM EMS analyzes 8 IROL reactive interfaces every 4 minutes.
  - Transfer Limit Calculation (TLC) is used to calculate real-time transfer limits to prevent voltage stability problems.
  - Voltage Stability Analysis (VSA) is a tool to augment the current voltage stability analysis functions

PJM IROL Facilities

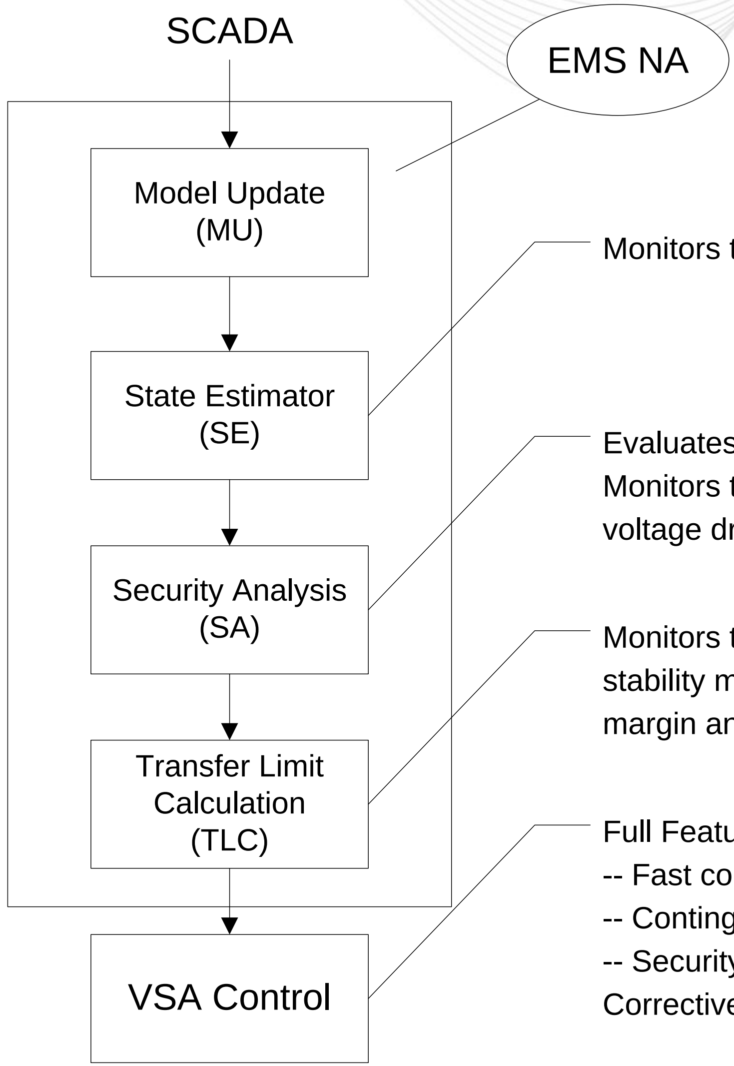
Out of the 10 IROL Facilities, 8 of them are Reactive Transfer Interfaces

Reactive Transfer Limit / Thermal Rating	Reportable IROL Violation
Eastern Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
Central Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
5004/5005 Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
Western Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
AP South Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
Bedington – Black Oak Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
AEP-DOM Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 Minutes (T_v)
Cleveland Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 Minutes (T_v)
Kammer 765/500kV Transformer Thermal Rating	Post-contingency Simulated Flows exceed the Load Dump Limit for 30 Minutes (T_v)
Belmont #5 765/500 kV Transformer Thermal Rating	Post-contingency Simulated Flows exceed the Load Dump Limit for 30 Minutes (T_v)

PJM Voltage monitoring and control

- PJM EMS model contains 14,500 buses, 13,000 lines and 6,500 transformers. PJM Security Analysis (SA) evaluates approximately 5,000 contingencies and monitors post-contingency voltages on about 3,000 buses every one minute.
  - PJM EMS analyzes actual and post-contingency high/low voltages
  - PJM EMS analyzes post-contingency voltage drops
- PJM dispatch utilizes the PJM Security Constrained Economic Dispatch (SCED) system to assist operators in making cost-effective decisions to control projected constraints and Reactive Interfaces.
- PJM Real-Time Market uses the same SCED reactive interface constraints in calculating the real-time LMP.

PJM Real-time Voltage Monitoring and Control



Monitors the actual voltage violations

Evaluates more than 2000 contingencies
Monitors the post-contingency voltage limit / voltage drop violations

