From Here to There
Grid Reliability in the Grid of the Future

Robert W. Cummings
NERC Senior Director of Engineering and Reliability Initiatives
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NERC’s Definition of Reliability

NERC’s traditional view of “reliability” in the power industry consists of two fundamental and aspirational concepts:

- **Adequacy** is the ability of the electric system to supply the aggregate electric power and energy requirements of the electricity consumers **at all times**, taking into account scheduled and reasonably expected unscheduled outages of system components.

- **Operating reliability** is the ability of the electric system to **withstand sudden disturbances** such as electric short circuits or unanticipated loss of system components.
Resilience is a Characteristic of a Reliable System

* Solely from the perspective of the Bulk Power System and does not include distribution systems.
From Here to There
Defined from a Reliability Perspective

- Two-way flow of energy and communications enabling new technologies to supply, deliver and consume electricity.

- Functions
  - Enhanced flexibility and control
  - Balancing variable demand & resources
  - Demand Response
  - Large deployment of sensor & automation technologies
  - etc.

Caution of the time – Smart Grid Integration must be Done Intelligently!
Grid of the Future

Questions

- What will it look like?
- Will we have 100% renewable resources?
- Will all resources be connected through power electronics?
- What will the load look like?
- Will we still a grid and transmission lines?
- How will micro grids interact?

Transition issues

- Transition to higher penetrations of inverter-coupled renewables may be painful...not without surprises
- Reductions in inertia and synchronizing torque will make the
Grid of the Future - Transition Issues

- Transition to higher penetrations of inverter-coupled renewables may be painful...not without surprises
  - Higher levels of inverter-based resources could be more stable
  - Reductions in inertia and synchronizing torque will make the grid more brittle
  - Behavior of inverters has to be understood and

- Reduced levels of fault current provided by inverters
  - How do you melt steel in an arc furnace?
  - System protection redesigns will be necessary in some areas

- Transportation of renewables from source to consumption
  - Wind and solar resources are abundant in areas far from demand centers
    - Not all areas can locally support their loads from renewables – NYC
  - Storage may not be practical in some areas
  - Co-locating renewables and storage is essential to minimize additional system connections
• Load composition changing
  ▶ Electric vehicle charging
  ▶ LED lighting
  ▶ Variable speed drive motors

• Distributed Energy Resources
  ▶ Inverter-based resources
    o Roof-top solar panels
    o Micro turbines
    o Small wind turbines
  ▶ Inverter-based resources on sub-transmission systems

• Micro-Grids

• Load becoming schizophrenic
  ▶ Load models no longer adequate for simulations
Changing Resources

Changing Dispatch Mix

- Higher penetration of renewables – variability of resources
- Minimum generation levels on conventional units
- Ramping needs increase for load following

Retirement of large fossil-fired generation plants

- Loss of dynamic reactive support for voltage control
- Possible reduced system inertia
- Lower levels of synchronizing torque

Changing System Inertia

- Lower inertia impacts on Primary Frequency Response
- Inertia-less system?

Behavior of Inverter-Based Resources
Inadvertent creation of new reliability hazards

- Very large DC transmission projects
  - New largest single hazards for the interconnections??

Series-compensated transmission lines

- Sub-synchronous resonance
- Sub-synchronous controls interaction
  - Inverter-based resources
  - Digital controls on conventional generation
  - System controls – SVCs, Statcoms, DC converter stations, etc.

- Fault-induced Inverter behavior– voltage and frequency ride-through
Potential Interaction Examples

Potential response to combination of voltage and frequency perturbations associated with complex system disturbances

High-quality supply loads that are Voltage/Frequency-sensitive

- Experience of 600 to 900 MW load loss during relatively minor faults – due to transfers of loads to backup supplies

Locational injection impact on transmission elements and interfaces

- Response masquerading as a power swings – protection system concerns
CAISO Load Balancing Concerns

Load, Wind & Solar Profiles --- Base Scenario
January 2020

6,700 MW in 3-hours

7,000 MW in 3-hours

12,700 MW in 3-hours
Updated Duck Curve – Exceeding Projections

Typical Spring Day

Megawatts

Hour

Actual 3-hour ramp 10,892 MW on February 1, 2016

Net Load 11,663 MW on May 15, 2016

over generation risk
ERCOT Interconnection Frequency Probability Density Function by Year
Trade-off between Inertia and Primary Frequency Response

