Industry Webinar
Reactive Power Planning

NERC System Analysis and Modeling Subcommittee (SAMS)
March 2017
Webinar Topics

• **Reliability Guideline on Reactive Power Planning**

• **Webinar Topics**
  - Fundamentals of reactive power planning
  - Relevant FERC Orders and NERC Reliability Standards
  - Reactive Power Analysis Timeframes
  - Reactive Power Assessment Techniques
  - Reactive Power Coordination
  - Industry Practices

• **Goals:**
  - Share takeaways from Reliability Guideline on Reactive Power Planning
  - Provide examples of reactive power planning practices
  - Update industry on efforts underway in the NERC SAMS
• **SAMS webpage**

• Purpose: support development and advancement of system analysis and modeling tools, techniques, and capabilities in planning for the reliability and operational security of the BPS

• Key Focus Areas
  - Develop technical reference materials
  - Identify emerging issues and evaluate new analysis techniques
  - Promote coordination between NERC Regions
  - Share lessons learned within industry
  - Support improvement of interconnection-wide models
  - Coordinate with industry experts and industry groups

• Chair: Michael Lombardi, NPCC
• Ryan Quint – *NERC*
• Bill Harm – *PJM*
• Rich Kowalski – *ISO-NE*
• John Simonelli – *ISO-NE*
• Gary Brownfield – *Ameren*
• Jose Conto – *ERCOT*
• Durgesh Manjure – *MISO*
Background, Relevant FERC Orders, and NERC Reliability Standards
• **NERC Project 2008-01 Voltage and Reactive Control**
  - Initiated to address FERC Order 693 (¶ 1860-1880)
• **Documents produced:**
  - Reactive Support and Control White Paper – NERC TIS (approved 6/09)
  - SAR to modify VAR-001 and VAR-002 standards
• **Additional recommendations to address planning horizon issues forwarded to the TPL SDT**
• Ensures that voltage levels, reactive flows, and reactive resources are monitored, controlled, and maintained within limits in real-time to protect equipment and reliable operation

• TOPs:
  ▪ Specify system-wide voltage schedule
  ▪ Schedule sufficient reactive resources to regulate voltage for normal and contingency conditions
  ▪ Operate and direct operation of devices to regulate voltage and reactive power flows
  ▪ Develop criteria for exemptions to automatic voltage control mode
  ▪ Specify voltage or reactive schedule for generation
• Ensures generators provide reactive support and voltage control in order to protect equipment and maintain reliable operation

• GOPs:
  - Operate generators connected to transmission system in automatic voltage control mode, or other mode as instructed by TOP
  - Maintain TOP’s voltage or reactive schedule, unless GOP is exempted
  - Notify TOP of any changes in status of voltage control
  - Notify TOP of changes in reactive capability
• Reactive planning is critical component of TPL standard

• PC establishes:
  ▪ Acceptable steady-state voltage limits
  ▪ Post-contingency voltage deviations
  ▪ Transient voltage response

• PC considers voltage:
  ▪ As it affects generator tripping
  ▪ As it affects instability, uncontrolled separation, and Cascading

• Consideration of dynamic load modeling, induction motor load behavior
• Order 827 eliminated exemptions for wind generators from the requirement to provide reactive power
• All newly interconnecting non-synchronous resources will be required to provide reactive power as a condition of interconnection
• Key distinctions:
  ▪ Power factor range
  ▪ Point of measurement
  ▪ Dynamic reactive capability
  ▪ Active power threshold
Reactive Power Fundamentals

What is reactive power?
Why is reactive power important?
Dynamic vs. Static Resources

• Dynamic reactive resources
  ▪ Adjust reactive power output automatically in real-time over a continuous range within a specified voltage bandwidth in response to grid voltage changes
  ▪ Maintain set point voltage or operate in voltage droop mode
  ▪ Many are power electronics based
  ▪ Can respond within electrical cycles using fast-acting controls