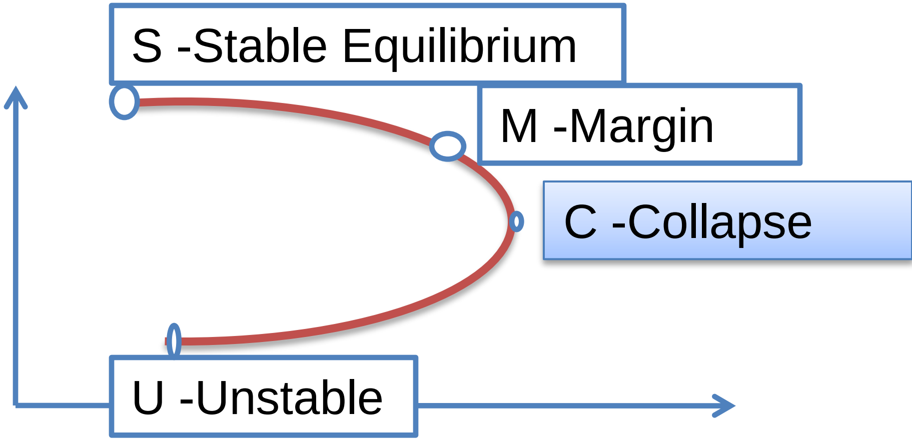
Monitors the pre-/post-contingency voltage stability margin in term of the load increase margin and interface increase margin

Full Feature online voltage stability analysis
-- Fast contingency screen
-- Contingency analysis
-- Security Enhancement (Preventive and Corrective Control Calculation)

TLC Application

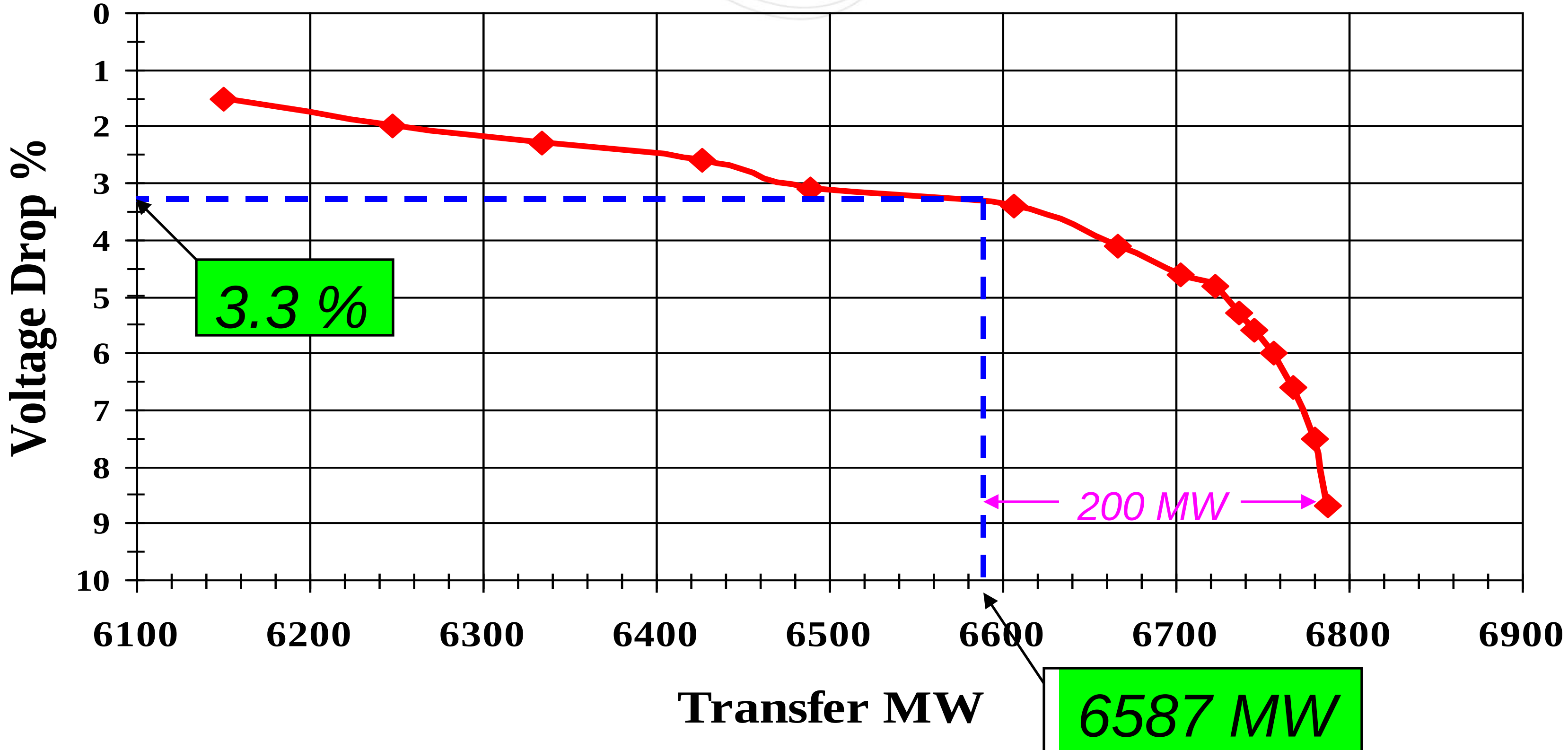
Determines the maximum pre- and post-contingency MW transfer interface flow under the of constraints of

- **Voltage stability (collapse)**
- **Voltage drop limits**
- **Voltage low limits**



Reactive Transfer Interface Limit Diagram

Transfer MW	6150	6247	6334	6426	6489	6606	6666	6702	6722	6736	6745	6756	6768	6780	6787
Volt. Drop (%)	1.5	2	2.3	2.6	3.1	3.4	4.1	4.6	4.8	5.3	5.6	6	6.6	7.5	8.7