Bus frequency (Hz) vs. Time (sec)

Generation Trip: 2,750 MW

**Case 1**: Net Load = 65 GW, PFR=1,300MW
**Case 2**: Net Load = 35 GW, PFR=2,500MW
**Case 3**: Net Load = 17 GW, PFR=4,700MW

Primary Frequency Response (MW): 3 > 2 > 1
Potential Roles of Energy Storage
• High-speed energy injection following loss of resources
  • High-speed response during Arresting Phase of a Frequency Event
    o Response proportional to the change in frequency and rate of change in frequency
    o Help to offset loss of system inertia due to displacement or retirement of generation

• Continuous proportional response to frequency deviations
  • Frequency control services

• Energy injection to perform ramping services
  • Reduce severity of solar-based resource drop-off in evening
Energy storage can move from a charge to discharge cycle similar to traditional generator droop characteristic.

Potential Operating Mode for Battery Charging

- Full Power Discharge
- 59.5 Hz
- 59.964 Hz
- 60.036 Hz
- 60.5 Hz
- Full Power Charge
- Deadband
Ramping / Load-Following Services
Role for Storage

• Supplement generation during severe upward ramps
  ⚫ Morning load pick-up before solar reaches full output
  ⚫ Evening load pick-up when solar output is dropping off

• Absorb energy during downward ramps
  ⚫ When solar and wind output ramps up to full output and morning load stabilizes

• Absorb energy to prevent over-generation
  ⚫ Charge storage when solar and wind output exceeds energy demand

• Load-following to provide balance for variable resources
  ⚫ Wind and solar variability due to changes in weather
Learning from History
Where Were You?

- 5:16:11 pm  1965 Northeast Blackout
- 9:29 pm     1977 New York Blackout
- 3:48 pm     1996 Western Blackout
- 3:05:41 pm  2003 Northeast Blackout
- 12:32:44 pm 2005 Los Angeles Blackout
- 5:14:54 am  2007 Saskatchewan Blackout
- 1:09:08 pm  2008 South Florida Blackout
- 11:45:06 am 2016 Blue Cut Fire Disturbance
Inverter-Based Disturbances
Blue Cut fire caused

- Thirteen 500 kV line faults
- Two 287 kV line faults

11:45:06 PDT Fault

- 500 kV line-to-line fault
- Cleared normally in 2.5 cycles (41.7 milliseconds)
- PV resources impacted – 1,178 MW
  - 26 different solar developments
  - All utility scale – connected at 500kV or 230kV
  - 10 different inverter manufacturers
  - No PV site system protection relays/breakers operated
  - All action was by on-board inverter controls
Blue Cut Fire Disturbance

- Event occurred on August 16, 2016
  - Back-calculated to about 2,500 MW loss based on interconnection-wide inertia
- NERC/WECC ad hoc task force created to identify causes
- Published disturbance report in June 2017
- Key Findings:
  - Use of momentary cessation
  - Frequency-related tripping
Solar Resource Loss

- 11:45:15 AM; 2,884.05 MW
- 11:45:16 AM; 1,705.7 MW
- 11:52:16 AM; 2,483.20 MW
- 11:52:15 AM; 2,191.64 MW
A phase-to-phase fault caused the voltage phasors to deviate from their normal 120° separation (a.k.a., Phase Jump). Occurs at fault inception and at fault clearing. The time domain shows the phase separation decreased when the fault occurred and shifted back when the fault cleared.
PV Inverter Operating Modes

- **Continuous Operation** – Actively injecting current into the grid
- **Momentary Cessation** – Momentarily cease injecting active current into the grid, but remain electrically connected
  - Triggered by abnormal system voltages (< 0.9 or > 1.1 per unit)
- **Trip Mode (Cease to Energize)** – Ceased injecting current and will delay returning to service. (typically 5 minute delay)
  - May also mechanically disconnect from the grid
- **Modeling is a real issue** – Little of this is modeled in conventional powerflow and dynamics simulations
• Recommended actions:
  - Mitigate erroneous frequency tripping
  - Recovery from momentary cessation