• Static reactive resources
  ▪ Fixed reactive power output at nominal voltage
  ▪ Output varies according to voltage squared
  ▪ Generally switched in and out of service based on system conditions
  ▪ Switching action can be manual or automatic
Reactive Power Resources: Fixed and Switched Shunts
Reactive Power Resources: Transmission Circuits

$\text{VAR}_{\text{produced}} = \frac{V^2}{X_C}$

$\text{VAR}_{\text{consumed}} = I^2 X_L$
Reactive Power Resources: Synchronous Generators
Reactive Power Resources: Synchronous Condensers

(a) Overexcited Synchronous Condenser

(b) Underexcited Synchronous Condenser
Reactive Power Resources: FACTS Devices

- FACTS Devices
  - STATCOM
  - SVC

Diagram showing the components of FACTS devices, including Converter, DC Source, TCR, and TSC.
Reactive Power Resources: VSC HVDC

Diagram showing components of VSC HVDC, including Phase Reactor, IGBTs, DC Sources, and Filters.
Reactive Power Analysis Timeframes
Steady-State Pre-Contingency

• Voltages maintained within ranges on BPS
• Elements maintaining terminal voltage set point value
• Manual readjustment of elements throughout day
  ▪ Shunt capacitor switching, load tap changing, etc.
• Automatic devices continuously operating to maintain steady voltage profile
• Voltage should remain within limits for credible contingencies
Mid-Term Dynamics

- Dampening oscillations, transitory state
- Returning to a new steady-state condition
- Dynamic resources adjusting
- Generator controls responding
- May consider load tap changing based on control delays
- Excitation limiters considered
- Slower manual controls not considered
Long-Term Dynamics: Post-Contingency

• New equilibrium following contingency
• Assess voltage stability and security at this new point
• All automatic controls responded
  ▪ Voltage controls, power factor, governor response, FACTS, AGC, etc.
• Automatic tap changes and switched shunts acting
• Manual controls not considered in this timeframe
  ▪ Manual load tap changing, manual capacitor switching, load shedding
• Assumes operators not acting this quickly
• All controls considered
• Applicable for associated emergency ratings
• Return to within acceptable operating limits
• All manual readjustments and automatic controls considered
  ▪ Generation re-dispatch
  ▪ Transformer tap changing
  ▪ Manual and automatic capacitor switching
  ▪ Fast- or slow-acting RAS
  ▪ Other system readjustments
  ▪ Transmission element switching (e.g., cables)
Reactive Power Assessment Techniques
• Voltage criteria testing
  ▪ Voltage/reactive contingencies could be different than typical thermal analysis contingencies
  ▪ Voltage drop criteria: difference between pre- and post-contingency steady-state voltages (e.g., 2-6% threshold)
  ▪ Absolute voltage criteria: acceptable lower and upper bus voltage magnitude limits (e.g., 0.95 pu and 1.05 pu)

• Voltage instability will not have converged power flow solution in post-contingency state
  ▪ Tool will generate erroneous conditions (flows, voltages, etc.)
  ▪ Post-contingency case should not be used to assess these conditions
  ▪ Use engineering judgment to study conditions leading up to collapse
Source: ©CIGRE, 1986
PV Analysis

The diagram illustrates the concept of Pre-contingency and Post-contingency analysis in the context of power system reliability. It depicts the voltage magnitude (V) as a function of power (P), with two key points:

- **Pre-contingency** and **Post-contingency** curves showing the voltage before and after a contingency event.
- **Total Transfer Capability (TTC)** and **Maximum Power Transfer** points indicating the limits of power that can be transferred in the system.
- The **knee/nose of PV Curve** is a critical point that marks the transition between the two curves.