5% VOLTAGE DROP POINT : 6728 MW   LAST SOLUTION POINT: 6787 MW

SAFETY MARGIN : 200 MW

TRANSFER LEVEL WITH MARGIN : 6787 - 200 = 6587 MW

Voltage Stability Analysis (VSA)

VSA is a tool that will be used to augment the function of TLC by providing control suggestions in three categories:

- Non cost control
  - Switch on/off capacitors and reactors. (VSA does not know what capacitors are available)
  - Adjust LTC and PAR tap positions.
  - Adjust generator var output.
- Off cost control (VSA does not consider cost)
  - Redispatch generator MW output.
- Load shedding
  - Provide load shedding suggestion based on buses and TOs.

VSA Control Target

The objective of VSA control calculation is to find the most efficient way to increase the collapse (load) margin.

Example: <u>Increase Load Margin</u>

Interface: East

Limiting Contingency: Salem 1 GEN

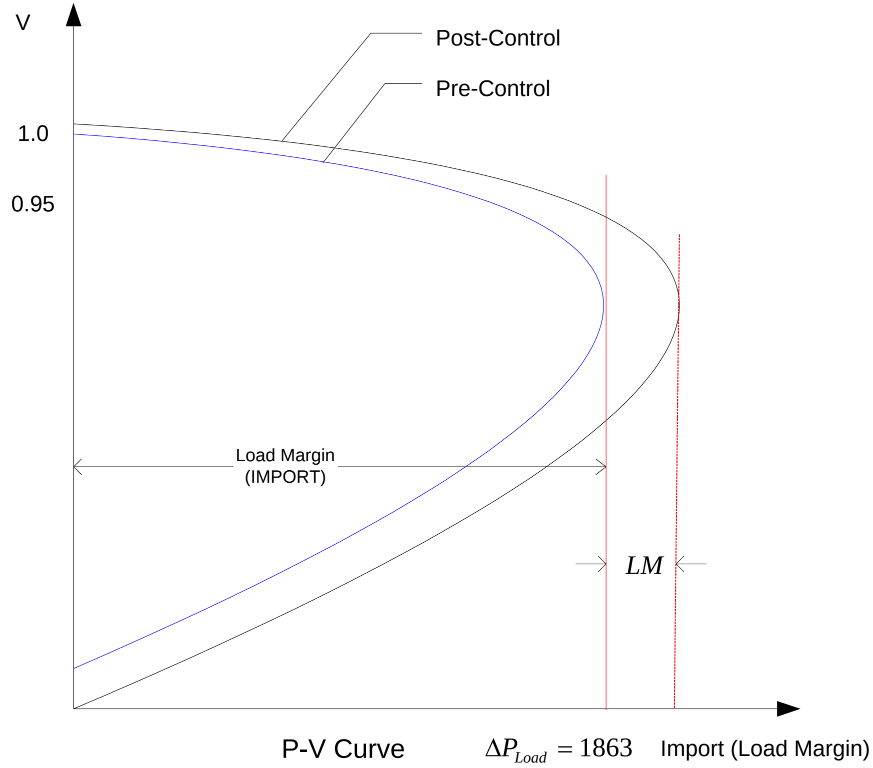
Pre-Control Load Margin: 1863 MW

VSA Control Solution:

