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Advanced Inverter Functionality to Support Grid Reliability & Related Interconnection Requirements

Daniel Brooks, Aminul Huque, & Jeff Smith

PC Enhanced Inverters Stakeholder Meeting
2014 March 28
Valley Forge, PA

Objectives & Agenda

Agenda:

- Levels of inverter-based generation
- Inverter generation reliability capabilities
- Potential Bulk System reliability impacts
- Benefits of inverter grid support
- Survey of existing grid code requirements

Basic Understanding of Need for Advanced Reliability Services from Inverter-Based Generation

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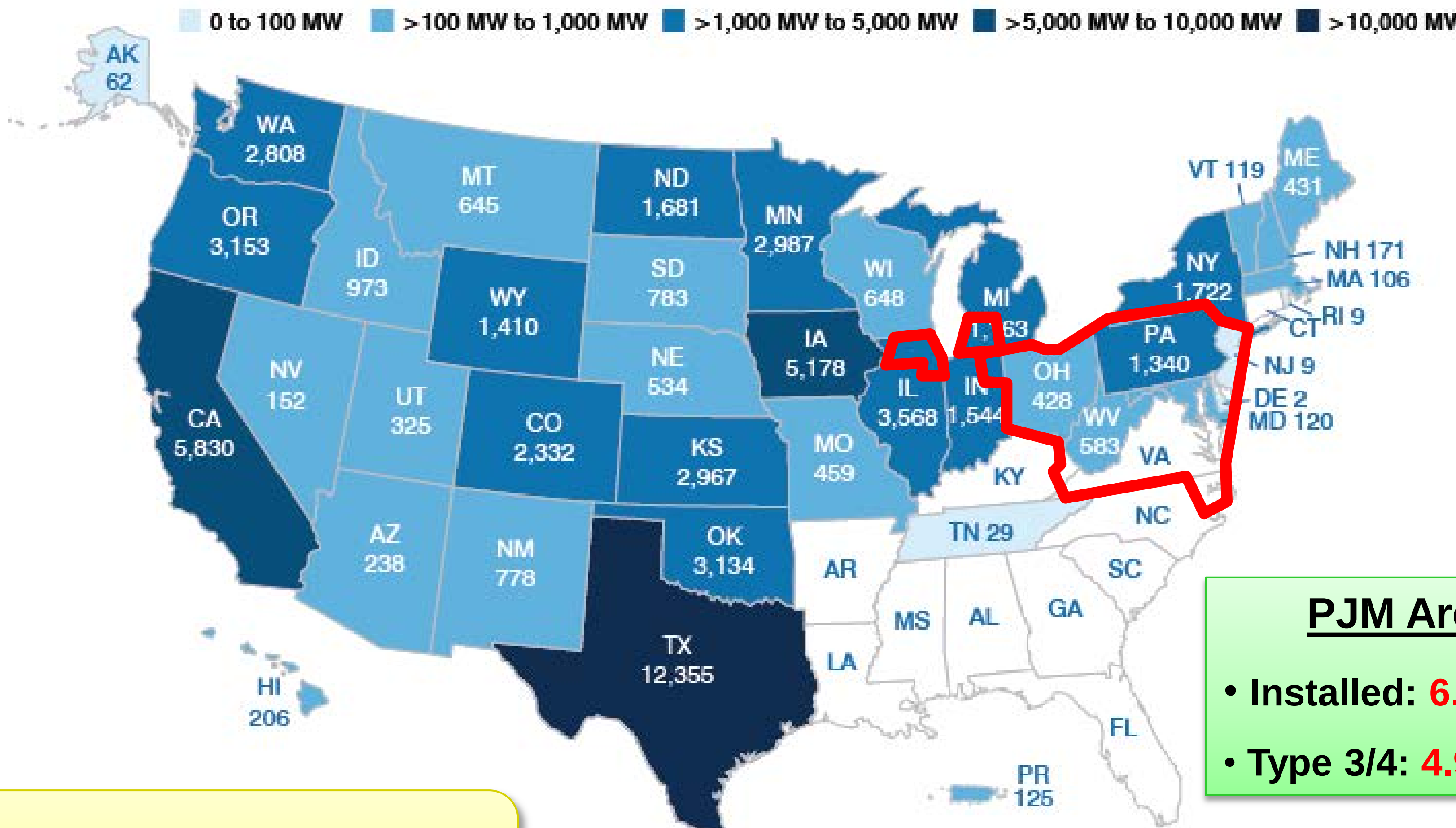
US Installed Wind Generation



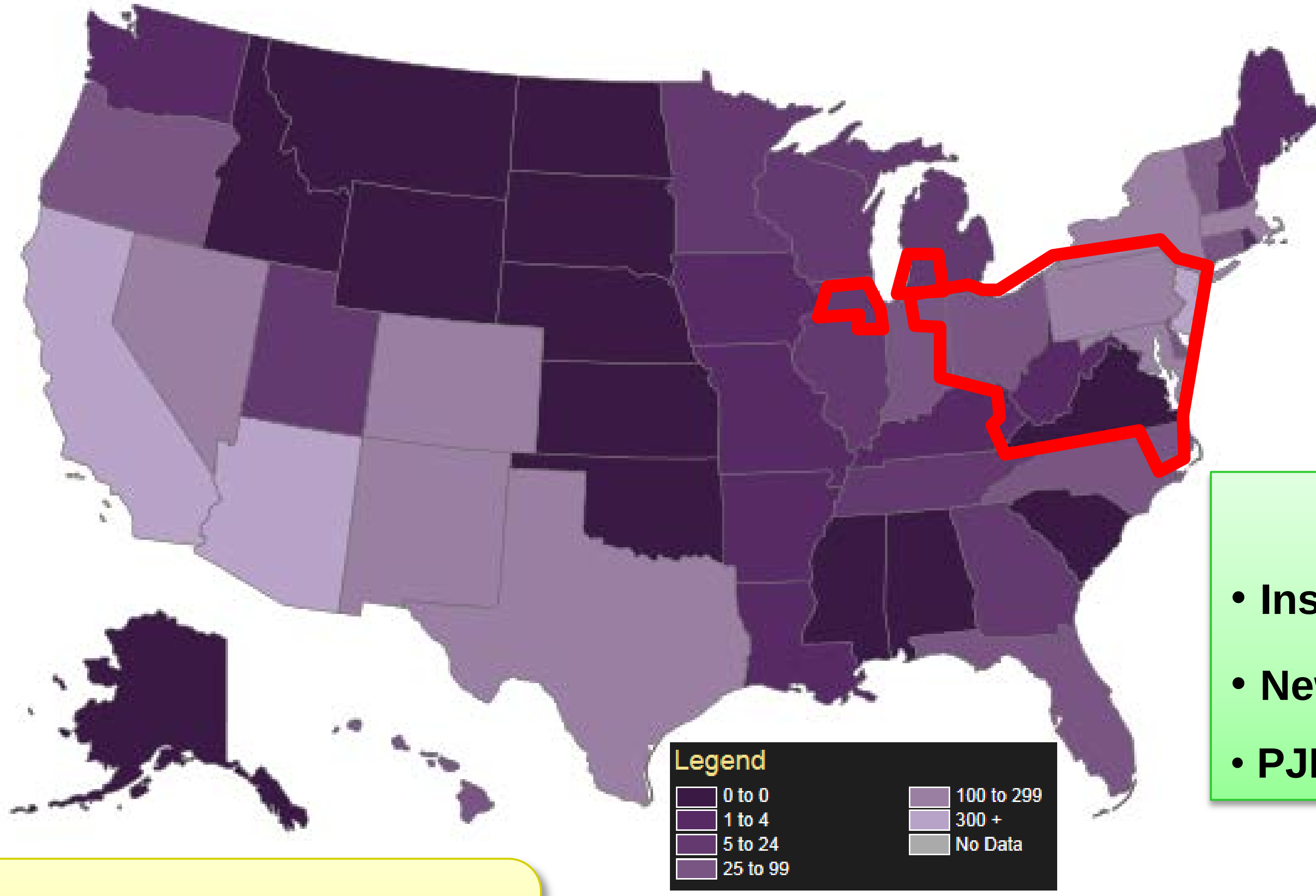
Total Installed: 61+ GW
Under Constr.: 12+ GW

Source: AWEA U.S. Wind Industry 2013 Q4 Market Report

PJM Area

- **Installed: 6.9 GW**
- **Type 3/4: 4.9 GW**

US Installed Solar PV



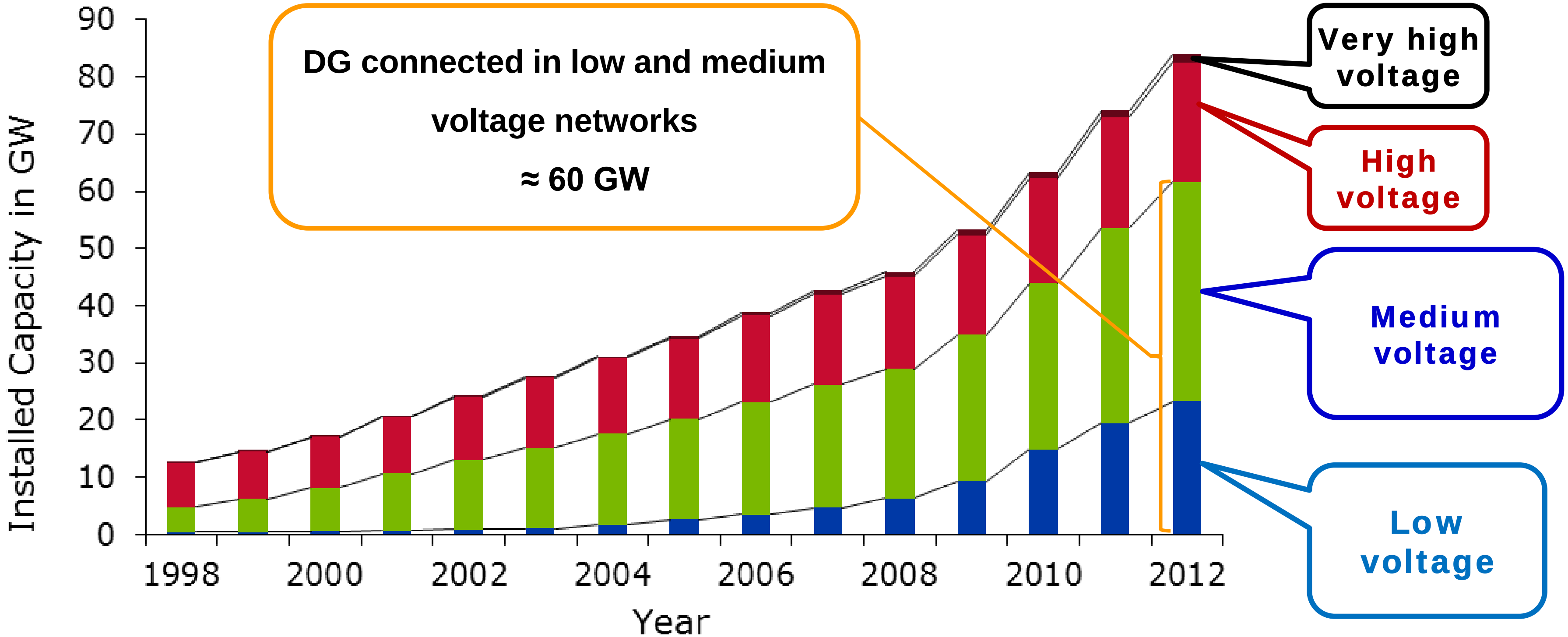
PJM Area

- **Installed PV: 1.4 GW**
- **New Jersey: 1.0+ GW**
- **PJM Model: ≈ 250 MW**

Total US: 13+ GW
2013 Install: 4.1 GW

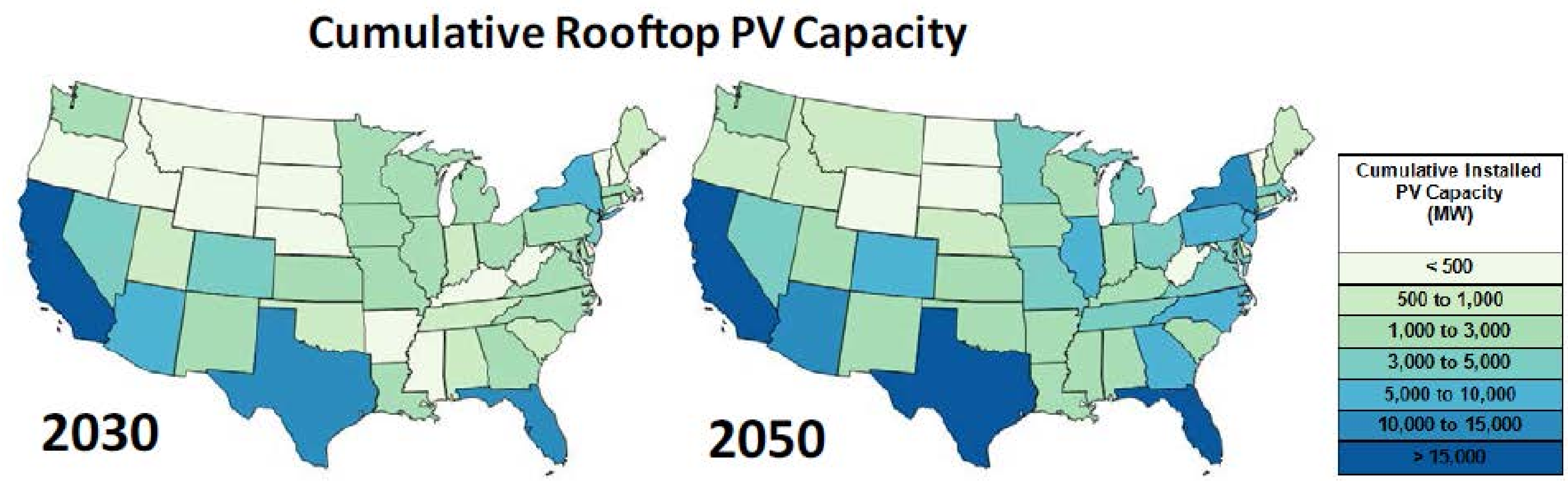
Source: NREL Open PV Project; Bloomberg

How much PV and Wind Is Possible? Germany Situation…



Source: Ecofys(2013) Graphics Used with Permission from : J.C. Boemer, TU Delft & Ecofys

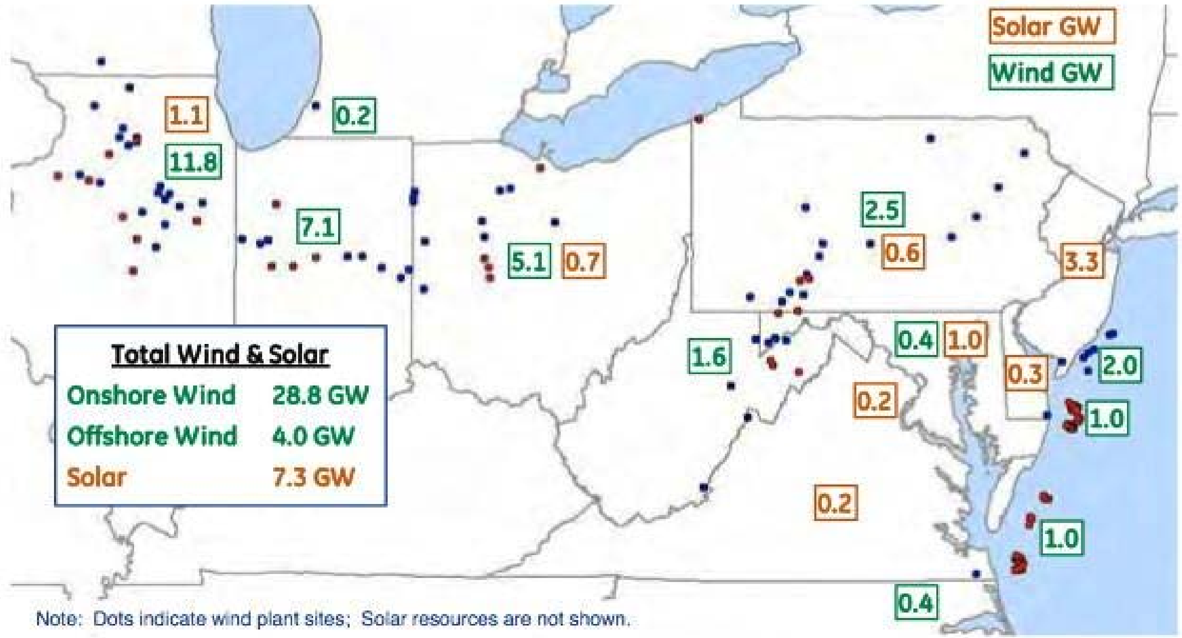
How much PV and Wind Is Possible? DOE SunShot Initiative Scenarios…



Source: NREL, "Sensitivity of Rooftop PV Projections in the SunShot Vision Study to Market Assumptions"

Optimistic, but policy objective PV assumptions, leads to Rooftop PV of 120 GW in 2030 & 240 GW in 2050.

PJM Renewable Integration Study Scenario



14% RPS Scenario

- Onshore Wind: 28.8 GW
- Offshore Wind: 4.0 GW
- Central Solar: 3.2 GW
- Distributed Solar: 4.1 GW

30% High PV Scenario

- Onshore Wind: 47.1 GW
- Offshore Wind: 5.4 GW
- Central Solar: 27.3 GW
- Distributed Solar: 33.8 GW

Recently reported study included scenarios ranging from 2% (BAU) to 30% energy from renewables

What's the Big Deal?

Germany

- Retrofitting >300,000 solar PV units due to voltage and frequency issues
- €70-180 Million!

US

- 80% of renewable generation impacts distribution
- Vast majority provides no grid support

WEIL Western Electric Industry Leaders

"There is an immediate need for new solar to be fitted with "smart inverters" to provide necessary voltage support to integrate effectively and prevent costly renovations and reliability impacts"
– *Western Electric Industry Leaders, Aug 2013*

pjm

"Forward Looking Smart Inverters = A Smart Choice"
- Terry Boston, (Summer Seminar, 2013)

Smart Inverter Capabilities

Aminul Huque, EPRI

March 31, 2014

Key Question?

Can Inverter-Based Generation be equipped with Grid Support Functionality?