The margin is highlighted as the difference between these two points, indicating the system's ability to withstand a contingency event without exceeding the TTC.
Transient Stability Analysis

• Transient voltage swings
• Severe low voltages during swings can lead to instability and other uncontrolled actions
• Avoidance of excessively large transient swings or poorly damped (or undamped) voltage oscillations
• Factors affecting voltage swings
  ▪ Pre-contingency transfer levels, voltage, and load levels
  ▪ Pre-contingency dynamic reactive reserves
  ▪ Pre-contingency loading on dynamic devices (e.g., machine reactive loading)
Reactive Power Sufficiency
Reactive Reserve

- Reserve of resource measured as difference between maximum Q for that operating point vs. actual Q output
  - Changes based on loading for synch generator (“D curve”)
- Necessary to ensure transient and post-transient voltage collapse does not occur
- Typically only dynamic reactive reserve counted since voltage collapse may be fast
- TOP/RC pre-contingency adjustments to maintain post-contingency reliability
  - Maintain dynamic reactive reserves
  - Ensure sufficient speed of response to meet system needs
- Operators often maintain reserve margin
Voltage Response

- Starting voltage, transient voltage response, duration of response are measure of system strength
- Range of voltages seen across system
- Duration determined by fault clearing and re-acceleration of motor loads
- Oscillations and voltage swings
- Transient voltage dip vs. transient voltage recovery
- Relevant IEEE standards for voltage sags
- Sensitivity of load to voltage excursions
- Transient voltage dip criteria
- Voltage sags inevitable – design to minimize impact
Dynamic and Static Reactive Resources

Pre-contingency

Post-contingency

Dynamic Compensation Ratios
- High
- Normal or Low

- Knee/nose of PV curves
- Margins
- Total Transfer Capability
- Maximum Power Transfer
Operating Voltages and Voltage Schedules

• TOP Operating Plan – safe and reliable voltage levels
  ▪ Local needs and wide-area considerations
  ▪ Adjacent TOP scheduling practices, minimizing reactive losses, maximizing transfer capability, etc.
• Good utility practice to stay “ahead of the curve” regarding voltage – not desirable to “chase” voltage in real-time
• System voltage schedule vs. generator voltage schedule
Typical generator modes of operation: Voltage Regulation, Constant Machine Power Factor, and Fixed Reactive output

TOP develops voltage schedules and GOP required to operate to the schedule with AVR in $V_{\text{reg}}$ mode

**Range:** range of acceptable operating voltages for n-0 and n-1 conditions.

**Under Normal Operating Conditions n-0**

- **Target Set Point:** preferred voltage or power factor
  - **Target Voltage:** slightly above nominal voltage level (e.g., 1.02-1.05 pu)
- **Tolerance Band:** minimum and maximum voltage or power factor
  - **Voltage Tolerance:** small bandwidth around target set point (e.g., 1-2%)

**Under Contingency Operating Conditions n-1**

- Post-contingency Voltage within tolerable range (e.g., 0.9 to 1.1 pu)
Table 1: Typical Operating Voltage Schedule Tables

<table>
<thead>
<tr>
<th>Bus #</th>
<th>Nominal Voltage [kV]</th>
<th>Typical Operational Voltage Schedules - On-Peak Period</th>
<th>Typical Operational Voltage Schedules - Off-Peak Period</th>
<th>Typical Acceptable Max/Min Voltage Schedule Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kV Sched</td>
<td>Tolerance Band</td>
<td>kV Sched</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>kV High</td>
<td>kV Low</td>
</tr>
<tr>
<td>1</td>
<td>345</td>
<td>356</td>
<td>359</td>
<td>353</td>
</tr>
<tr>
<td>2</td>
<td>115</td>
<td>116</td>
<td>118</td>
<td>114</td>
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<td>115</td>
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<td>4</td>
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<td>119</td>
<td>121</td>
<td>117</td>
</tr>
<tr>
<td>5</td>
<td>345</td>
<td>358</td>
<td>361</td>
<td>355</td>
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<tr>
<td>6</td>
<td>115</td>
<td>118</td>
<td>120</td>
<td>116</td>
</tr>
</tbody>
</table>
Operational Time-Dependent Voltage Limits