Increase BRANDONS 24.0 kV

Voltage Setting: 24.2 kV→24.7 kV

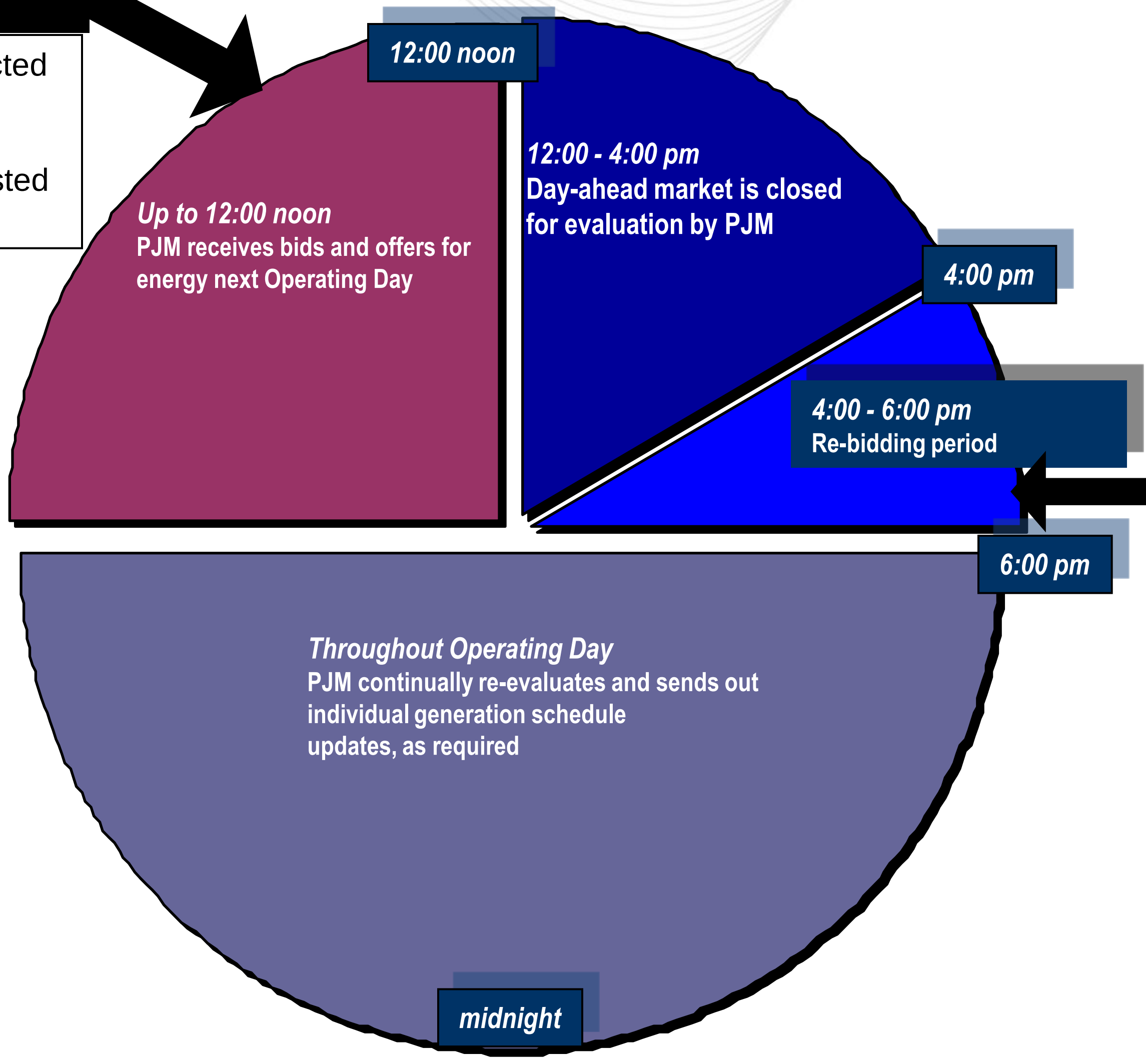
Post-Control Load Margin: 1883 MW



Reactive Transfer Constraints in Day-Ahead Market

Reliability Engineer Input

RE provides projected Reactive Interface Limits (Peak and Valley) and forecasted constraints



Reliability Engineer Input

RE commits additional Generation based on Forecasted constraints

Local interfaces and thermal surrogates

- In additional to the system-wide reactive transfer interfaces, PJM also models the following (when possible) for local voltage problems :
  1. Local interface – when a complete circle can be drawn around the load pocket where the voltage problem is observed.
  2. Thermal surrogate – when the raise-help generation of the thermal surrogate constraint is identical to the MW generation necessary to provide voltage support. There should be no lower-help generation for the thermal surrogate.
- The objective is to provide the correct LMP signals for the voltage support actions in the Real-Time Market and the DA Market when appropriate.

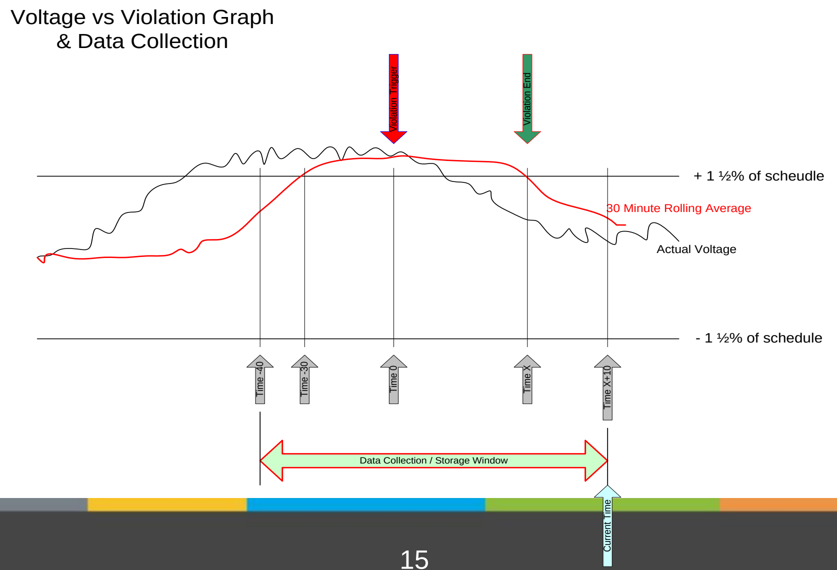
PJM Default Generator Voltage Schedules								
Voltage Level (kV)	765	500	345	230	138	115	69	66
Schedule	760	525	350	235	139.5	117.0	70.0	67.0
Bandwidth	+/-10.0	+/- 8.0	+/- 7.0	+/- 4.0	+/- 3.5	+/- 3.0	+/- 2.0	+/- 1.5

- Default voltage schedules for generators
  - TO can provide a different voltage schedule
- TO and/or PJM can direct generator to deviate from voltage schedule based on system conditions
- PJM can direct the switching of reactive control devices to maintain voltages as system conditions dictate.
- Only PJM can direct a generator to adjust voltage schedule if such adjustment impacts the units MW output