Today's Smart Inverter Technology

Enabling Changes in Grid Codes

Inverters converts DC energy to AC energy and interface the generating plant with electricity grid

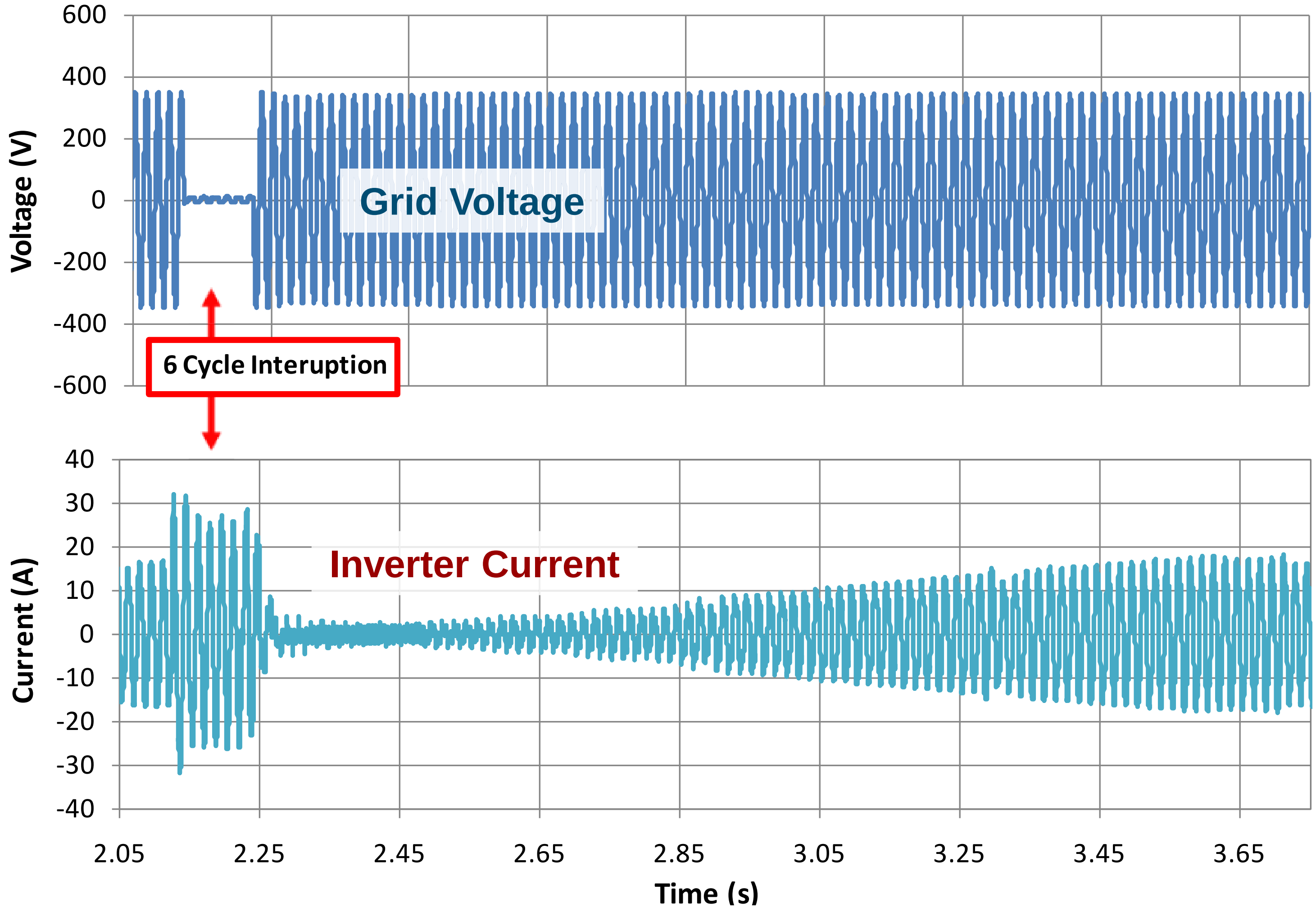
DC Power

AC Power

Traditional Inverter Functionality	Smart Inverter Functionality
• Matching plant output with grid voltage and frequency • Providing safety by providing unintentional islanding protection • Disconnect from grid based on V/f set points	• Active power reduction in case of over-frequency • Fault Ride Through (FRT) • Reactive power and voltage support • Communication with grid • Many more

What is Low Voltage Ride Through (LVRT)?

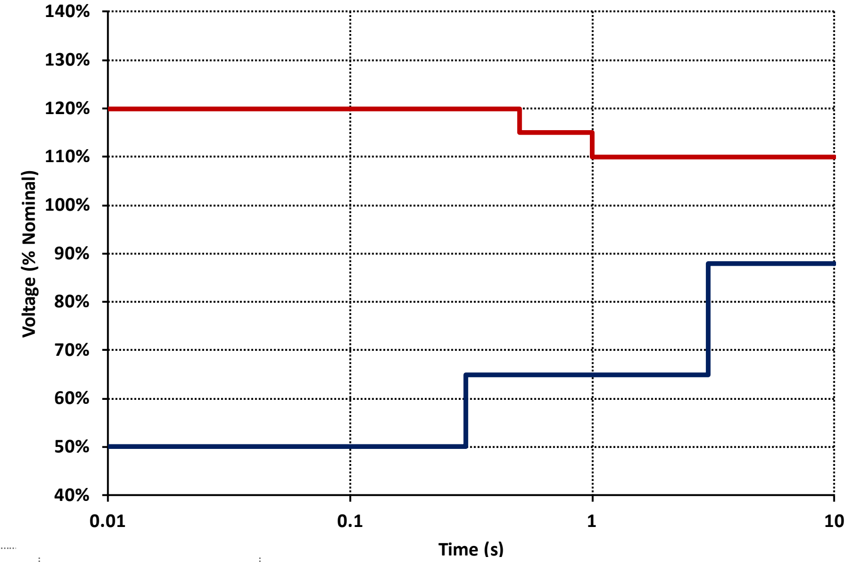
Inverter able to ride through momentary low voltages and interruptions

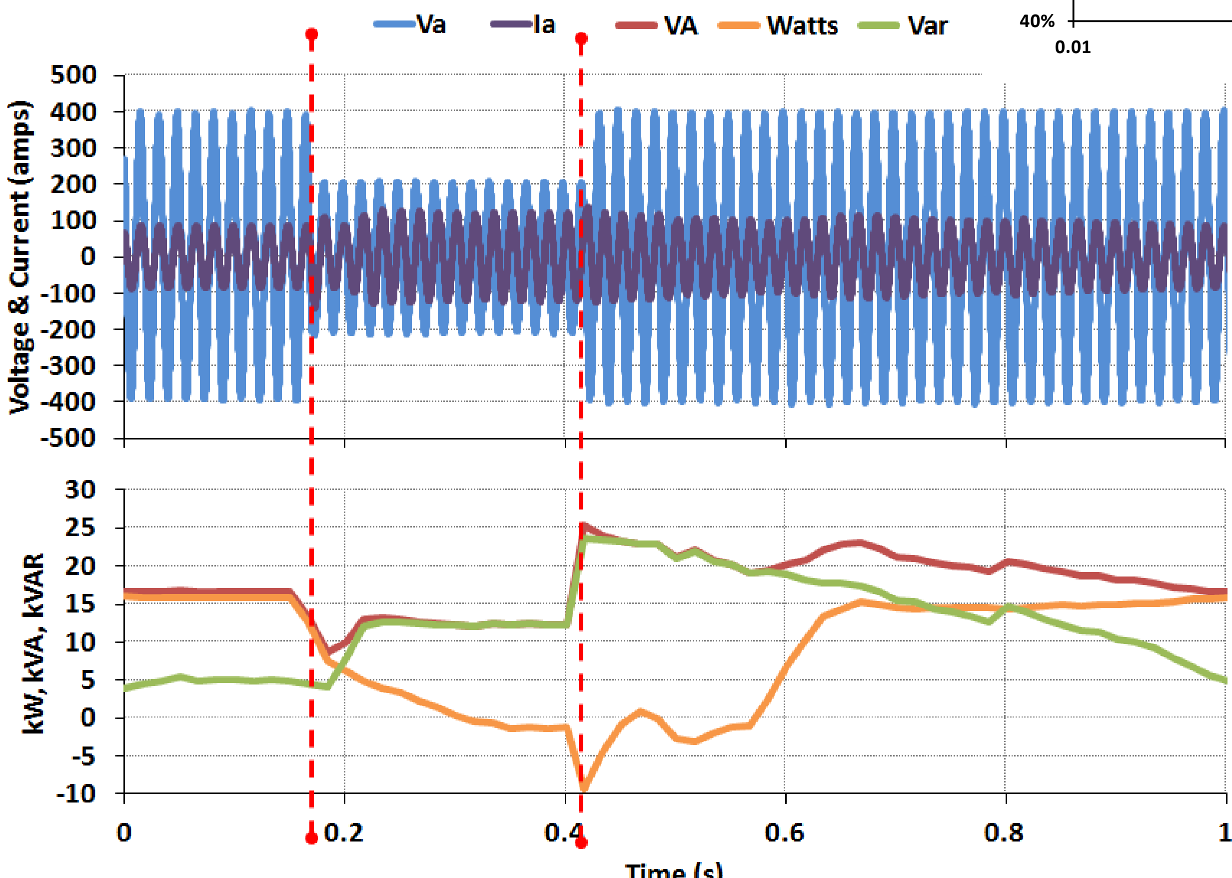


Testing L/HVRT Capability

EPRI Knoxville Lab

Ride-thru of a voltage sag event to 52% nominal with 15 cycle duration





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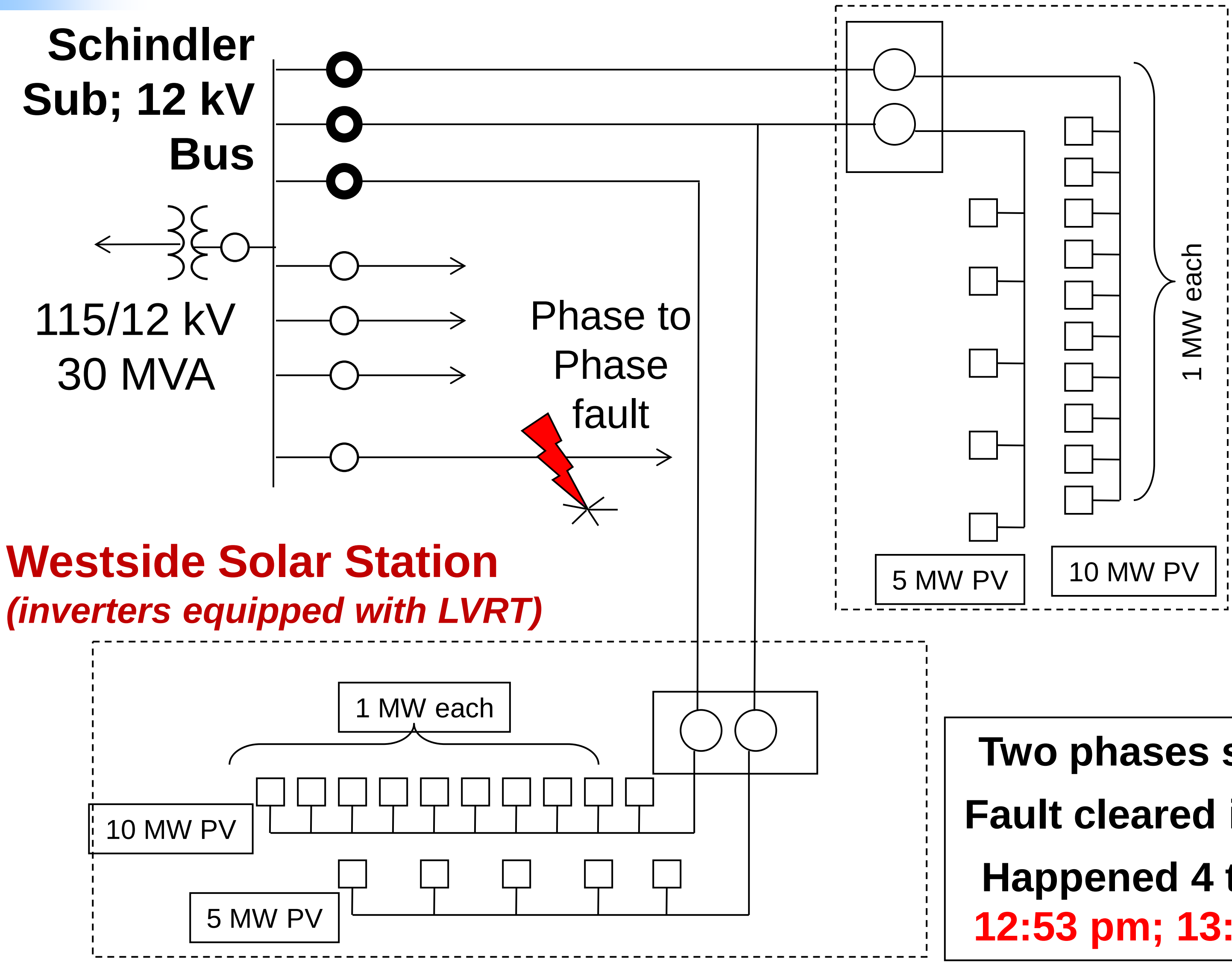
LVRT – PG&E Experience

Pacific Gas and Electric Company



Five Points Solar Station

(inverters not equipped with LVRT)

March 17, 2012

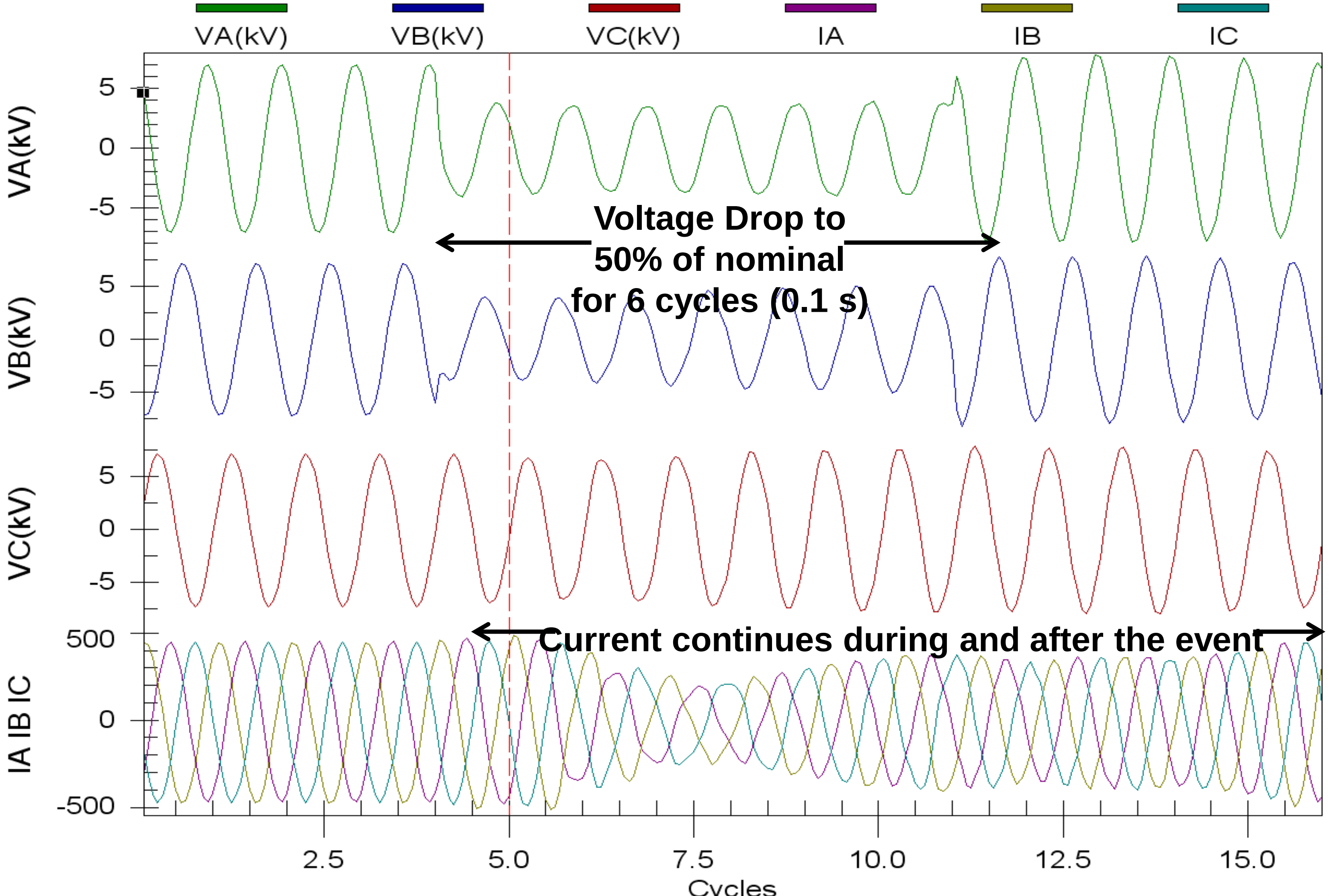
Two phases slapped together

Fault cleared in 6 cycles (0.1 s)