### Normal Voltage Limits (NORMVL)

<table>
<thead>
<tr>
<th>TO</th>
<th>115 kV</th>
<th>345 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Voltage Limits (kV)</td>
<td>High Voltage Limits (kV)</td>
</tr>
<tr>
<td>TO 1</td>
<td>100.0</td>
<td>121.0</td>
</tr>
<tr>
<td>TO 2</td>
<td>105.3</td>
<td>122.0</td>
</tr>
<tr>
<td>TO 3</td>
<td>105.3</td>
<td>121.0</td>
</tr>
</tbody>
</table>

### Long Time Emergency Voltage Limits (LTEVL)

<table>
<thead>
<tr>
<th>TO</th>
<th>Time Applicable</th>
<th>115 kV</th>
<th>345 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Voltage Limits (kV)</td>
<td>High Voltage Limits (kV)</td>
<td>Time Applicable</td>
</tr>
<tr>
<td>TO 1</td>
<td>Infinite</td>
<td>105.0</td>
<td>121.0</td>
</tr>
<tr>
<td>TO 2</td>
<td>30 minutes</td>
<td>105.8</td>
<td>124.0</td>
</tr>
<tr>
<td>TO 3</td>
<td>Load cycle</td>
<td>103.5</td>
<td>121.0</td>
</tr>
</tbody>
</table>

### Short Time Emergency Voltage Limits (STEVL 15 Minutes only)

<table>
<thead>
<tr>
<th>TO</th>
<th>115 kV</th>
<th>345 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Voltage Limits (kV)</td>
<td>High Voltage Limits (kV)</td>
</tr>
<tr>
<td>TO 1</td>
<td>102.0</td>
<td>121.0</td>
</tr>
<tr>
<td>TO 2</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>TO 3</td>
<td>100.0</td>
<td>121.0</td>
</tr>
</tbody>
</table>

### Drastic Action Voltage Limits (DAVL 5 Minutes only)

<table>
<thead>
<tr>
<th>TO</th>
<th>115 kV</th>
<th>345 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Voltage Limits (kV)</td>
<td>High Voltage Limits (kV)</td>
</tr>
<tr>
<td>TO 1</td>
<td>100.0</td>
<td>121.0</td>
</tr>
<tr>
<td>TO 2</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>TO 3</td>
<td>96.0</td>
<td>121.0</td>
</tr>
</tbody>
</table>
Generator Voltage Control

- Largest and most prevalent reactive power resource of BPS
- Large dynamic reactive capability – robust reactive resource
- TOPs provide voltage schedule
  - Range or target with tolerance
  - At high or low side of GSU, or at POI
  - Bandwidth reflective of expected system conditions
- GOP ensure automatic voltage control mode, AVR in service
- GOP notifies TOP if AVR removed from service
- GOP may employ different control strategies to ensure voltage at location deemed by TOP
- Under special circumstances, TOP can specify alternative method of control such as Q schedule
Generator Automatic Voltage Control Techniques

Line Drop Compensation (+)
Terminal Voltage Control
Reactive Current Compensation (-)

RCC = -5%

Cross Current Compensation

$X_C (I_{Q1} + I_{Q1})$
LDC = 5%

$X_D I_{Q1}$
RCC = -12%
Light Load Operating Conditions

• Operational flexibility
  ▪ e.g., morning hours, spring or fall, holiday weekend, etc.