Generation Performance Monitor (GPM)

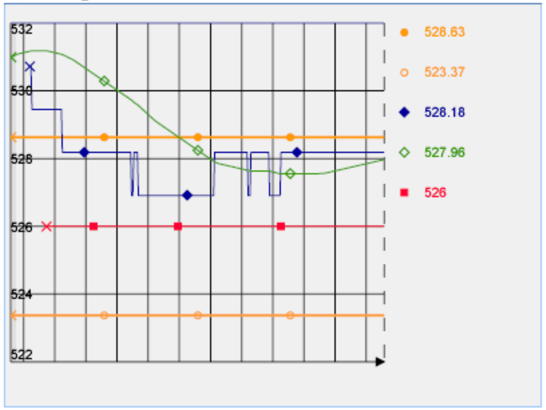
- Track MW/MVAR Generation Performance (MW phase II)
- Provide real-time visualization to PJM, Transmission Owner, MOC, and Generators.
- Enhance real-time coordination between PJM, TO, and GO.
- Provide feedback loop to enhance quality of real-time data.

Note 1: PJM uses the Generation Performance Monitor (GPM) to track a generators ability to follow a designated voltage schedule. GPM compares the integrated 30 minute average to the designated voltage schedule and flags performance outside a threshold. Generation Owners are expected to resolve performance issues within 30 minutes through generator modifications or updating reactive D-curve and/or voltage regulator status within eDart.



Generation Performance Monitor (GPM)

Voltage Performance



Bus Status

Schedule	Status
Export to Excel	

Units

Unit	On/Off	Lag/Lead	MVAR
	●		View
	●		View
Export to Excel			

Legend

Violation	Violation
Warning	Warning
●	Unit On
○	Unit Off
	Voltage Schedule Upper Limit
	Voltage Schedule Lower Limit
	Real-time KV
	30 Minute Average KV
	Voltage Schedule
Lag Limit	Unit has reached upper MVAR limit
Lead Limit	Unit has reached lower MVAR limit

All Data is in Eastern Prevailing Time.

PJM EMS – MVAR Reserves Summary

SE▸RT System Summaries▸PJM Reactive Reserve Summary▸PJM Reactive Reserve

Units With Possible Reduced MVAR Capability | Unit Reserve MVAR | Shunt Reserve MVAR | PJM Reactive Reserve

PJM Reactive Reserve Summary (POOL)

1 - 16 of 16

Pool	Actual Unit MVAR	Lagging Reserve MVAR	Shunt Reserve MVAR
PJM	4379	32509	44444
ECAR	1915	17594	4651
ILL_EQ	1591	6519	293
WIS_EQ	535	4186	394
SPP_EQ	595	6084	935
NYPP	217	7508	5540
NEPX	671	14651	243
OH	-474	16954	1076
WEST	298	8611	1049
CPL	519	1452	1250
CPLW	28	175	0
DUKE	1350	4547	571
ENTRGY	141	4053	52
SC	13	572	0
SOUTHQ	131	10374	374
TVA	-80	3574	397

PJM Reactive Reserve Summary (ZONE)

1 - 25 of 81

Zone	Actual Unit MVAR	Lagging Reserve MVAR	Shunt Reserve MVAR
PS-N	294	857	2145
PS-S	850	346	504
LINVFT	-60	0	75
PE	407	2758	4000
PL	503	846	1913
UGI	0	0	30
BC	296	1270	1258
JC-N	0	8	895
JC-S	65	464	852
ME	221	776	930
PN	212	2238	733
PEP	48	886	1097
AE	75	395	1111
DPL	-233	953	905
RECO	0	0	32
APSS	107	2427	2182
COMED	1810	5002	6369
AEP	-866	7418	11433
AES	0	0	0
BELV	5	15	0
BLUR	0	0	0
BRISTO	0	0	0
CNSTEL	0	0	0
COLUMB	0	0	0
CTYCOL	0	0	0

Executed At:08:16:06 SE Status:DONE

PJM Transient /Dynamic stability concerns

- 17 transient/dynamic stability areas are identified.
- Most of them are transient stability concerns related to generating units.
- There is one transient stability driven interface: Northeast PA (NEPA) Transfer (Export) interface.
  - The interface encircles a group of generation in northeast PA. No N-1 stability issue when all facilities are in service.
  - Based on generation and transmission facilities out of service, NEPA transfer export limit is adjusted. Loss of rotational inertia and voltage support reduces system stability.
  - Unit/Facility subtractors are pre-calculated from off-line planning model.
  - If it is active in real-time, NEPA interface will impact the Real-Time Market. It can also be included in the Day-Ahead Market.

Future Enhancement Opportunities

1. **Transient Stability Analysis & Control (TSA)**
2. **Optimal Dynamic Voltage Control System (AVC)**
3. **Transmission outage analysis automation**

Transient Stability Analysis & Control (TSA)

- Monitor and determine transient stability of the PJM system subject to 3000 pre-defined contingencies.

- Compute stability limits by using real time data input and real time network models.
    - Replace the current computation process which uses the tables generated by off-line planning model years ago.