Happened 4 times: 12:52 pm; 12:53 pm; 13:22 pm; 14:21 pm

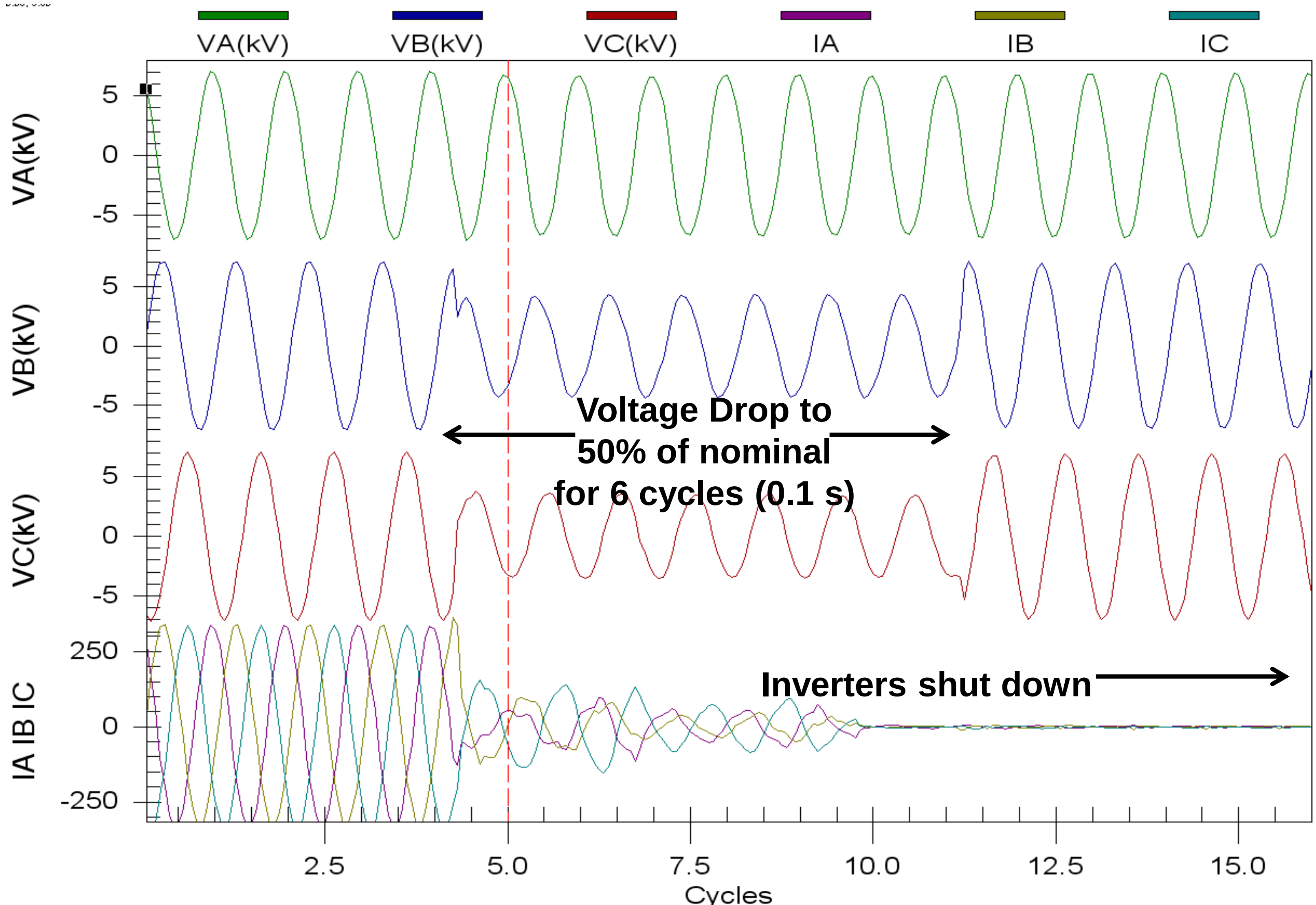
Westside Solar Station with LVRT

March 17, 2012 at 12:52pm

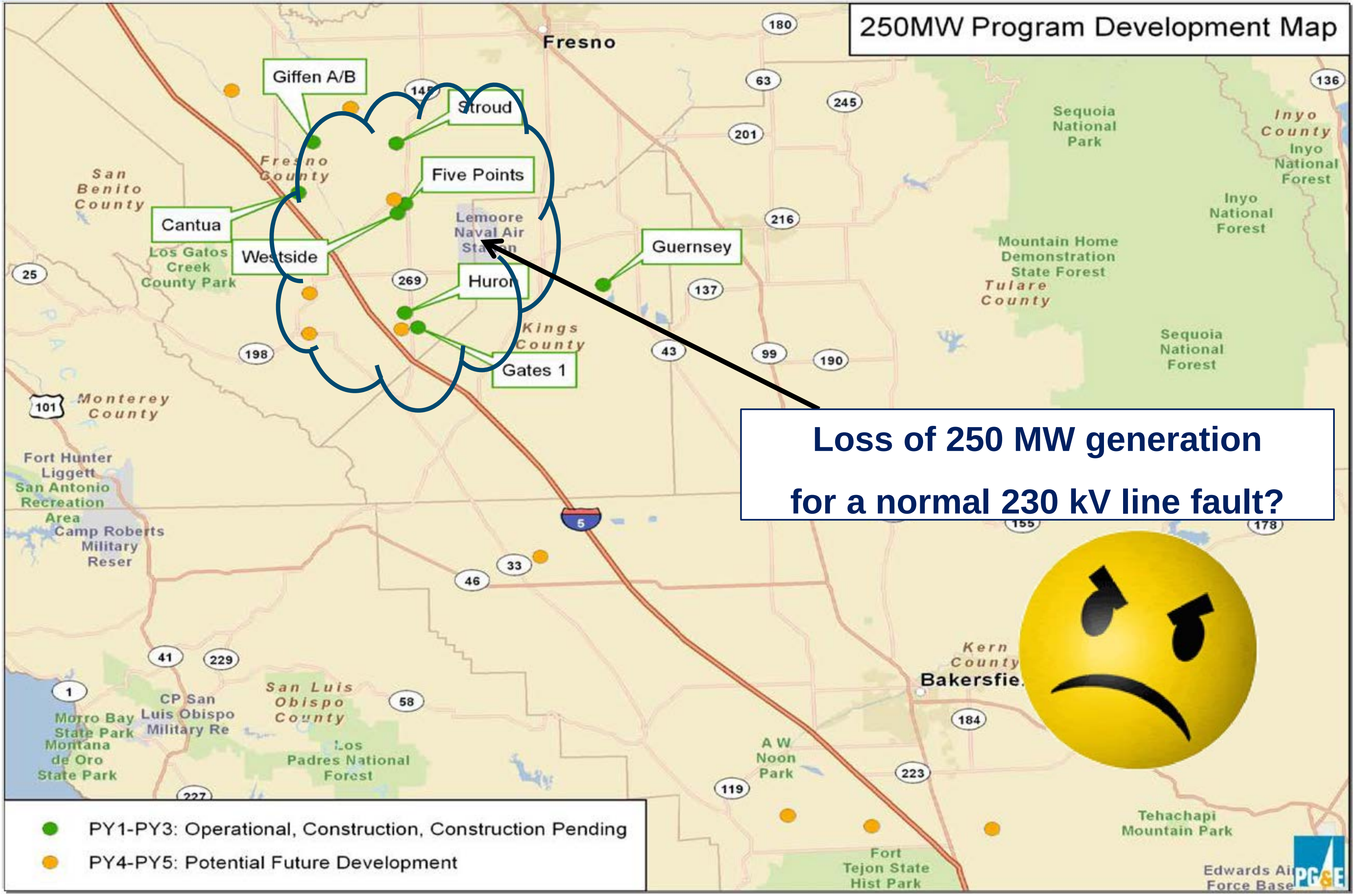


Five Points Solar Station w/o LVRT

March 17, 2012 at 12:52pm

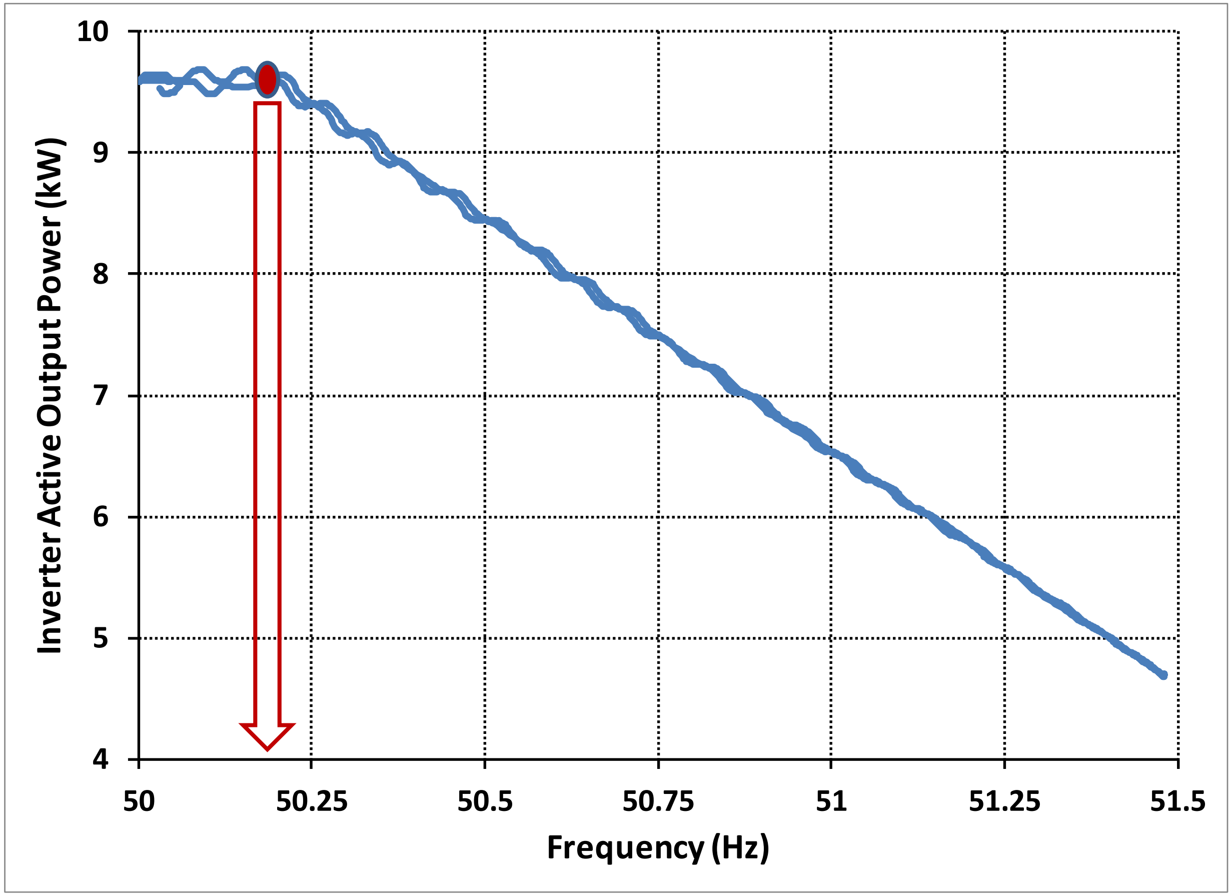


Transmission Line Fault



Don’t Make the Same Mistake!

“50.2 Hz” frequency concern(!) in Germany



Retrofitting/ Replacing

15,000 PV systems

Sized 10kW+

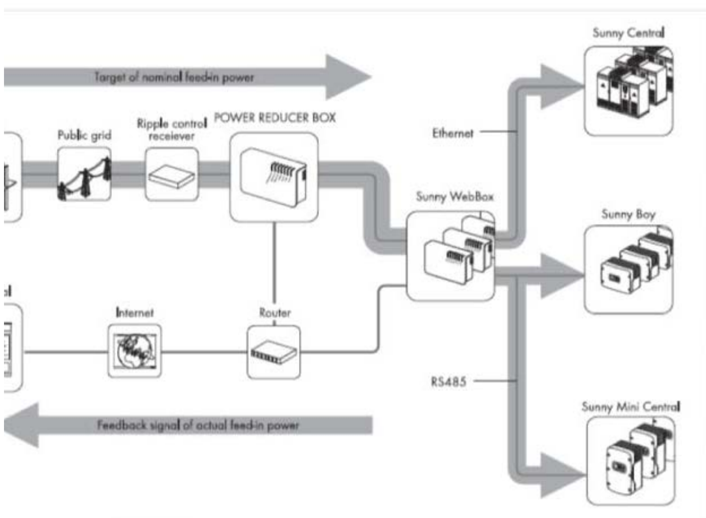
9 GW Nominal Power

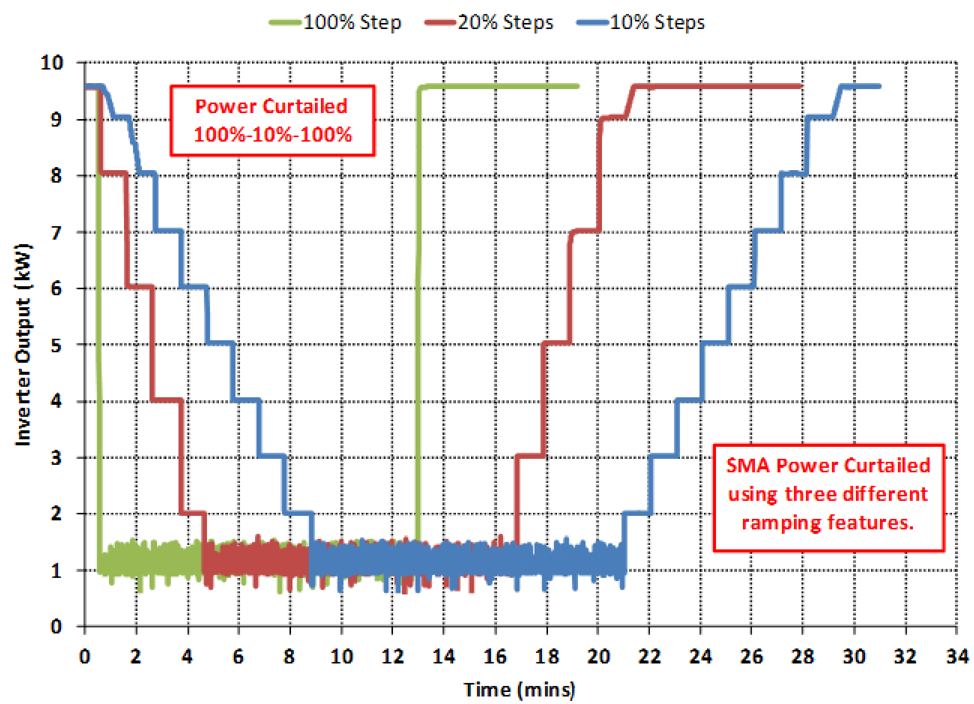
Over 3 – 4 years

Costing €70 – 180 Million

Real power control, ramping, and curtailment

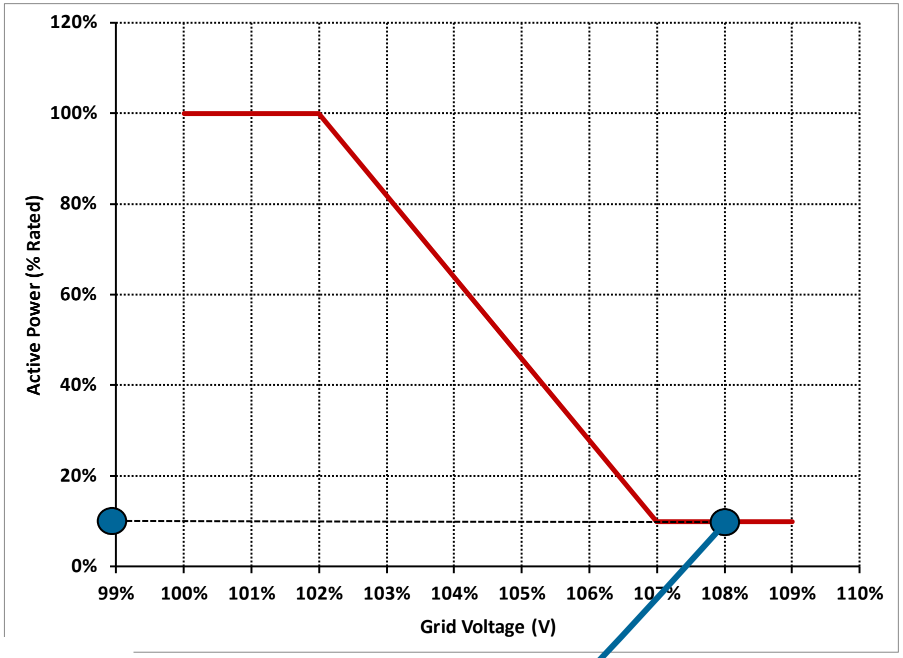
100% → In 6 seconds → 25% → In 4 seconds → 75%