• Planning assessments of representative light load conditions
  ▪ Ensure reflective load levels in light load planning case

• Need for mix of leading and lagging resources

• Must ensure reliability under full range of possible load levels

• High voltage issues
  ▪ Equipment damage
  ▪ Generation tripping
Reactive Power Coordination
• Modeling of end-use loads
• Voltage and reactive power performance
• Load power factor
  ▪ Forecasting
  ▪ Requirements
  ▪ Monitoring
  ▪ Review
  ▪ Correction
Transmission-Generation Coordination

- Capabilities in accordance with most recently signed interconnection service agreement
- TO periodically review with GO expected reactive power performance for each unit
- MOD-025 capability verification
- Planned changes/updates to gen capability
- Ensure realistic performance capability from units
  - “Inside the fence” plant voltage constraints (e.g., auxiliary bus voltage)
- TO/TP review of (real-time and planning) data to confirm simulated vs. actual
Planning Coordinator to Transmission Planner Coordination

- PCs should coordinate with their TPs to develop processes to assure adequate reactive resource capabilities within footprint
  - Reactive power assessment techniques
  - Reasonable projections of reactive power requirements
  - Reflective projections of reactive power resources
- TPs should plan Q resources to match their Q requirements for normal and contingency conditions
- PCs should coordinate among TPs to ensure sufficient Q available to address localized issues
Planning Coordinator to Planning Coordinator Coordination

- Coordinate with adjacent PCs
- Specific attention to seams between PCs
- Unified coordination with the RC for operational issues
Industry Practices:
Customized Reactive Power Planning
• Voltage profile WG sets coordinated system voltage profile for N-0 and N-1 network conditions.
• Online Voltage Stability Limits using VSAT
• HVRT requirement
  - Intermittent Renewable Resources tested at 50% or 100% output and at 0.95 p.f. lagging or leading.

• Studies of low SCR networks had recommended synchronous condenser to satisfy reactive power requirements.
• Steady-state voltage limits established planning and ops
  ▪ Coordination of TOs, TOPs, and GOs
  ▪ Recognize the practical limitations of reactive device switching
• Utilize time-dependent emergency transmission voltage limits
  ▪ Coordinated with equipment owners, deployed in ISO-NE control room.
• Annually determine acceptable load power factor (LPF) min/max required for system sub-areas
  ▪ “After the fact” audits to determine compliance with the requirements
• Reactive market pays resources for lead/lag reactive capability.
  ▪ Resource reactive capability audited ever 5 years as part of the market
• Assessments performed during real-time operations:
  ▪ Steady-state voltage assessment (pre- & post-contingent, RTCA)
  ▪ P-V Analysis (online VSAT)
  ▪ Dynamics analysis (transient voltage violations, online TSAT)
  ▪ Static & Dynamic reactive reserve calculations

• Mitigation plans for potential violations closely coordinated with member TOPs

• Real-time operations are supported by day-ahead, operational-planning and long-term planning studies

• Reactive power and voltage control service settled under Schedule 2 of MISO’s tariff
• EMS real-time contingency analysis (Static and Dynamic) is primary tool to assess the PJM system

• 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

• Transfer Limit Calculation (TLC) is used to project limitations of increased transfers
  ▪ Determines the maximum pre- and post-contingency MW transfer interface flow for
    o Voltage low limits
    o Voltage drop limits
    o Voltage stability limits
• Each limit calculated for each of the reactive interface lines
• Each limit may be driven by different contingencies with different violated buses to a particular transfer
  - “Recommended Limit” is the lower of the “Voltage Drop Violation Point/Post-Contingency Low Voltage Violation Point” or the “Voltage Stability Limit Point” minus the “Interface Margin”.
• Voltage Stability Analysis (VSA) used to augment analysis of TLC
• VSA provides control recommendations
  o Non cost control
  o Off cost control (VSA does not consider cost)
  o Load shedding
  • Voltage sensitivities
• PJM On-line TSA for Transient Stability and Voltage Dip in the real time operations
• Reactive power is an Essential Reliability Service to the Bulk Power System

• Sufficient levels of reactive power to maintain acceptable voltage levels is critical to reliability

• Static and dynamic reactive power support necessary to transfer active power to serve load

• NERC ERSTF/ERSWG efforts
  ▪ ERSTF Framework Report
  ▪ ERS Measure 7 – Reactive Support
  ▪ ERS Sufficiency Guidelines – Sub-Area Concept
  ▪ 2017: How best to track and trend localized voltage/reactive issues?
Questions?