- Provide recommended transient stability control measures required to prevent the system from losing transient stability for potentially unstable system condition and/or contingencies

Real time model:

- Real time network model (14,500 bus) and State Estimation solution
- Operation dynamic generator models (2600 generators)
- Contingency models (Each contingency contains common fault and switching events (circuit tripping, generator tripping, shunt switching, etc.))

Real input data (Interface with PJM EMS**):**

- SE solution with network model in PSSE format
- Dynamic data for each generator
- Contingency data
    - Three Phase Fault
    - Unbalanced Fault (forming Seq. network models on-line)
- Stability limit data

Transient Stability Analysis & Control (TSA)

- Completed Stability Areas Study with the following TOs:
  - **PSEG:** Artificial Island Stability Benchmarking Analysis
Internal and External Model Impact
  - **DOM:** Dom's Stability Areas Study
  - **PPL:** Initial NEPA Interface Study
  - **ComEd** Reviewing currently

- Validation of TSA software
  - Compared with the PSSE transient program by using same cases
  - The simulation results of TSA and PSSE were same

- Validation of TSA models (Real time network model, Dynamic generator models and contingency models)
  - TSA results were consistent with Planning Studies
  - Impact of Using PJM EMS or MMWG Internal Model is negligible
  - Impact of Using PJM EMS or MMWG External Model is negligible

- **Target TSA real-time implementation in 4th Quarter of 2012.**

Current approach of determination of the voltage schedule in PJM system:

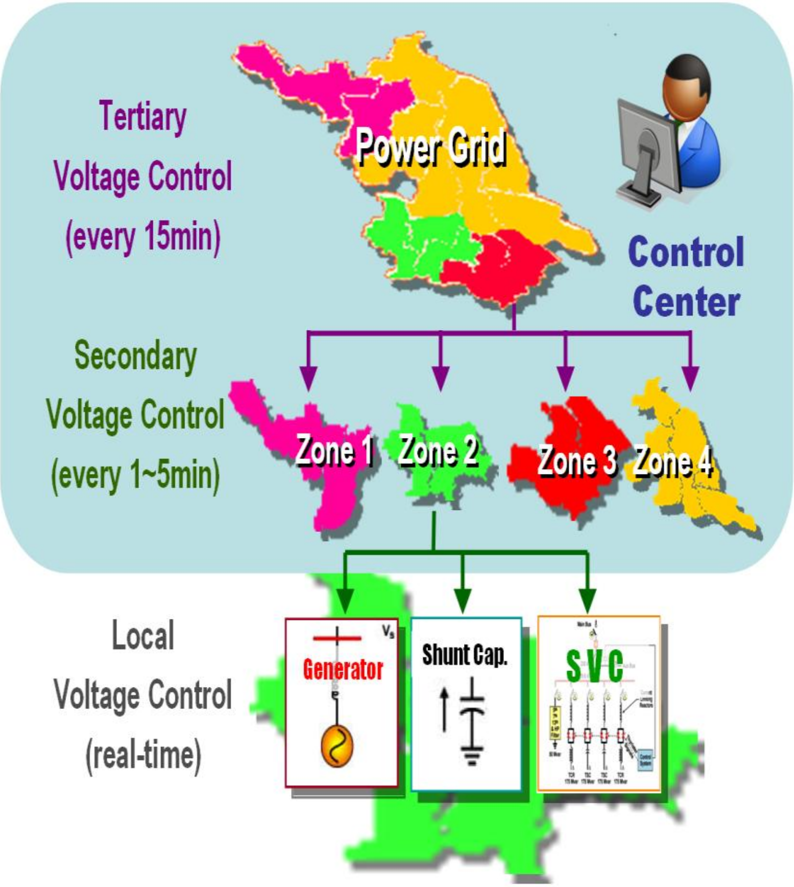
1. Each TO determines their own area voltage schedule based on their Power Study and experiences. If TO has no voltage schedule for the area, PJM offer a default voltage schedule.
2. This approach lacks of system-wide coordination to determine PJM system voltage schedule.
3. Potentially, area voltages may not follow the schedules very well and lead to unexpected flow of reactive power.

Optimal Dynamic Voltage Control System (AVC)

The Proposed Solution will:

1. Determine voltage schedule and mvar control system-wide
2. Combine optimization and traditional approach (rule based)
3. Achieve the objective of minimum of system loss, or maximum of MW transfer
4. Improve system voltage profile, real time security and reliability.
5. Enhance the transfer interface utilization and reduce congestion cost. Provide positive impacts to both Real-time and Day-Ahead Markets.

Optimal Dynamic Voltage Control System ---Two Levels of Optimizations



1. TVC is the tertiary voltage control level, responsible for economy (reduction in system loss), and is a slow control. TVC is a optimal solution to set the voltage setting (Vp1 to Vpn) for the pilot (key) buses in the system.

2. SVC is the secondary voltage control level, responsible for quality and security, and is a fast control. SVC is a optimal solution to set voltage schedule (Vg) for each generator in the system.