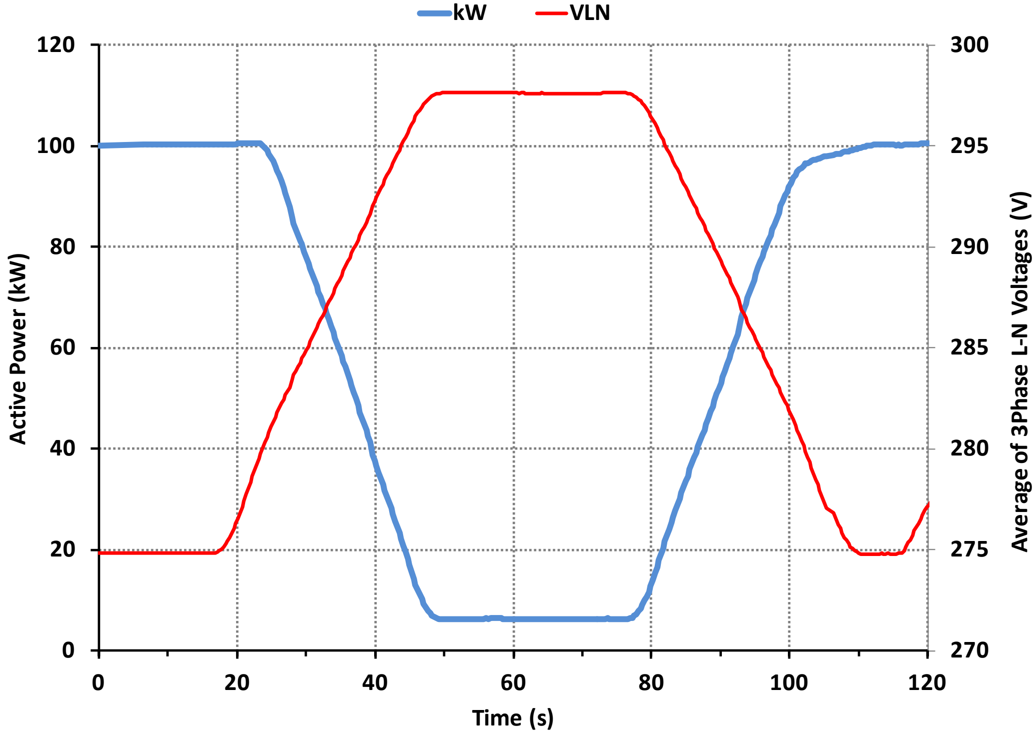


Volt-Watt Function Test

EPRI Knoxville Lab

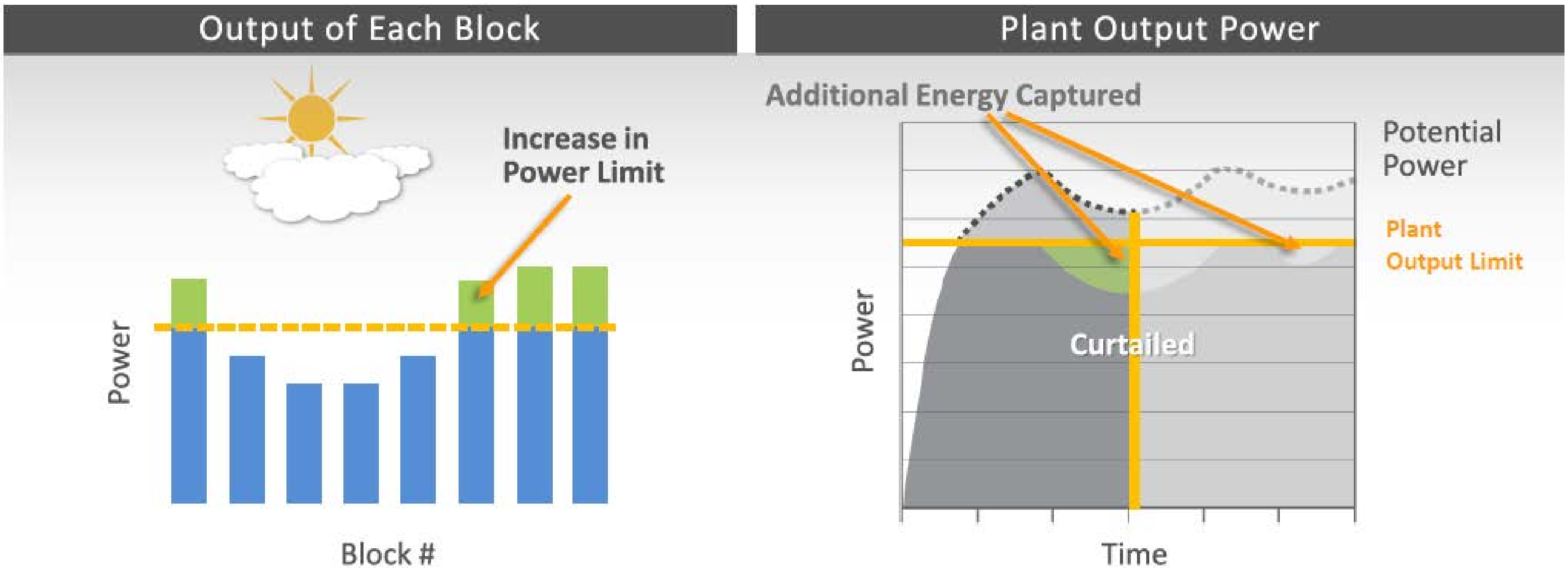


Inverter reducing power output in response to a voltage swell (108% V_N) event



Benefit of Plant Level Control

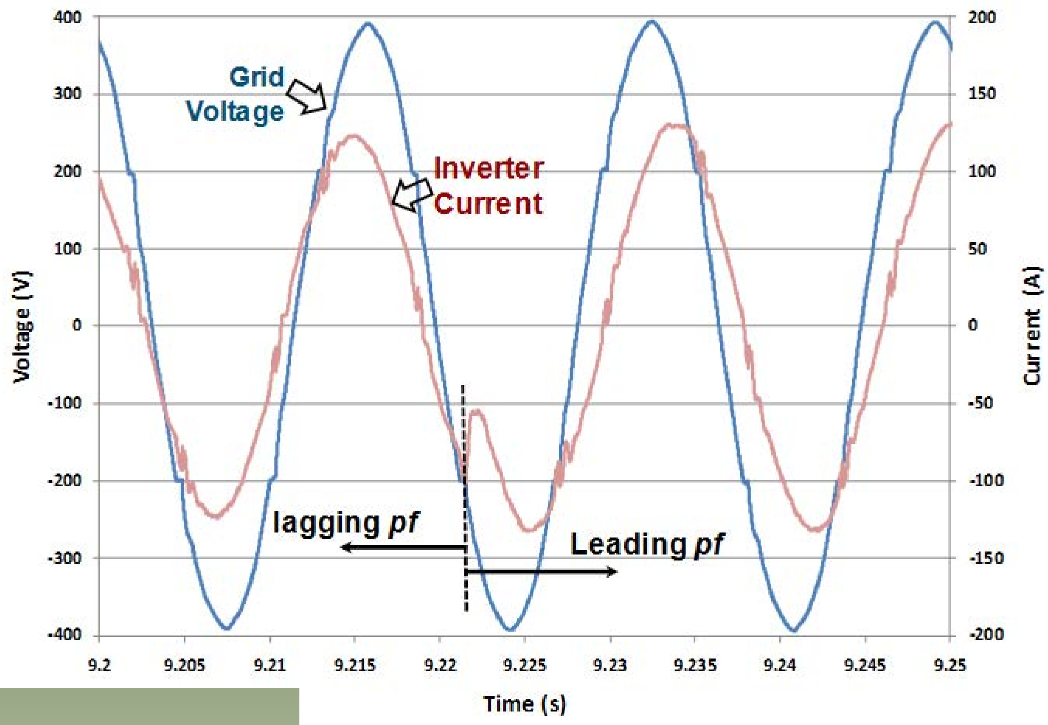
Do Not Share

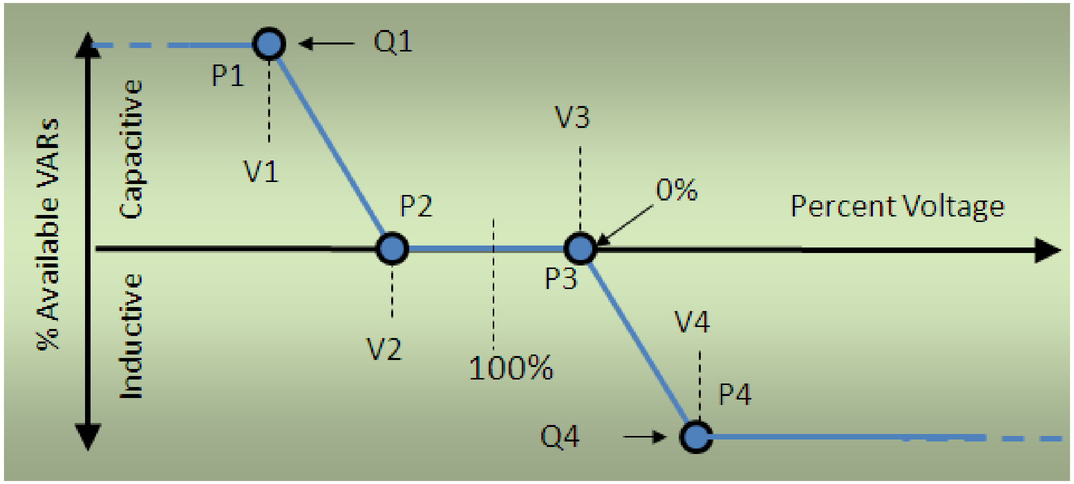


Source: Dr. Mahesh Morjaria; First Solar

Voltage Regulation – Reactive Power Support

- Power factor setting
- Constant VAR consumption/injection
- Volt-VAR control
- Voltage Setpoint





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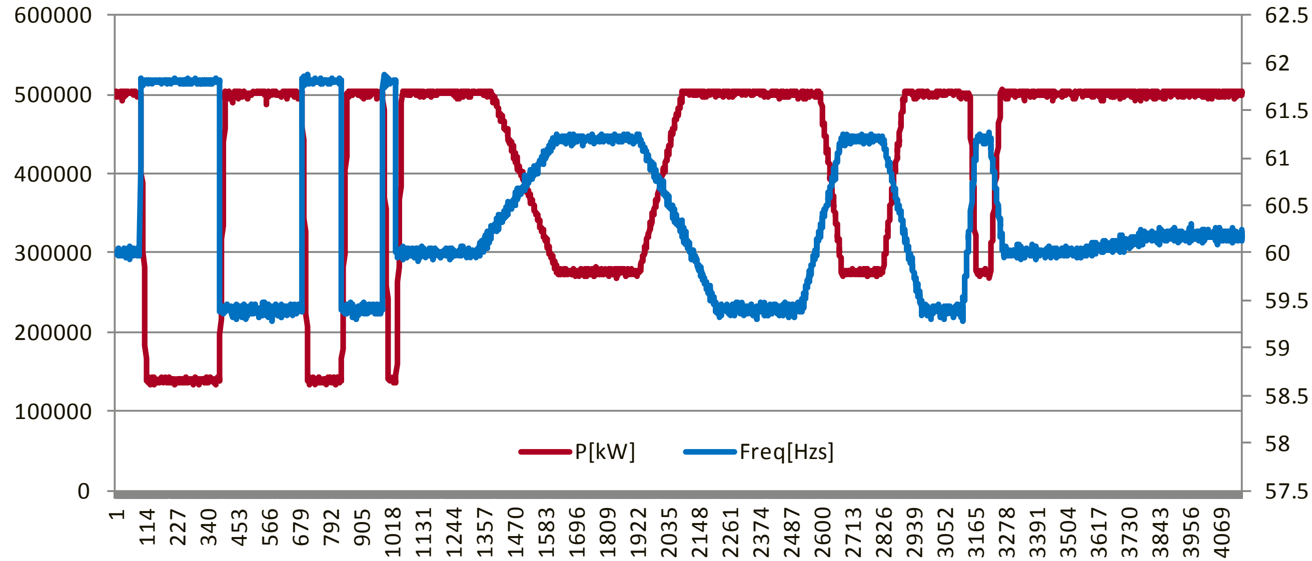
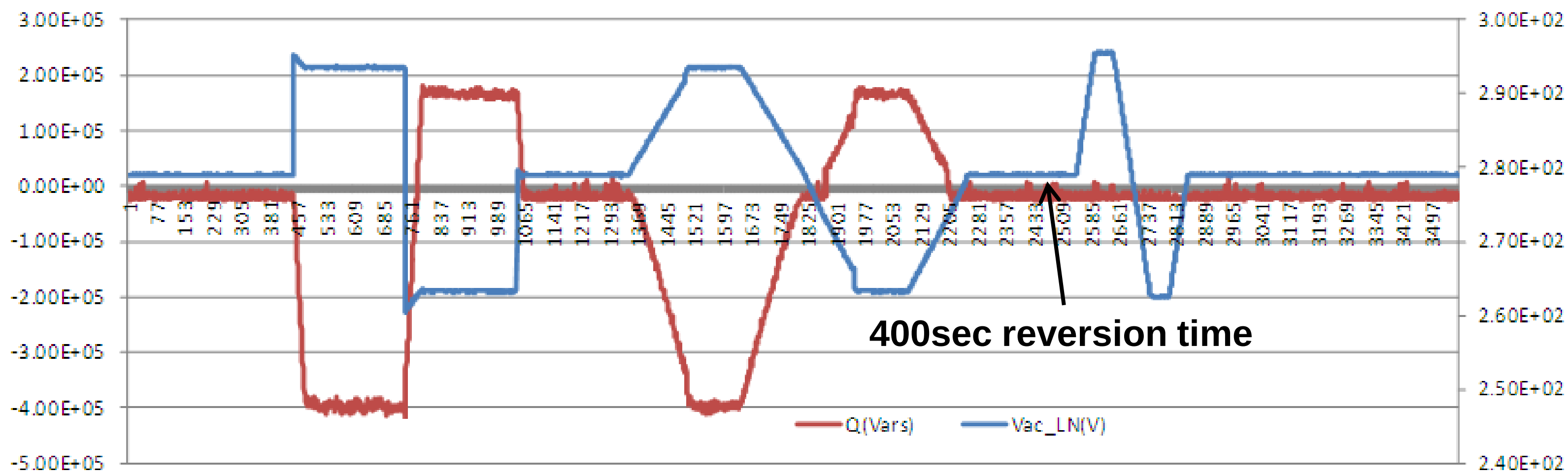
Test Results from NREL's ESIF

Frequency-Watt Function

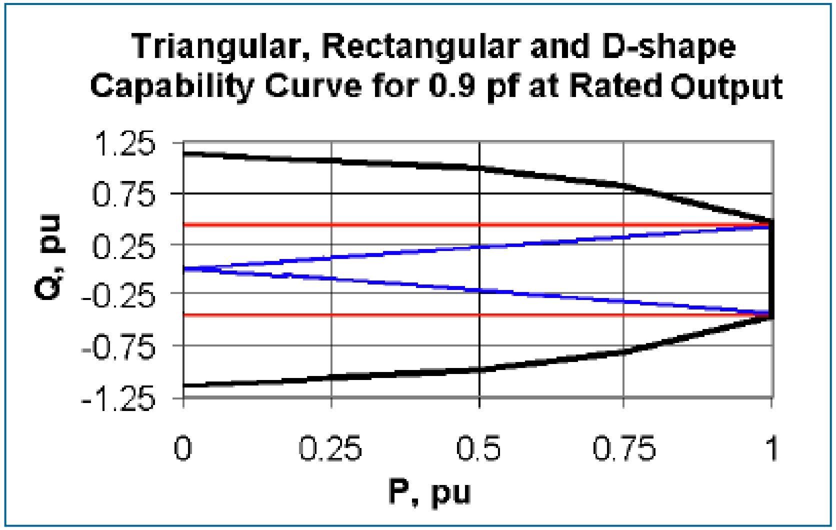


Volt-Var Function

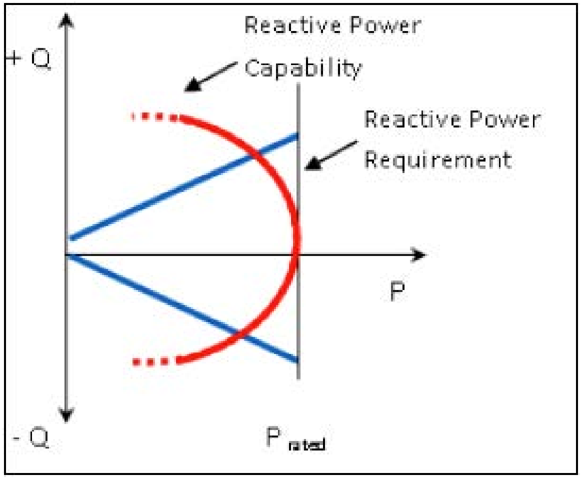


Considerations: Reactive Range

Typical Type 3/4 WTG VAR Capability Options



PV Capability (I limits) Vs. Triangle Require.



- Plant requirements can differ
  - Reduced range at low wind/PV levels
- Solar PV inverters over-sized for full range at max power output
  - historically distribution w/unity PF control
- Dynamic vs. static capability
  - switched shunts often included for static range
  - SVC/STATCOM may be used for additional dynamic range

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Bulk System Reliability Impacts and Benefits of Inverter Generation Support

March 31, 2014

General Reliability Concerns

Reliability Functions

- Reactive power/voltage control
- Active power control
  - inertia/primary freq response
- Disturbance performance
  - voltage & frequency ride through

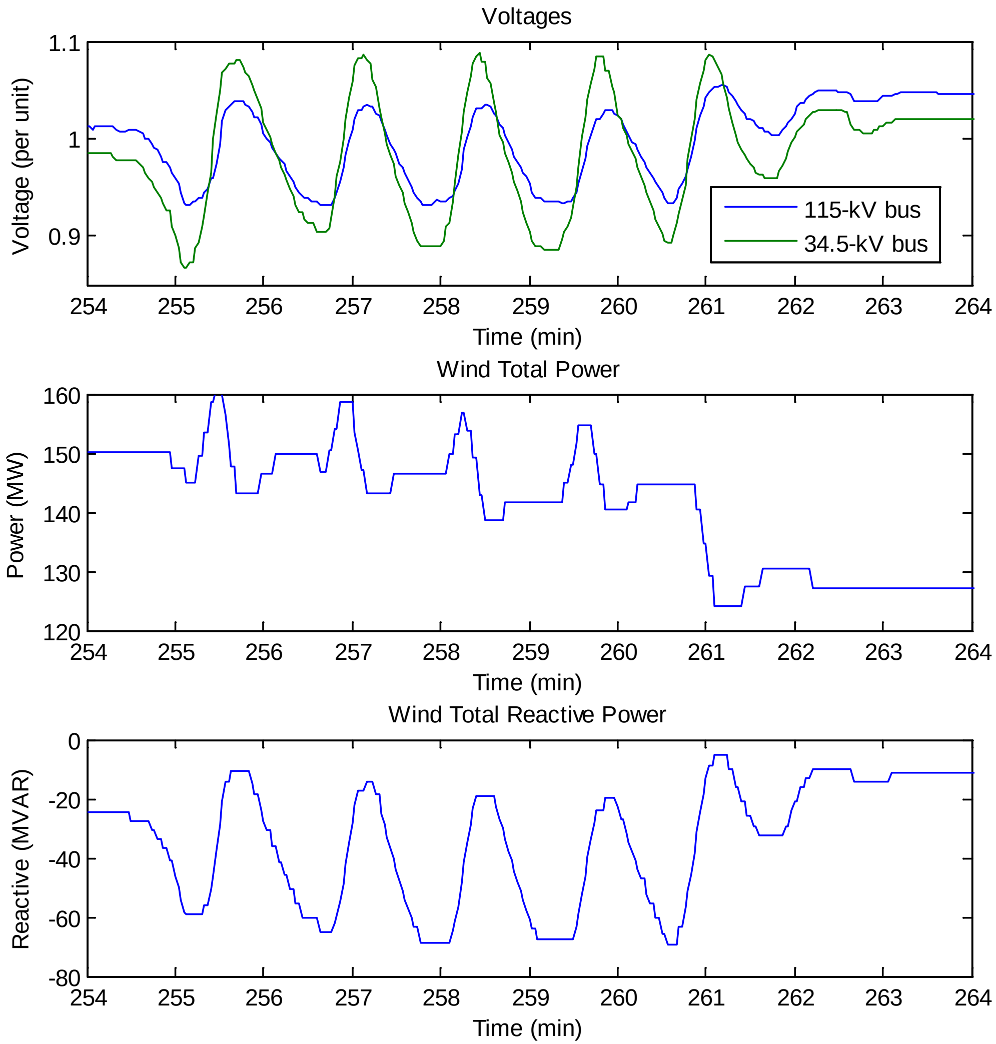
Other Considerations

- Inverter capabilities
- Available headroom for wind/PV
- Distribute

Inverter-Based Generators must supply Reliability Services as they Displace Conventional Sources of those reliability services!

Reactive Power & Voltage Control

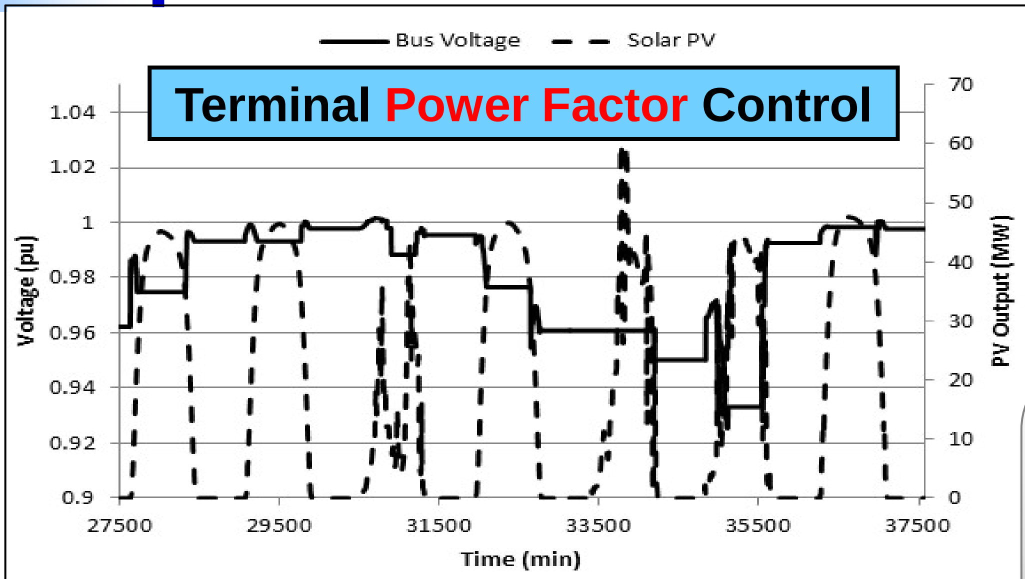
Voltage Support Is Necessary!

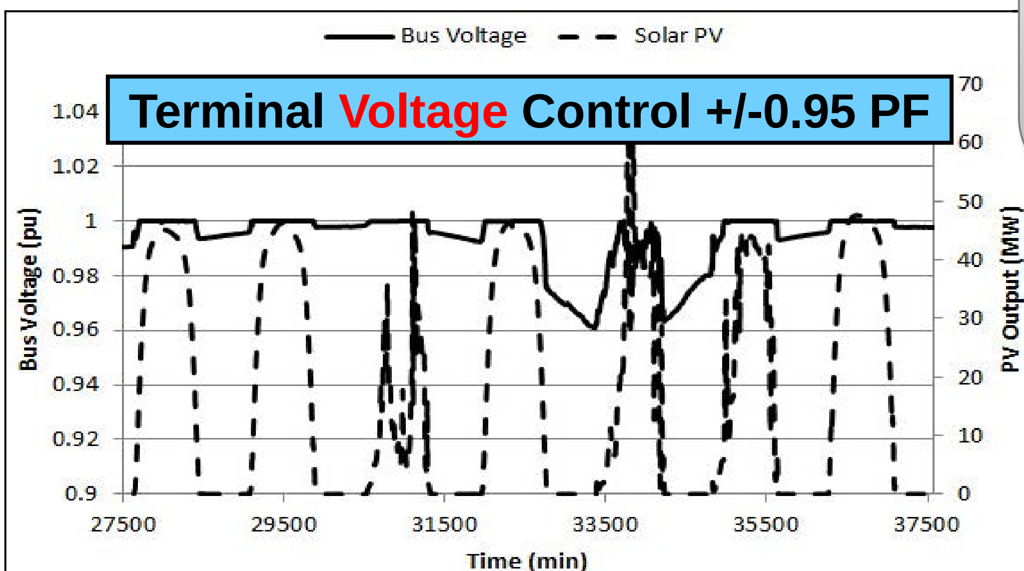


- Measured voltages → 150 MW WPP Connected to 115-kV
- Project did not have dynamic reactive capabilities
- Several "oscillatory" events were observed with all lines in service
- The power output was curtailed
- STATCOM with voltage controller was installed

SOURCE: Dmitry Kosterev, BPA, "BPA Wind Voltage Control Requirements," presented at EPRI/NREL/PJM Inverter Generation Interconnection Workshop, Apr 11-12, 2012.