• Data collection to understand extent of condition
Potential Revisions to PRC-024

- Do not disconnect, no “Momentary Cessation” in No Trip zone
- Frequency calculated as $f$ over time window (0.1 sec)
Momentary Cessation Recommendations

1) MC_V reduced
2) Delay shortened
3) Ramp rate faster

Voltage

Current

Time

$V_{mc}$

$\Delta t_{sr}$

$\Delta t_{rr}$
• Ensure that plant-level ramp rate interactions are NOT interacting with local inverter controls during dynamic events
Canyon 2 Fire Disturbance

- Event occurred on October 9, 2017
  - Back-calculated to 1,500 MW loss based on interconnection-wide inertia
- NERC/WECC event analysis, NERC Inverter-based Resource Performance Task Force (IRPTF) technical support
- Published disturbance report in February 2018
- Key Findings:
  - No frequency-related tripping
  - Continued use of momentary cessation
  - Transient overvoltage-related tripping
• Mitigating actions:
  ▶ Dynamic model improvements
  ▶ Mitigation of momentary cessation
  ▶ Plant control loop coordination
  ▶ Mitigation of voltage-related tripping
  ▶ Information sharing among operating entities

• Planning and operations studies to ensure no potential stability risks
  ▶ Response to Regional Entity of study findings by December 7, 2018
No erroneous frequency tripping
- Actions from first Level 2 Alert appear to have mitigated identified issue
- By the Canyon 2 Fire disturbance, 97% of manufacturer’s BPS-connected fleet had been updated

Continued use of momentary cessation
- Most inverters use momentary cessation ($V < 0.9 \text{ pu}$)
- Recovery following momentary cessation varies, relatively slow for grid dynamics
- Updated recommendation for momentary cessation – eliminate the behavior to the greatest extent possible

Transient overvoltage tripping and application of the PRC-024-2 ride-through curve
• Existing models largely DO NOT accurately represent installed resource performance
  Identically issue that must be addressed for models in planning and operations studies
  Developed notification to help industry in modeling efforts
  Guidance provided as part of second NERC Alert
Additional Events Under Analysis

20 April 2018 – Angeles Forest Disturbance
• 500 kV line-to-line fault – cleared in 2.6 cycles
• Involved ~1,100 MW of BPS-connected PV
• 200 MW gas turbine loss/associated steam reduction

11 May 2018 – Palmdale Roost Disturbance
• 500 kV line-to-line fault – cleared in 3.6 cycles
• Involved ~900 MW of BPS-connected PV

Both were very similar to Canyon 2 Fire event
• 2nd Alert issued 1 May – few changes had been made
• Inverter tripping: overvoltage, DC reverse current, etc.
Progress Being Made

• Frequency calculation problems have been mitigated
• Momentary cessation is improving – plants returning more quickly
  - Seconds rather than minutes
  - Several instances of less than 1 second
Multi-Pronged Approach

- Disturbance analyses and reports
  - Blue Cut Fire, Canyon 2 Fire, (and Angeles Forest / Palmdale) Disturbances
- Level 2 NERC Alerts
  - Identifying extent of condition, and recommending mitigating actions
- IRPTF Reliability Guideline
  - Recommended BPS-connected inverter-based resource performance
- Modeling and simulations
  - Modeling Notifications
  - Leading interconnection-wide stability studies to identify potential risks
- Industry education – webinars and workshops
- Outreach to BPS-connected non-BES resources (e.g., < 75 MVA)
- Reliance on SGIA, LGIA, and Facility Connection Requirements
Reliability Guideline for Inverter-Based Resource Performance
• BPS-connected inverter-based resource performance
• Guideline based on findings and recommendations of NERC disturbance reports
• Intended as cornerstone document for industry moving forward
• Comment Period: May 4-June 29
• Going to NERC Operating Committee for approval in September
• The “Grid” is becoming a huge controls problem!
  - Interaction of controls, system protection, and behavior of new and existing loads and resources will make or break reliability
  - Current analysis tools are inadequate to study the potential controls interactions

• If you can’t model something, it is impossible to predict how it will behave when connected to the system!

• The changes are happening YESTERDAY!
  - What we thought was the future is here now!

• The Grid of the Future will ONLY be as Smart as we make it!
Questions and Answers