Optimal Dynamic Voltage Control System (AVC)

1. Average reduction of transmission system loss: 1.0688 %
   - For the example of Monday, 21MW, Save energy about 184 million kWh/year
   - If electricity rate is $0.08/kWh, Save money: $ 14.7 million/year

2. Average increase of system MVAR reserve: about 1 %

PJM has completed the proof of concept evaluation of AVC. The next step will be sending the AVC voltage schedules to TOs through GPM for their evaluation.

Transmission outage analysis automation

- Currently the transmission outage analysis team/Reliability Engineer studies the next-day transmission outages for two specific hours. Thus, only two sets of projected reactive transfer limits are provided to the DA Market Operator.
  - Valley set : to be used during the midnight hours
  - Peak set : to be used for all other hours.

- There is an on-going outage analysis automation effort which will enable the team to perform transmission outages for multiple hours of the day.
  - More sets of projected reactive transfer limits can be made available to the DA Market. Potentially, there can be 24 hourly sets for the DA Market.

Questions

Appendix

Voltage Operating Criteria

Voltage Limit Exceeded	If Actual voltage limits are violated	Time to correct (minutes)
High Voltage	Use all effective non-cost and off-cost actions.	Immediate
Normal Low	Use all effective non-cost actions, off-cost actions, and emergency procedures except load dump.	15 minutes
Emergency Low	All of the above plus, shed load if voltages are decaying.	5 minutes
Load Dump Low	All of the above plus, shed load if analysis indicates the potential for a voltage collapse.	Immediate
Transfer Limit Warning Point (95%)	Use all effective non-cost actions. Prepare for off-cost actions. Prepare for emergency procedures except load dump.	Not applicable
Transfer Limit	All of the above, plus shed load if analysis indicates the potential for a voltage collapse.	15 minutes or less depending on the severity

Legend
NON-COST
OFF-COST
LOAD SHEDDING

Voltage Limit Exceeded	If post contingency simulated voltage limits are violated	Time to correct (minutes)
High Voltage	Use all effective non-cost actions.	30 minutes
Normal Low	Use all effective non-cost actions.	Not applicable
Emergency Low	Use all effective non-cost actions, off-cost actions, and emergency procedures except load dump.	15 minutes
Load Dump Low	All of the above plus, shed load if analysis indicates the potential for a voltage collapse.	5 minutes
Voltage Drop Warning	Use all effective non-cost actions.	Not applicable
Voltage Drop Violation	All effective non-cost and off-cost actions plus, shed load if analysis indicates the potential for a voltage collapse.	15 minutes

PJM BASE LINE VOLTAGE LIMITS

PJM Base Line Voltage Limits								
Limit	765 kV	500 kV	345 kV	230 kV	138 kV	115 kV	69 kV	34 kV
High	803.2 (1.05)	550 (1.10)	362 (1.05)	242 (1.05)	145 (1.05)	121 (1.05)	72.5 (1.05)	37.4 (1.10)
Normal Low	726.8 (.95)	500 (1.00)	328 (.95)	219 (.95)	131 (.95)	109 (.95)	65.5 (.95)	31.3 (.92)
Emergency Low*	703.8 (.92)	485 (.97)	317 (.92)	212 (.92)	127 (.92)	106 (.92)	63.5 (.92)	30.6 (.90)
Load Dump*	688.5 (.90)	475 (.95)	310 (.90)	207 (.90)	124 (.90)	103 (.90)	62 (.90)	0.0
Voltage Drop Warning*	2.5%	2.5%	4-6%	4-6%	4-6%	4-6%	4-6%	5%
Voltage Drop Violation*	5-8%**	5-8%**	5-8%	5-8%	5-10%	5-10%	5-10%	8%

* Refer to PJM Manual for Emergency Procedures (M-13)

** The voltage drop violation percentage may vary dependent on PJM analysis.

Non-cost Responses to Voltage Violations

- Switch capacitors in/out of service
- Switch reactors out/in to service
- Adjust output of Static Var Compensators
- Adjust generator excitation
- Adjust transformer tap position
- Switch lines or cables out of service
  - Pre-studied for high voltage control

Off-cost Responses to Voltage Violations

- Curtail Non-firm transactions NOT willing to pay congestion prior to redispatch of generation
- Redispatch generation
- Dispatch synchronous condensers
- Initiate ALL Emergency Procedures EXCEPT Load Shed
  - Including Manual Load Dump Warning

Load Shedding Response to Voltage Violations

- Determine if load shedding is required
  - **All other control actions have been exhausted**
  - **Under emergency low or load dump low voltage limit on an actual basis or Reactive Transfer Limit to avoid voltage collapse**
  - **Under load dump low voltage limit or voltage drop violation limit on contingency basis <u>if</u> analysis indicates potential for voltage collapse**
- Determine amount of load shed necessary
- Shed load proportional among Native Load customers, Network customers and firm point-point service