EPRI PV Voltage Control Project** Results
Impact of PV Reactive Power Control





***Bulk Electricity System Impacts of Distributed and Transmission System Connected Solar PV*, EPRI, Palo Alto, CA: 2012. 1024349.**

- **Selected Bus Voltage -- July**
- **High solar PV output**
- **PF Control → Lower Voltages**
- **Voltage Control → More Robust Voltages**

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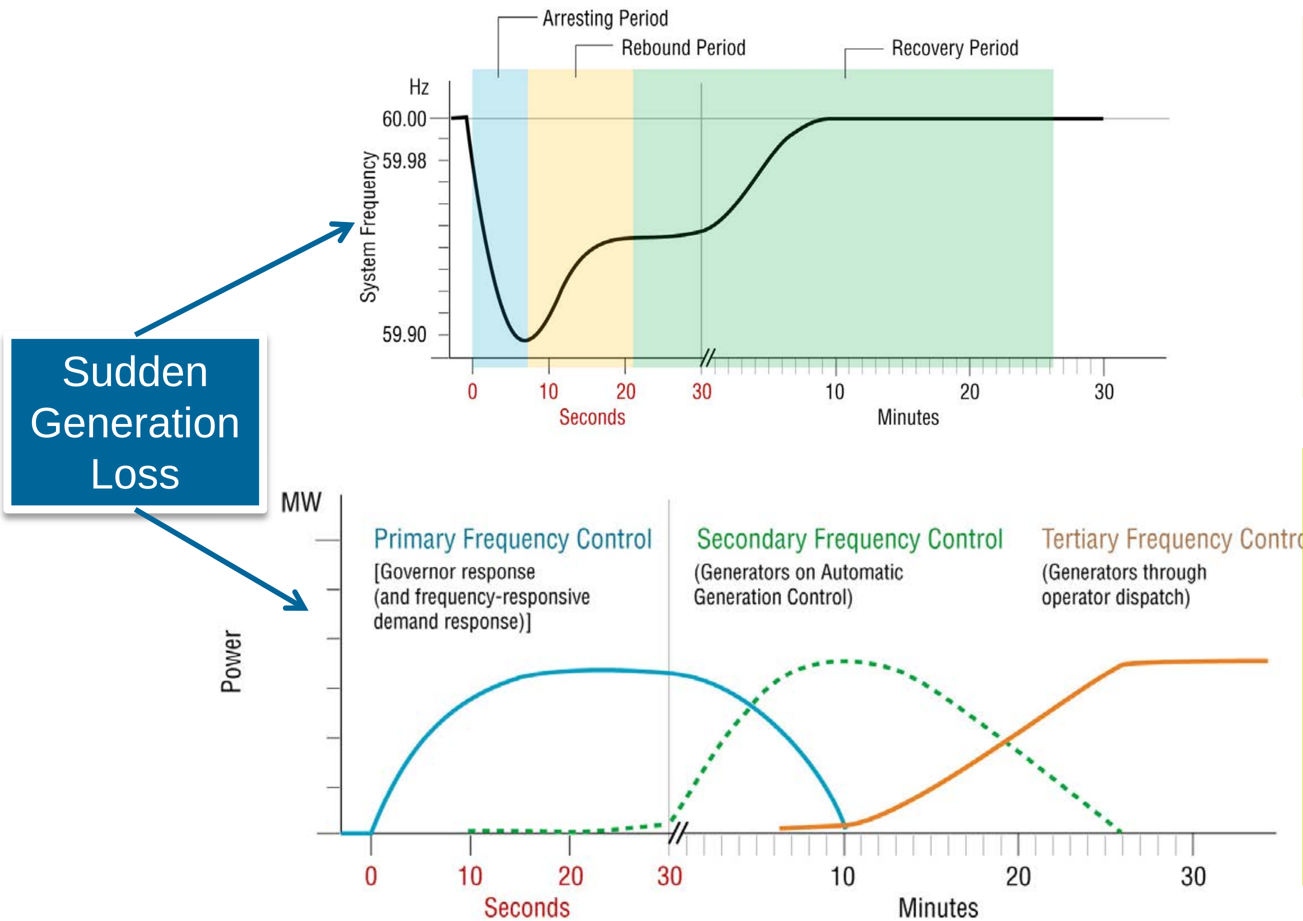
Active Power Control

High Levels of Inverter-Based Generation Can Impact Frequency Stability

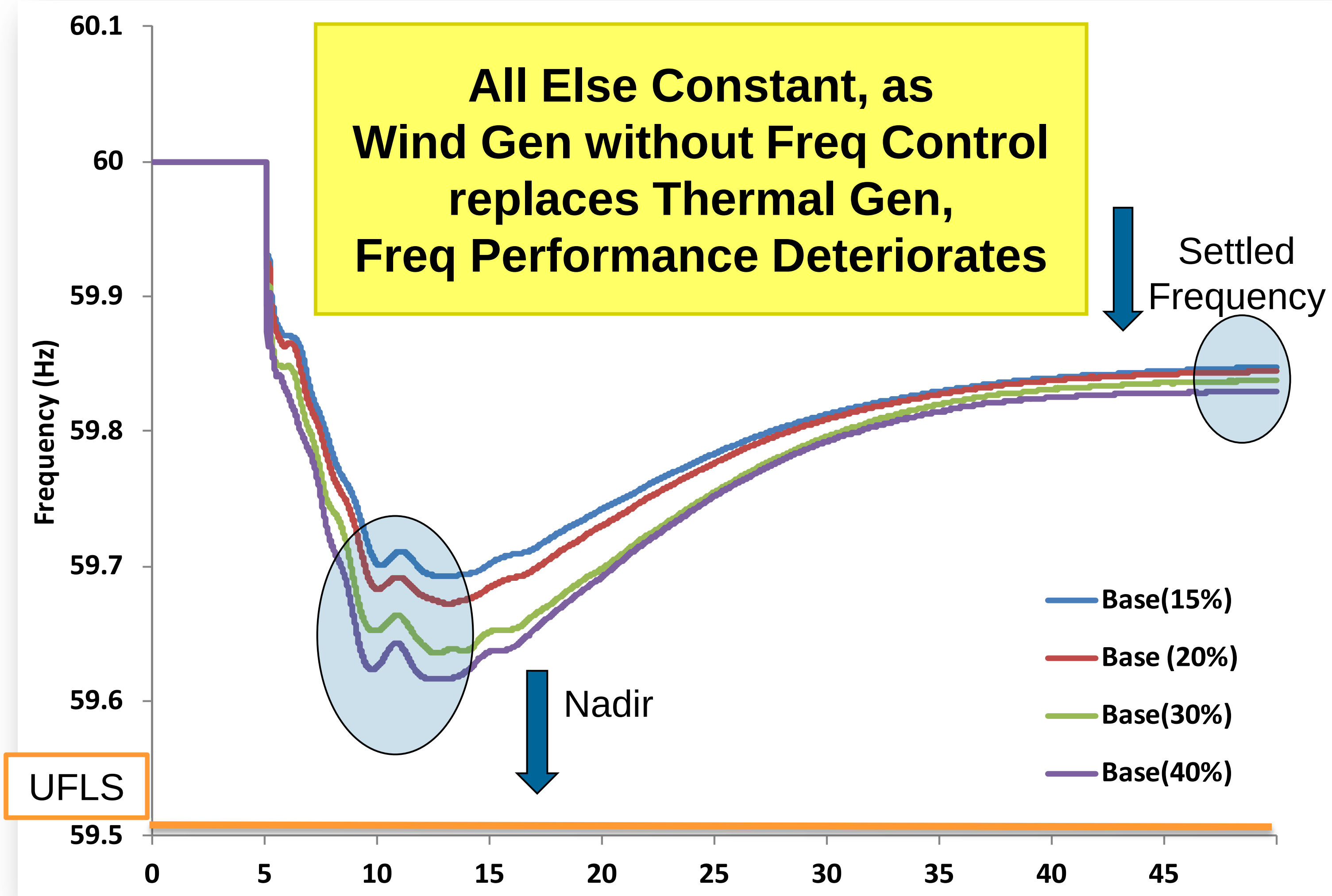


VG may displace conventional units & reduce system inertia & primary frequency response

Non-synchronous VG may provide inertia & primary frequency response through power electronics

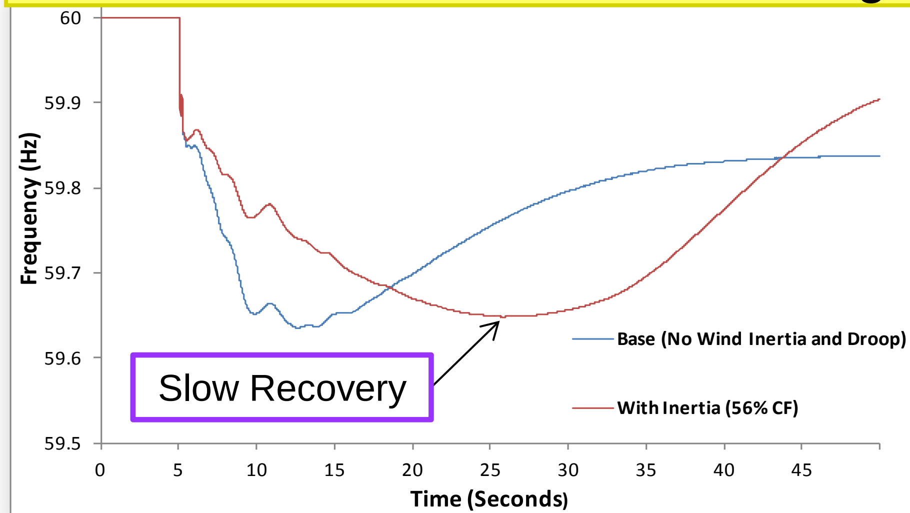
Graphics Source: LBNL-4142E ***Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation,*** *Prepared for Office of Electric Reliability Federal Energy Regulatory Commission, Dec 2010*

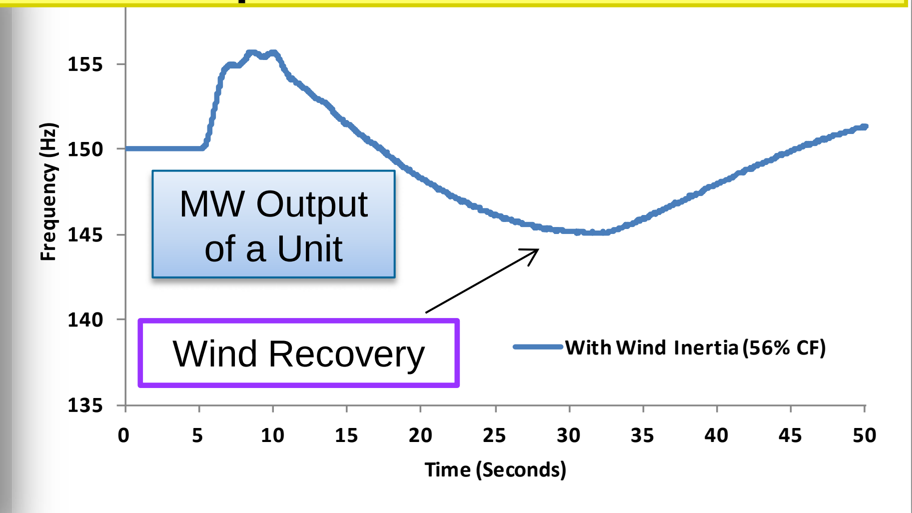
EPRI Frequency Response Project (WECC)
Impact of Wind Without Frequency Response



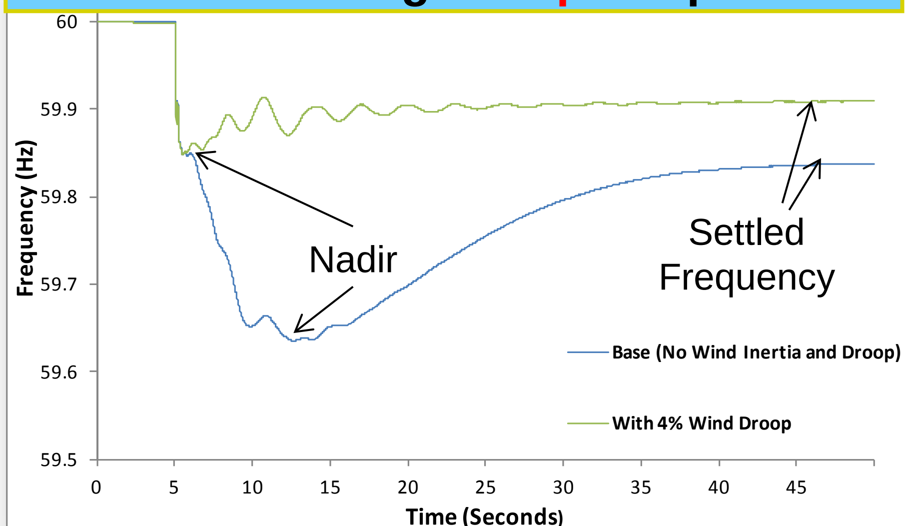
EPRI Frequency Response Project (WECC) Benefits of Wind With Frequency Response

Wind Providing Inertial Response





Wind Providing Droop Response



- **Wind Inertia & Droop Control Improve Freq Performance**
- **Controls must be tuned to ensure desired performance**

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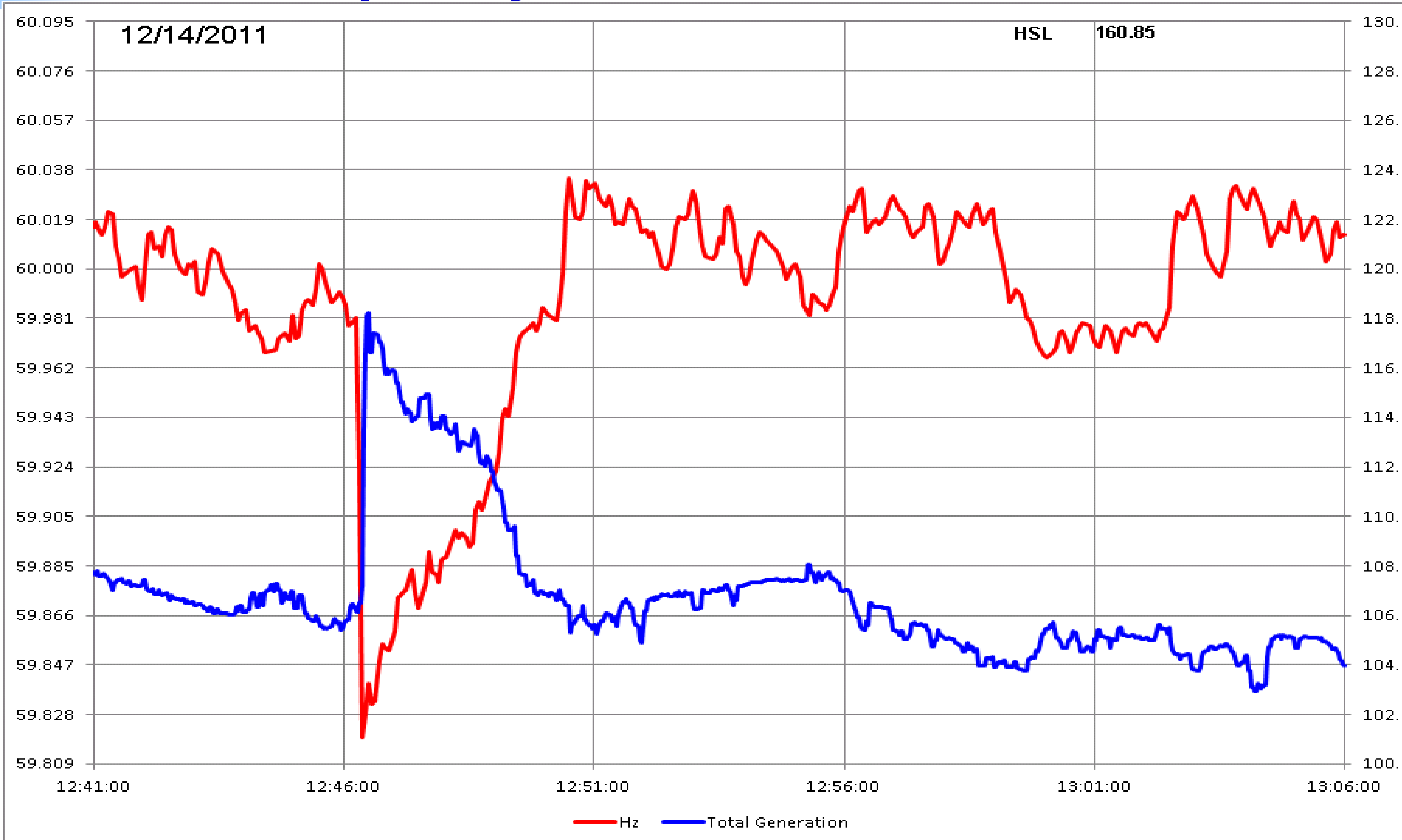
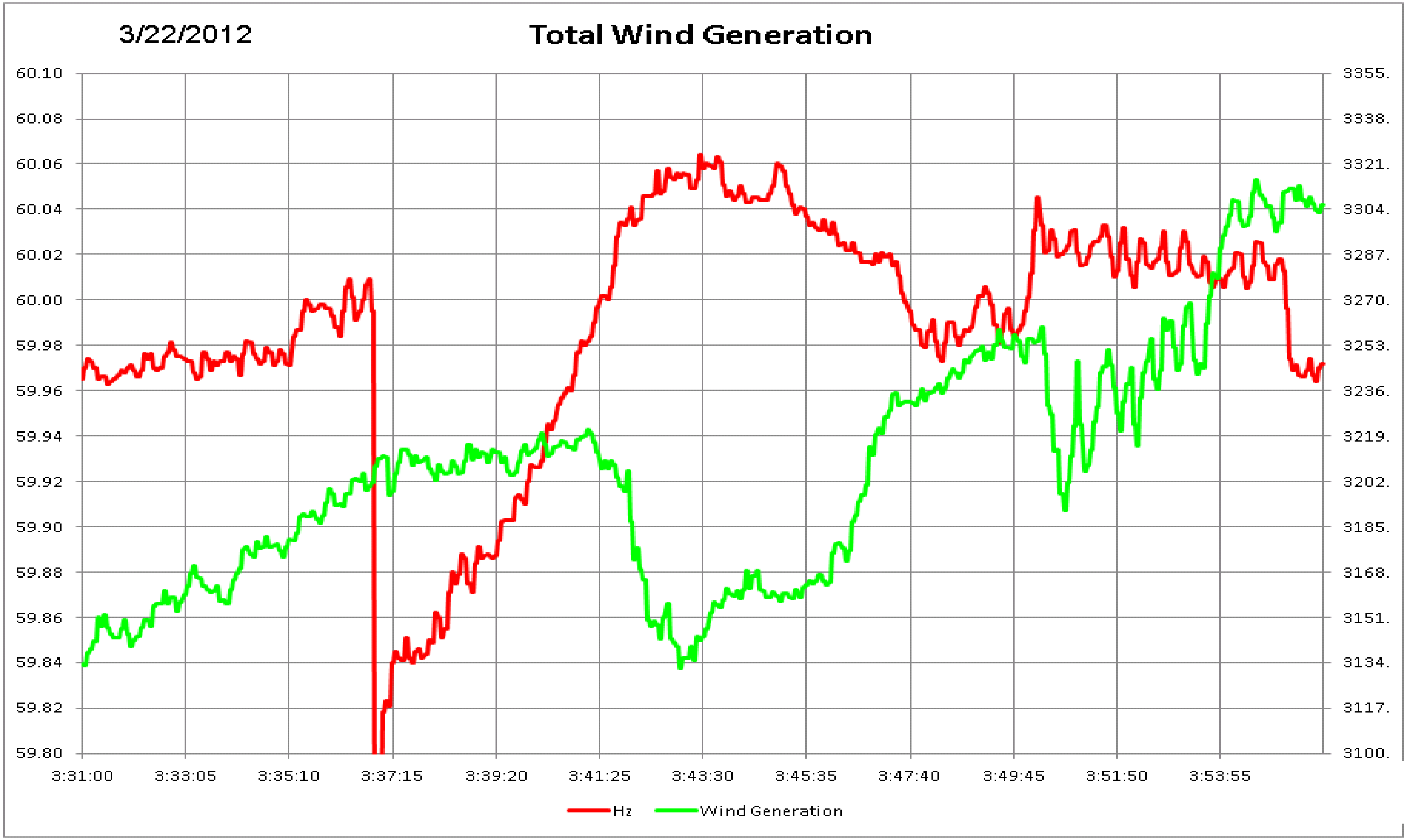
ERCOT – Measured Wind Generator's Response to Low Frequency



SOURCE: Sandip Sharma, ERCOT, "Frequency control requirements and performance in ERCOT ISO," presented at EPRI/NREL/PJM Inverter Generation Interconnection Workshop, Apr 11-12, 2012.

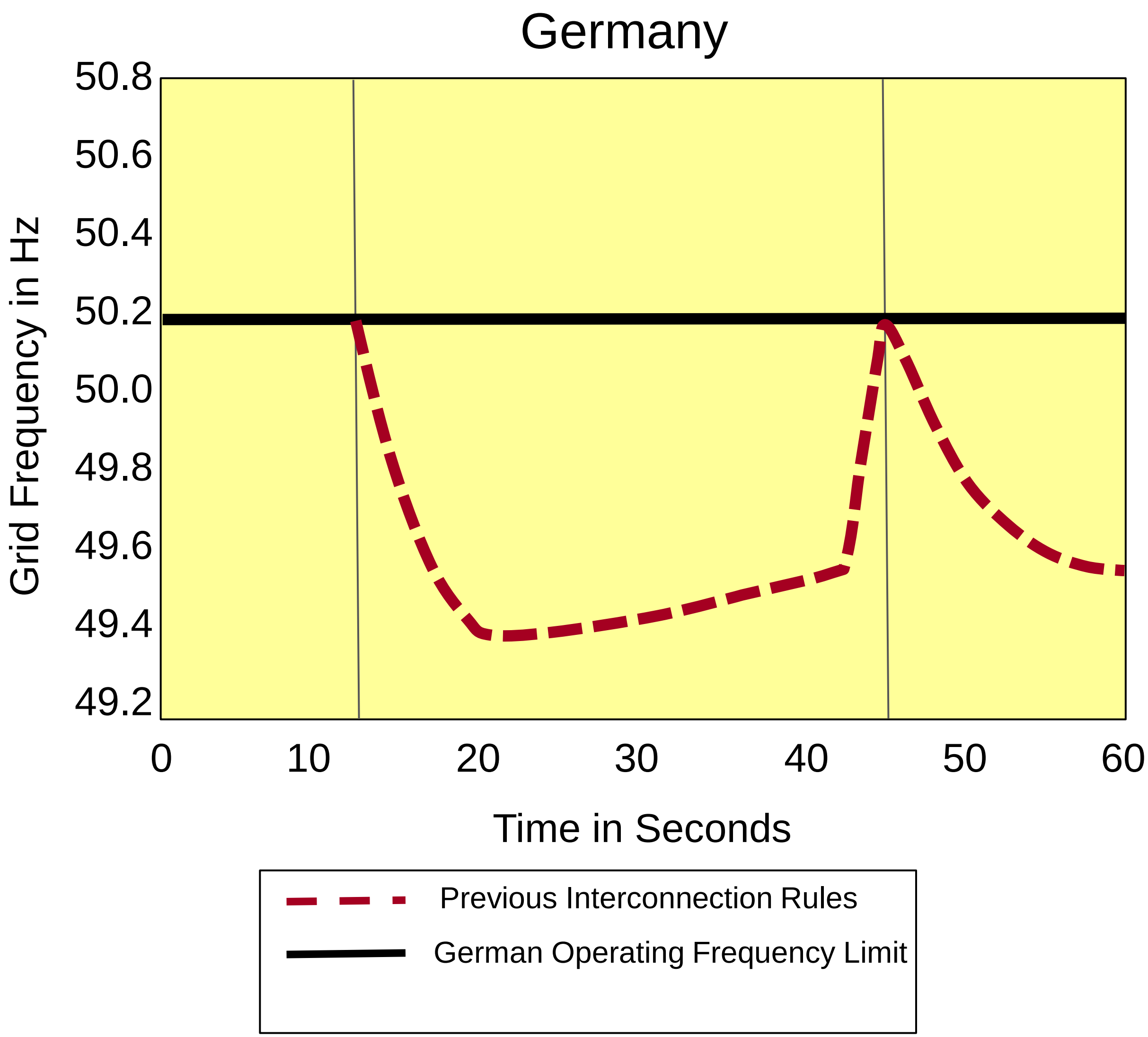
ERCOT – Measured Wind Generator's Response to High Frequency



SOURCE: Sandip Sharma, ERCOT, "Frequency control requirements and performance in ERCOT ISO," presented at EPRI/NREL/PJM Inverter Generation Interconnection Workshop, Apr 11-12, 2012.

Disturbance Performance

Frequency Ride-Through: Risk of Wide-Spread PV Disconnection



As of 2012 PV Inverters were not required to provide frequency support and disconnect from the grid if the frequency reaches 50.2 Hz

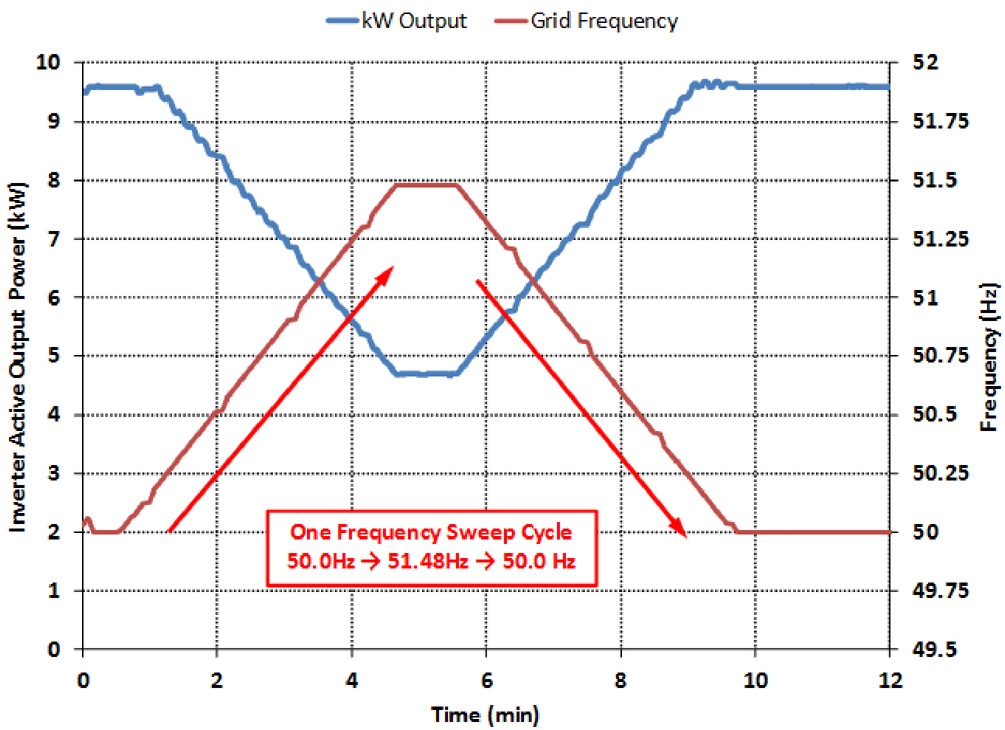
This is similar to all current interconnection requirements in US as per IEEE 1547-2003

Source: T. K. Vrana (2011)

Changes in German Grid Code

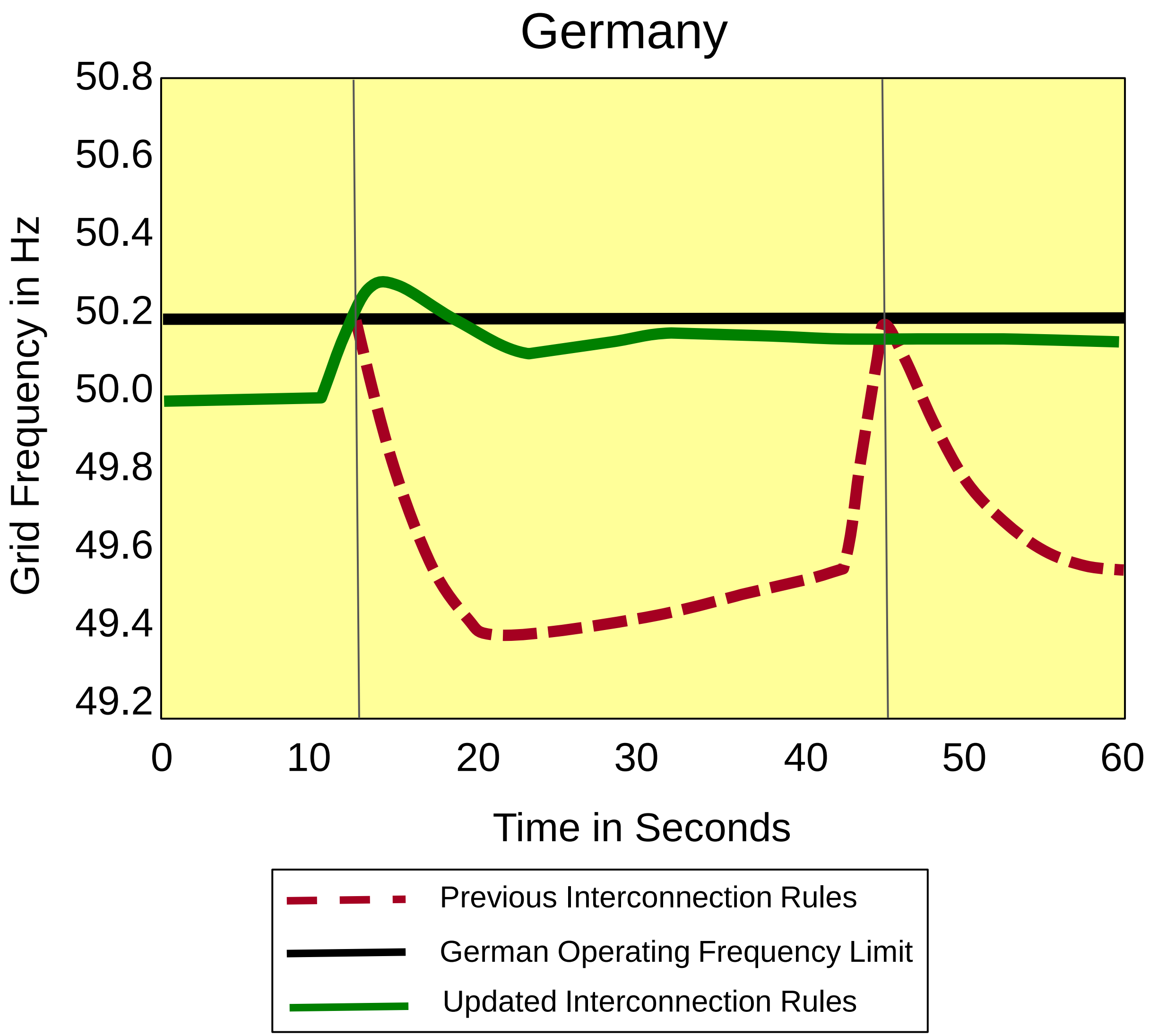
Frequency Support

- **Frequency control is required of all generators**
  - Instead of disconnecting @50.2 Hz, gradually reduce active power output (droop curve) in proportion to the frequency
  - Retrofit cost mostly through software update ~ $100-250M



Enacted through EEG (German Renewable Energy Sources Act) & EnWG (German Law on the Energy Industry)

Updated Interconnection Rules Reduces Risk of Frequency Instability



Source: T. K. Vrana (2011)

Distributed PV Potential Impact: Low Voltage Ride-Through

FERC Order 661A

- Interconnection of wind plants
- Requires wind plants remain in service during
  - Normally cleared 3-phase faults to a max. 9 cycles (TOP to provide clearing time)
  - 1-phase faults with delayed clearing
  - TOP to provide post-fault voltage recovery

Must NOT TRIP Requirement

IEEE Standard 1547-2003**

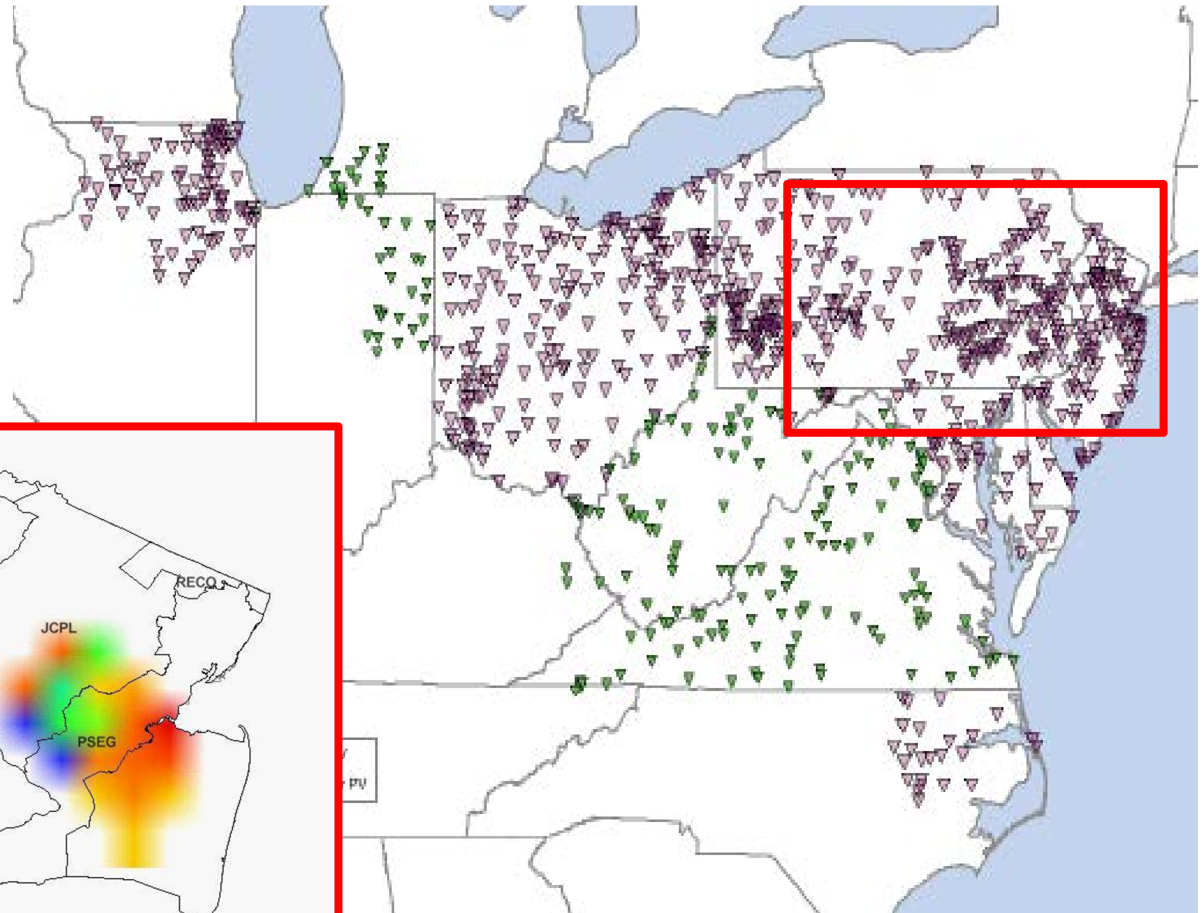
- Interconnection of DER
- Requires wind plants disconnect during

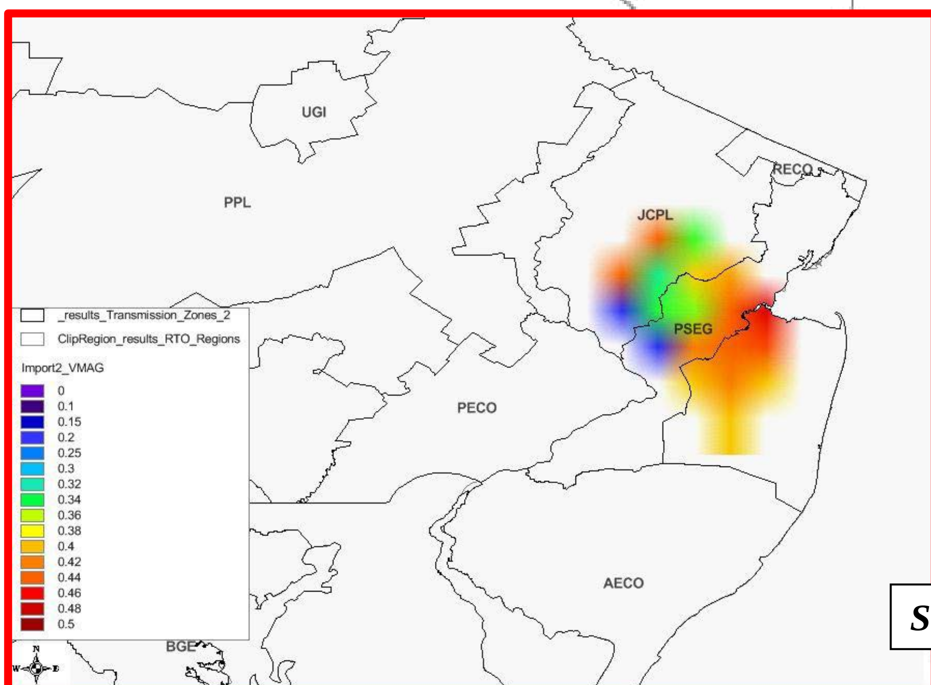
Voltage Range (% base voltage)	Clearing time(s)
V < 50	0.16
50 ≤ V < 88	2.00
110 < V < 120	1.00
V ≥ 120	0.16