PJM Transient/Dynamic Stability Procedures

Stability Procedures from M-03	Type of Operating Procedure	Transmission Operations Manual Section Ref
Conesville 345 kV Plant Operating Guidelines	Unit Stability	Section 5 - AEP
Rockport Operating Guide	Unit Stability	Section 5 – AEP
Smith Mountain 138 kV station Stability	Stability	Section 5 – AEP
Gavin – Mountaineer Stability	Stability	Section 5 – AEP
Kincaid Stability Trip Scheme	Unit Stability	Section 5 ComEd
Powerton Stability Limitations	Unit Stability	Section 5 ComEd
Quad cities and Cordova Stability Limitations	Unit Stability	Section 5 ComEd
Byron and Lee County Operating Guides	Unit Stability	Section 5 ComEd
University Park North Energy Center Restriction	Unit Stability	Section 5 ComEd
Elgin Energy Center Stability Bus Tie Scheme	Unit Stability	Section 5 ComEd
Conemaugh Unit Stability – PN	Stability	Section 5 Penelec
Conemaugh #2 Unit Stability Trip Scheme-Conemaugh-Juniata 500 kV Outage - PN	Stability	Section 5 Penelec

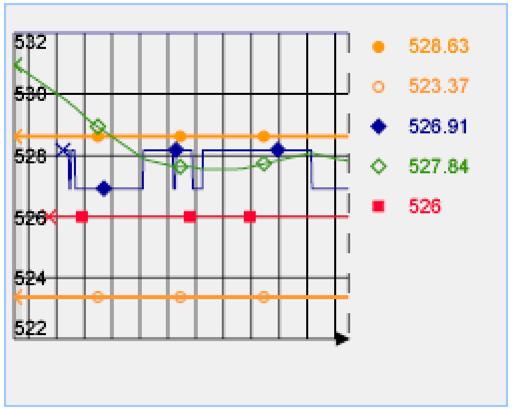
PJM Transient/Dynamic Stability Procedures

Stability Procedures from M-03	Type of Operating Procedure	Transmission Operations Manual Section Ref
Seneca Stability - PN	Stabillity	Section 5 Penelec
Northeast PA (NEPA) Transfer Limit	Stability	Section 5 PPL
Potomac River Station Operation	Stability	Section 5 PEPCO
PSE&G Artificial Island Stability	Stability	Section 5 PSE&G
Ronco Stability	Generator Stability	Section 5 - AP

Generation Performance Monitor (GPM)

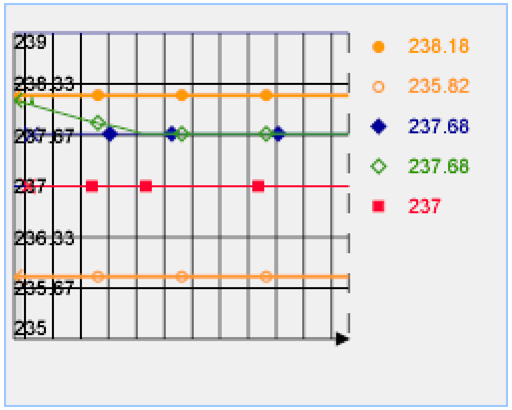
Schedule	Status
500	

Export to Excel



Schedule	Status
230	

Export to Excel



Schedule	Status
345	

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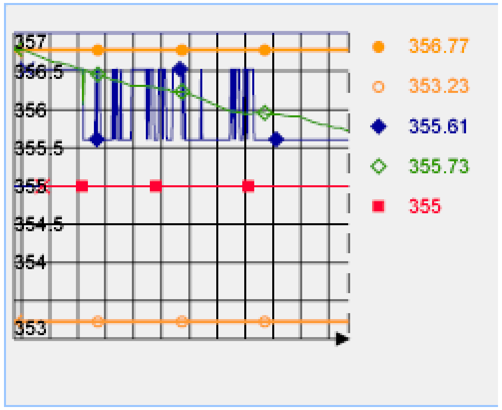

Schedule	Status
500	

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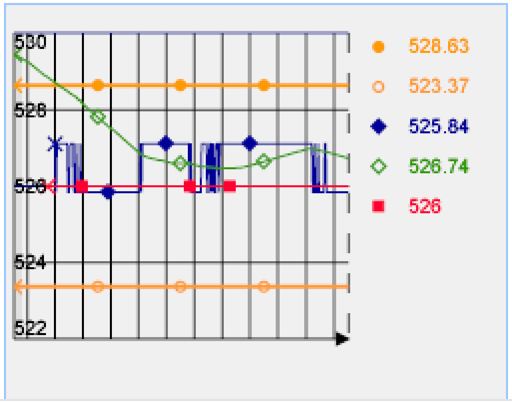

Schedule	Status
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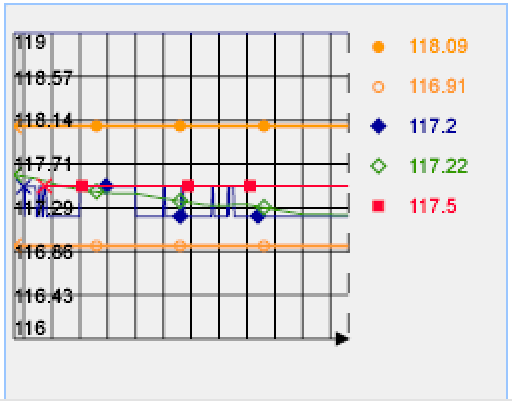
Export to Excel



Schedule	Status
30	

Export to Excel