**Proposed Update in 1547a

Must TRIP Requirement

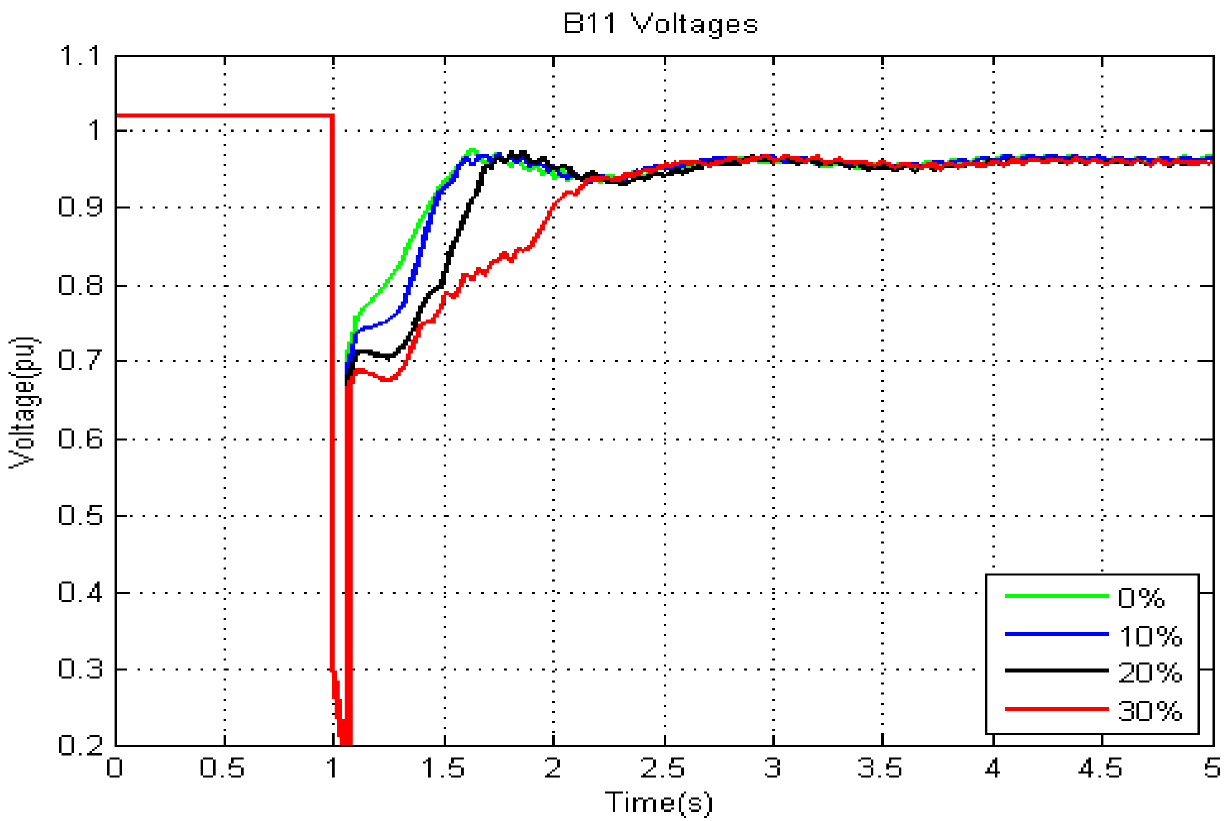
PJM Example LVRT Impact





Source: Mahendra Patel, PJM.

Example EPRI Simulation Results: Generic Case



As PV Increases → Voltage Recovery Increases

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Overview of Existing Interconnection Requirements

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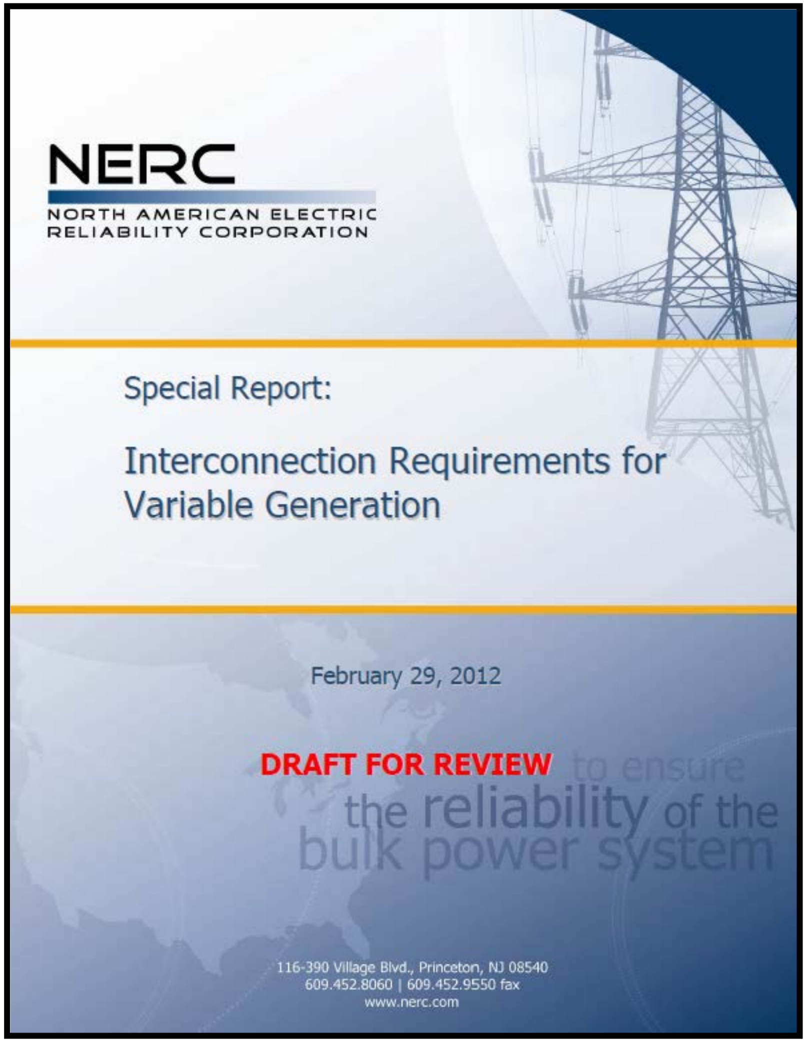
Must Have Interconnection Requirements as VG Penetration Levels Increase!

- Reactive power/voltage control
- Disturbance performance
  - voltage & frequency ride through
- Active power control capabilities
  - inertia/primary freq response
  - ramp rate control
- Models for studies
  - validated dynamic/SC models
- Communications between VG plants and grid operators



Bulk Transmission System Interconnection Requirements

Reactive Support: US – FERC Order 661A

- Only Wind Plants > 20 MVA
- Reactive Range Requirement:
  - ***PF range of +/- 0.95 at the POI
  - ***Provide dynamic voltage support
  - SVC or STATCOM can be used

*** If TO study confirms requirement for safety or reliability

Ambiguity/Difficulty in applying FERC 661A:

- **No specific quantification of Dynamic Range**
- **Justification Project-by-Project or All Projects**

Reactive Support: Example US TSOs

- ERCOT (Wind)
  - Continuous +/- 0.95 PF @ POI
  - Voltage control at setpoint
- BPA (Wind)
  - Dynamic Continuous +/- 0.95 PF @ 34.5-kV bus
  - Switched caps: cover VAR losses between WTGs & POI
  - Voltage control at setpoint
- CAISO (Wind and PV)***
  - Dynamic Continuous +/- 0.95 PF @ POI
  - Allow for reduced VAR capability at high/low voltage

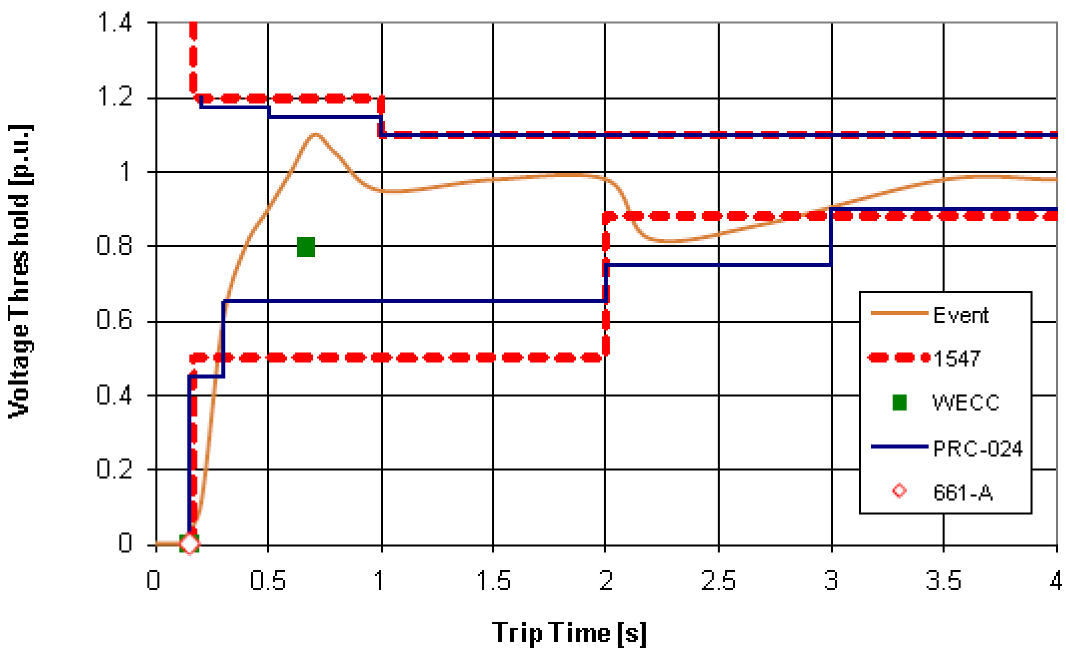
***Rejected by FERC

Active Power Control: Example TSOs

- Germany
  - Above 50.2 Hz reduce active power with a gradient of 40% of available power per Hz
- Hydro Quebec
  - Wind plants > 10 MW
  - Inertial response similar to a conventional generator (3.5 s) only for freq. disturbances >0.5 Hz
- ERCOT
  - PFR for over-frequency events w/5% droop
  - PFR for under-frequency if headroom (curtailed or above rated wind speed)

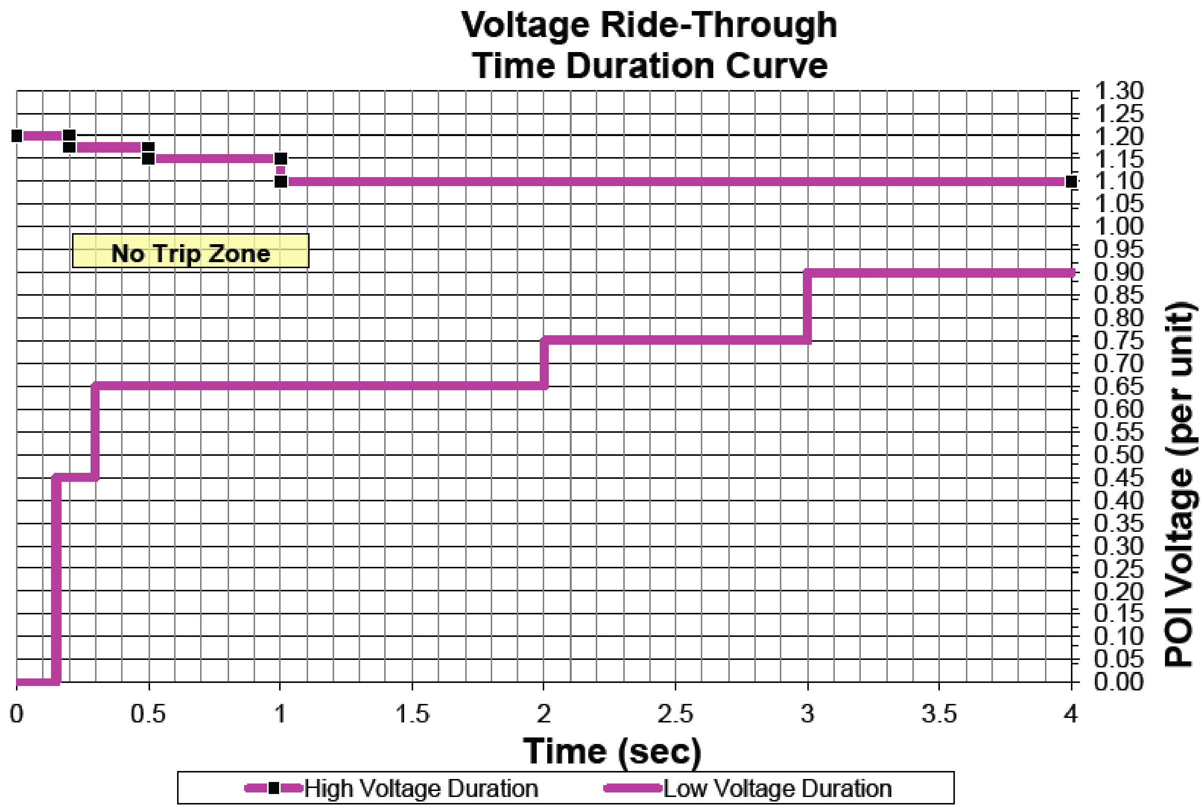
Low Voltage Ride Through: FERC Order 661A

- LVRT requirement only; No high voltage requirement
- <u>Wind plant</u> ride through voltage to 0 at transformer primary
  - Normally cleared 3-phase faults (max. 9 cycles)
  - 1-phase faults w/delayed clearing
  - TOP provide:
    - clearing times
    - post-fault voltage recovery



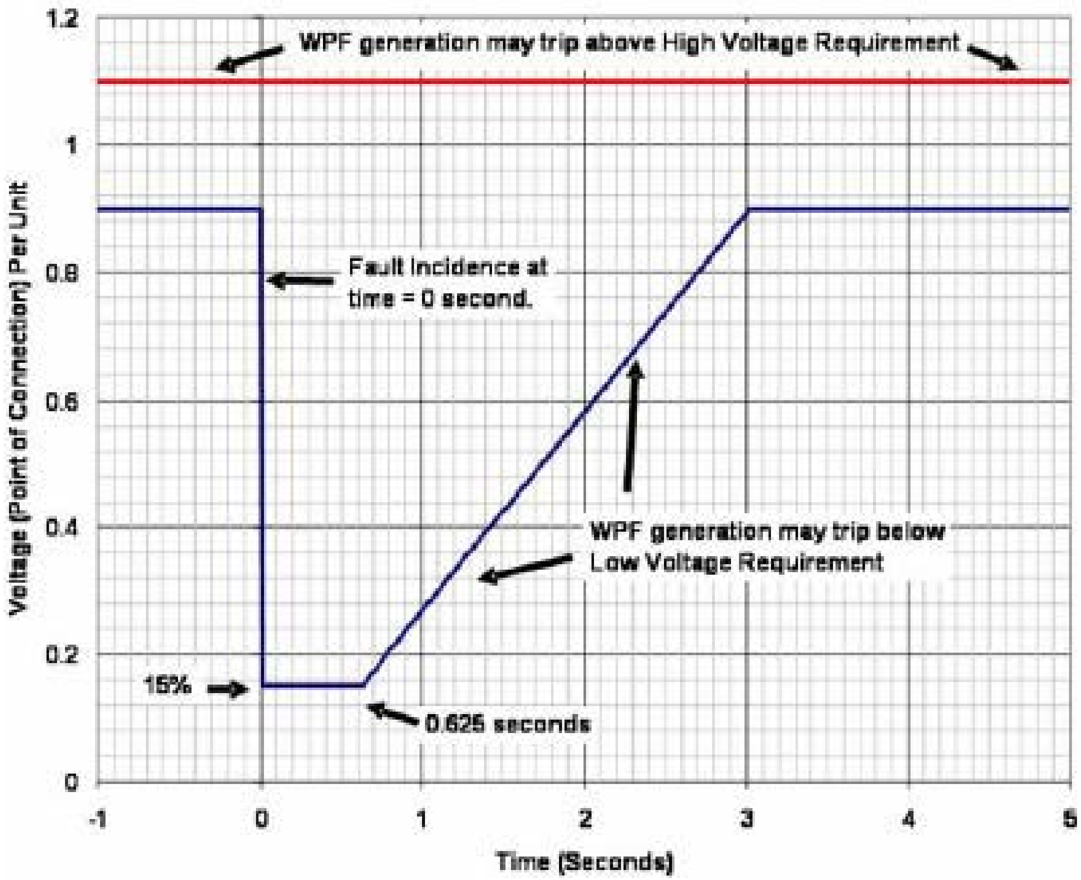
Low Voltage Ride Through: NERC PRC 024

- Applies to ALL generators
- Generator relay requirement
- NOT plant ride-through requirement



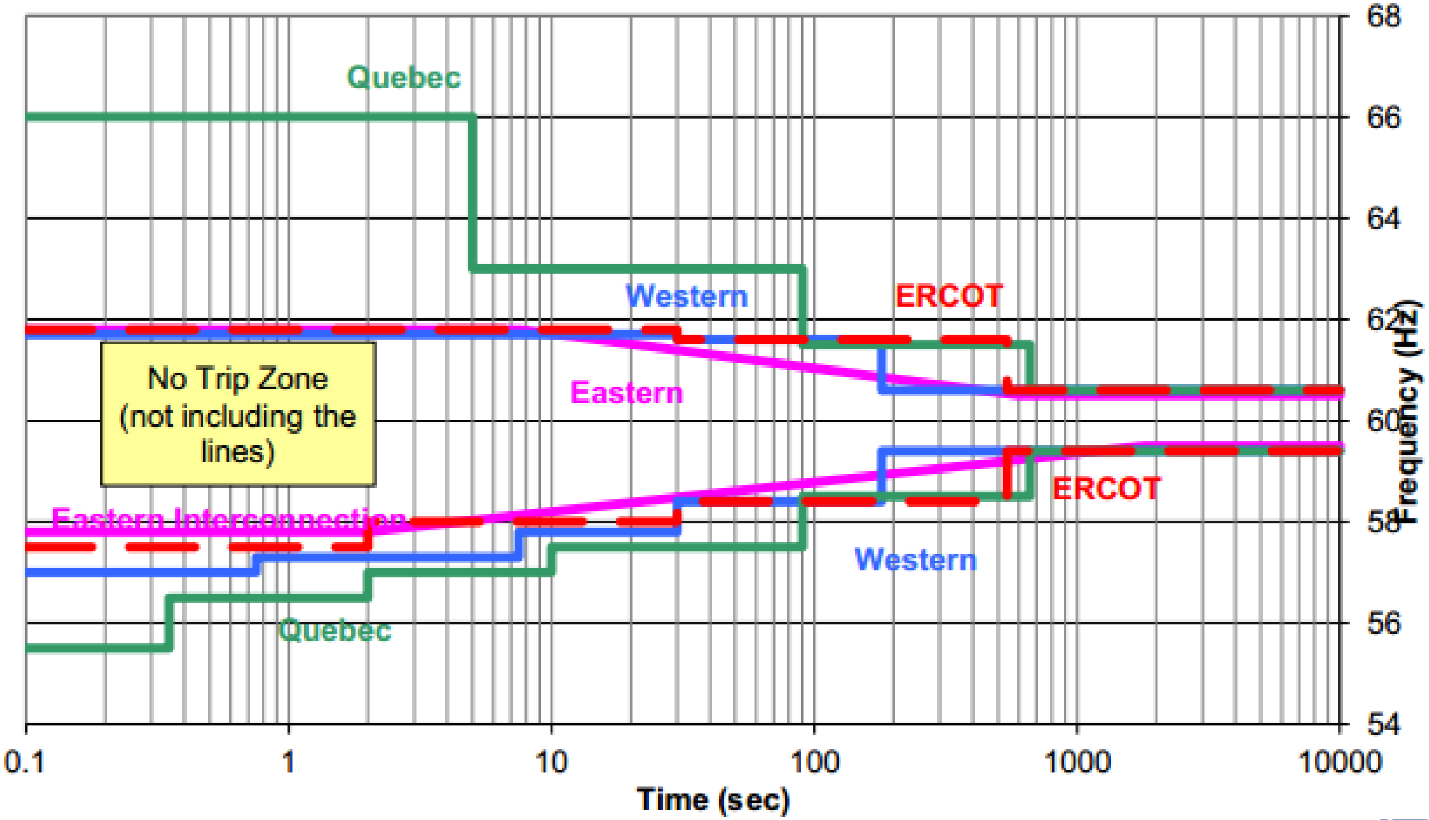
Voltage Ride-Through: AESO (Canada)

AESO standard specifies via VRT (high and low) curve, similar to European approach



Frequency Ride-Through: NERC PRC 024

- Applies to ALL generators
- Generator relay requirement
- NOT plant ride-through requirement



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Distribution System Interconnection Requirements

The Grid Code for DG Situation in US

Standard referred in most interconnection requirements in US

1547 – 2003: focused on low penetration and prohibits DG providing voltage or frequency support or requiring EMS capability *(smart inverter functionality will need to be disabled to meet IEEE 1547/UL1741)*

1547a – 2014: Draft Amendment is available; does not prohibit V/F support but does not require it and also does not require EMS capability

1547 – Revision: Full revision of IEEE 1547 will start in April 2014; Possibility for accelerating 1547 revision by developing inverter specification as per 1547

EPRI Working on Recommended Technical Guidelines for Smart Inverter Advanced Grid Support Function Settings

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Major Changes in 1547 Amendment

IEEE 1547 – 2003	IEEE 1547a - 2014
DR shall not actively regulate the voltage at the PCC	DR may actively participate to regulate the voltage by changes of real and reactive power
DR shall cease to energize if frequency >60.5Hz	DR shall be permitted to provide modulated power output as a function of frequency
Tighter abnormal V/F trip limits and clearance times	Much wider optional V/F trip limits and clearance times
	Under mutual agreement between the EPS and DR operators, other static or dynamic frequency and clearing time trip settings shall be permitted.

Changes in "*Response to Abnormal Voltages*"

Table 1—Interconnection system response to abnormal voltages

Voltage range (% of base voltage[a])	Clearing time(s)[b]
V< 50	0.16
50 ≤ V< 88	2.00
110 < V < 120	1.00
V ≥ 120	0.16

[a]Base voltages are the nominal system voltages stated in ANSI C84.1-1995, Table 1.
[b]DR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times.

IEEE 1547-2003

IEEE 1547a

Table 1 ~~Default~~ Interconnection system default response to abnormal voltages

Default settings[a]		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
V < 45	0.16	0.16
45 < V < 60	1	11
60 < V < 88	2	21
110 < V < 120	1	13
V > 120	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted
[b] Base voltages are the nominal system voltages stated in ANSI C84.1-20~~06~~11, Table 1.

Changes in "*Response to Abnormal Frequency*"

Table 2—Interconnection system response to abnormal frequencies

DR size	Frequency range (Hz)	Clearing time(s)[a]
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60.5	0.16
	< {59.8 – 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	0.16

[a]DR ≤ 30 kW, maximum clearing times; DR > 30 kW, default clearing times.

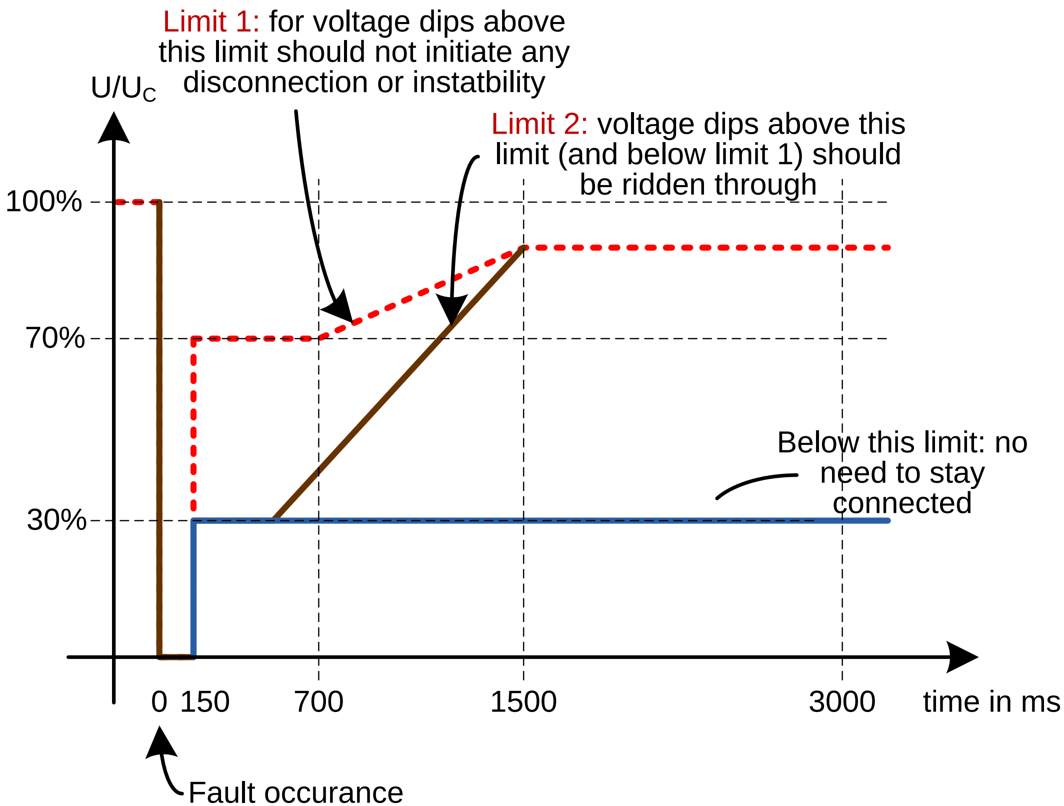
IEEE 1547-2003

IEEE 1547a

Table 2—Interconnection system default response to abnormal frequencies

	Default settings		Ranges of adjustability	
Function	Frequency (Hz)	Clearing time (s)	Frequency (Hz)	Clearing time (s) adjustable up to and including
UF1	57	0.16	56 – 60	10
UF2	59.5	2	56 – 60	300
OF1	60.5	2	60 – 64	300
OF2	62	0.16	60 – 64	10

Specific VRT Requirements – Germany: MV Grid Code



Source: BDEW, Technical Guideline, Generating Plants connected to MV network, 2008)

- Not to disconnect from network in the event of network faults
- Support with reactive current
- After fault clearance not to extract more inductive reactive power than prior to fault
- Reactive current on LV side of transformer 2% of rated current for each 1% of voltage dip (outside 10% deadband)

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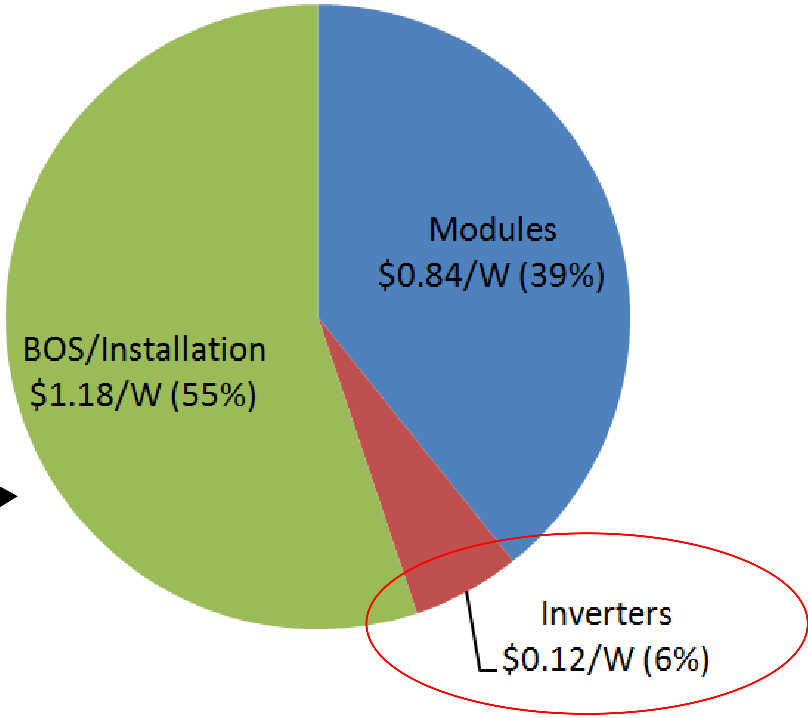
Cost Considerations for Advanced Inverter Functionality

March 31, 2014

Inverter Cost and Reliability Impacts PV System Performance

- Inverter cost is a small percentage of the total plant cost/installed cost
- Inverters with grid support functions are not expected cost any higher than current price once the interconnection requirements start incorporating the functional capabilities
- Communication (where needed!) cost will be additional

Average U.S. Utility-Scale PV Price Breakdown (May 2013)



Q1 2013 US PV System Cost

Residential - $4.93/W

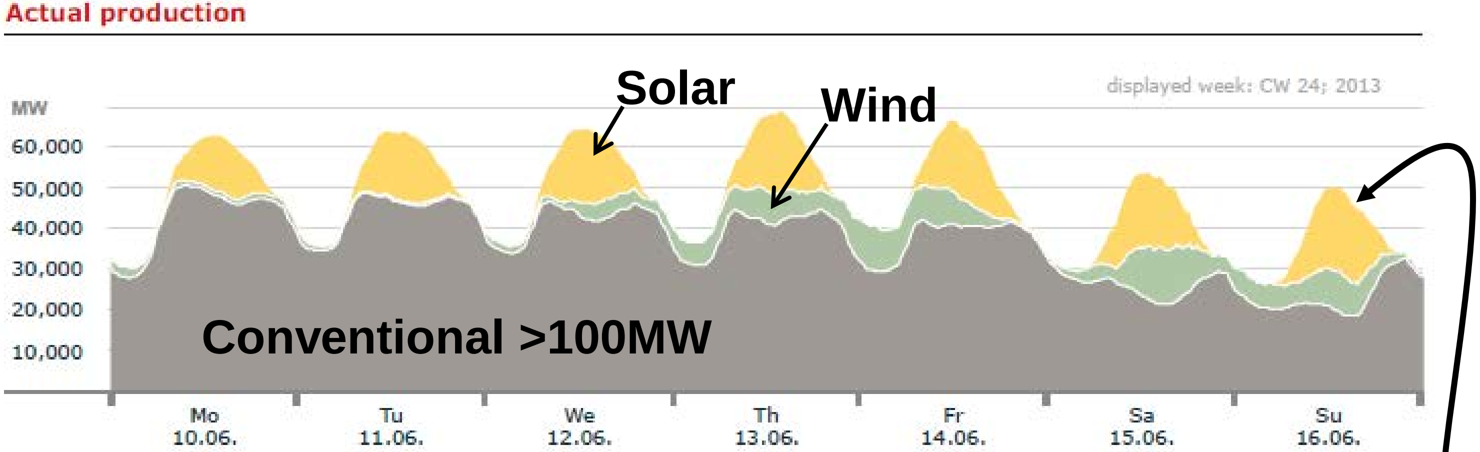
Commercial-scale - $3.92/W

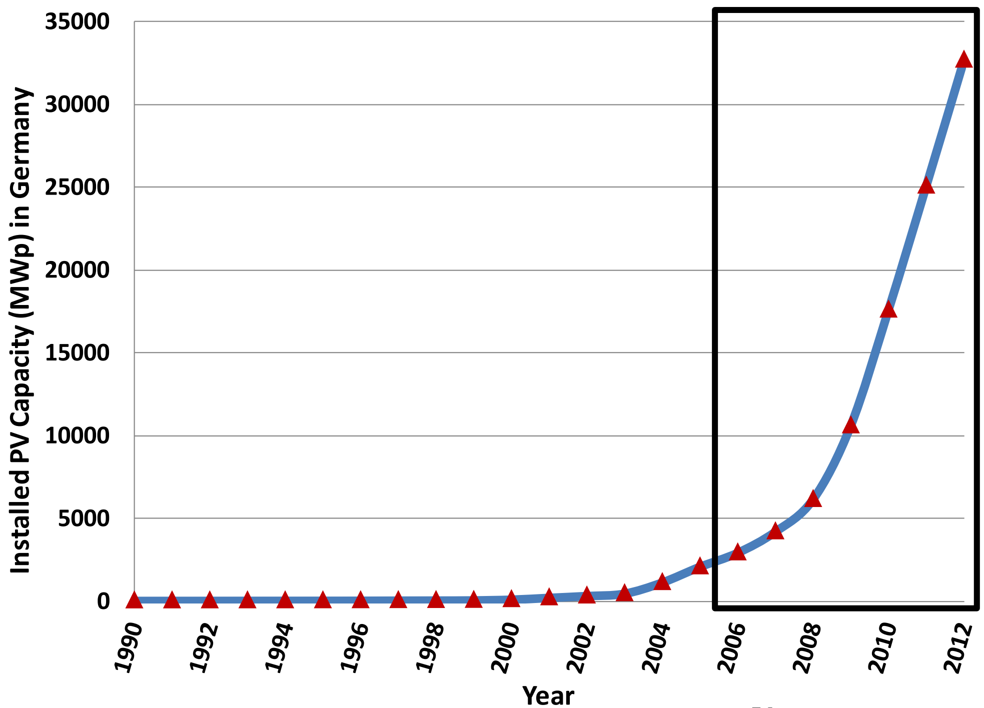
Utility-scale - $2.14/W

National average - $3.37/W

Sources: *Sources: GTM Research/SEIA, NREL, Lawrence Berkeley National Lab, BNEF, European Photovoltaic Industry Assn (EPIA), BSW Solar*

German Experience of High Penetration of PV





Bright, breezy Sunday between 2pm to 3pm

Grid at that time could take up to 45GW

PV and wind supplied 28.9 GW – more than half the total!

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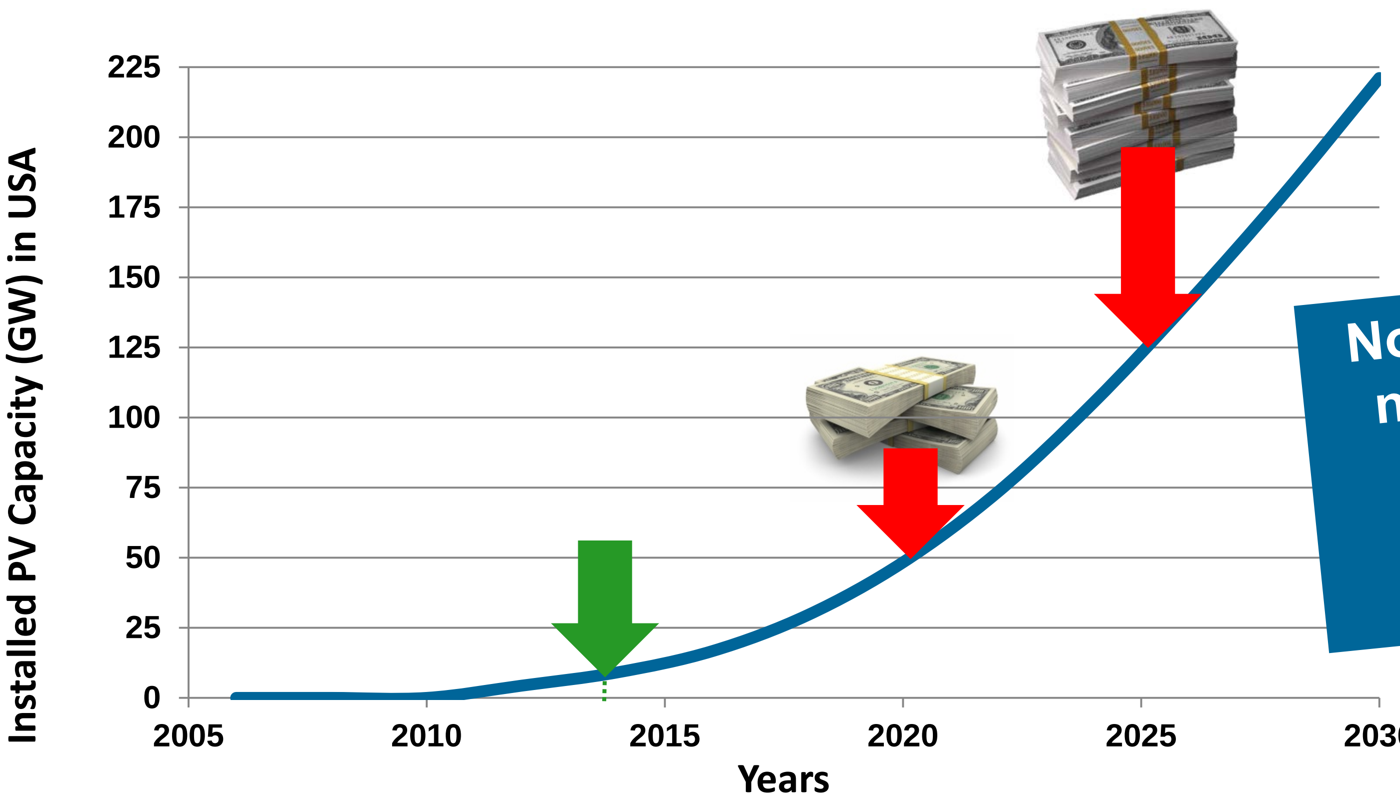
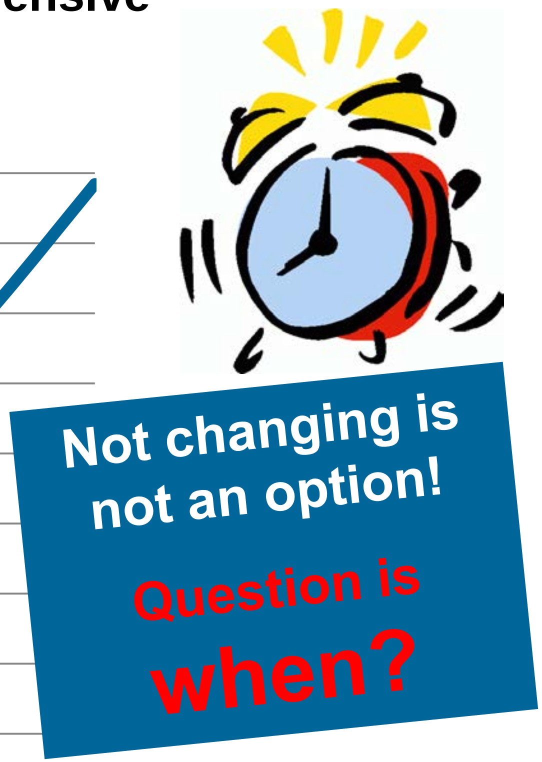
What if Standards are not Changed?

Retrofitting inverters in a later date could be pretty expensive





Source: DOE SunShot Vision Study (Total PV Capacity in U.S. 2008 – 2030)

Together…Shaping the Future of Electricity

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