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NREL NATIONAL RENEWABLE ENERGY LABORATORY

Greening the Grid

Best Practices for Grid Codes for Renewable Energy Generators

Adarsh Nagarajan, Ph.D. | Research Engineer | October 4, 2018

Topic for today's seminar: Grid Codes

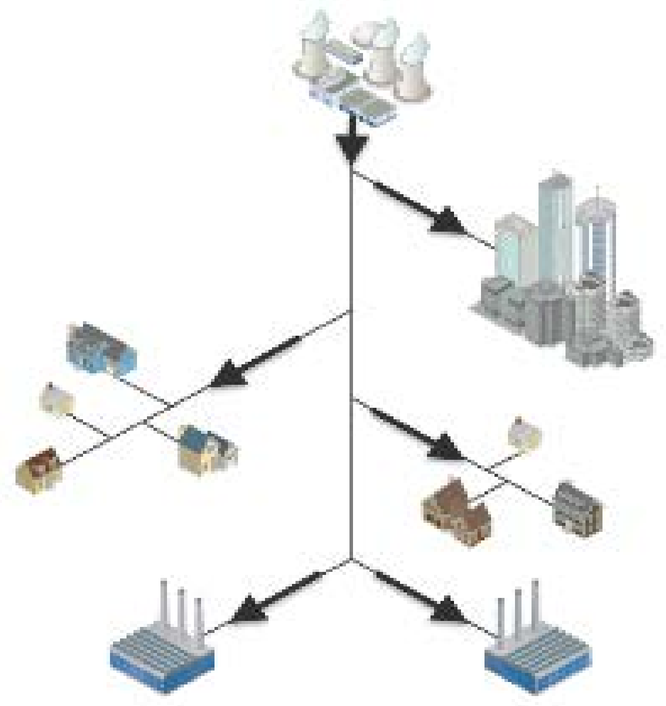
- What are Grid Codes: Key mechanisms that utilities use to ensure safe and reliable interconnection processes when connecting new resources

- Understand new challenges in the design and implementation of grid codes in different contexts.

- Review recent considerations such as voltage/frequency ride-through and voltage regulation of inverter-based variable generation on the grid.

Evolution of the grid →
Evolution of Distributed Energy Resource (DER) behavior

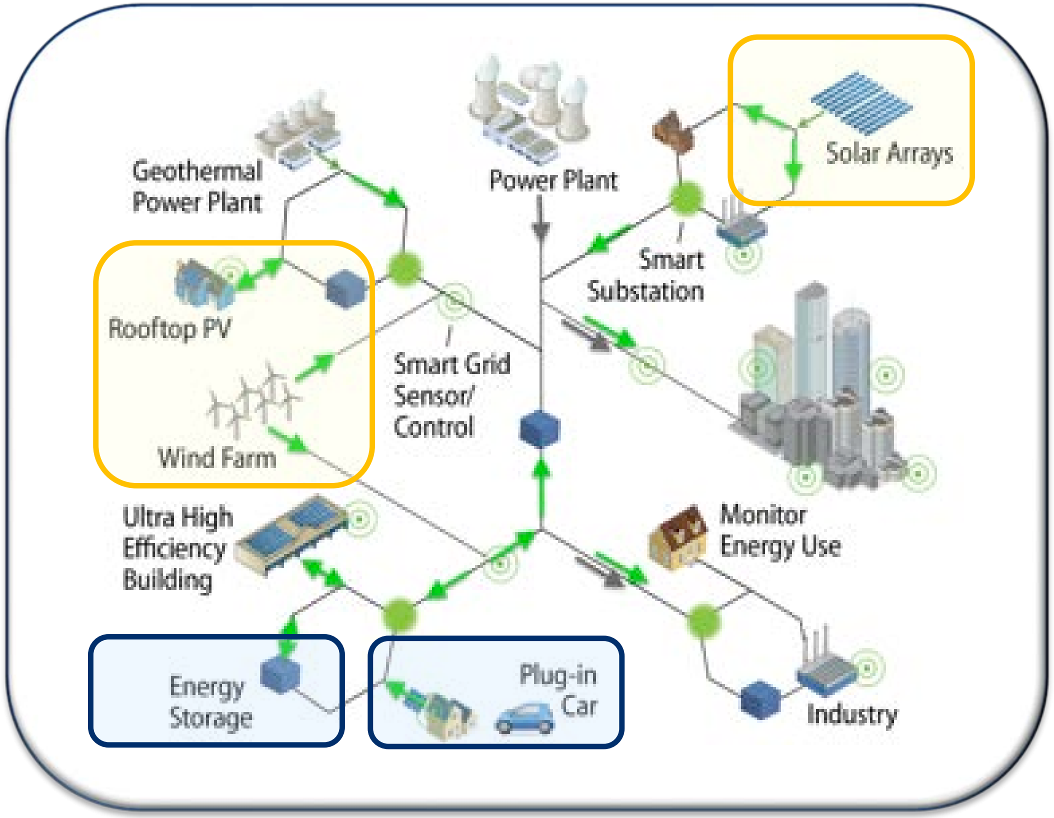
Legacy Power System



IEEE 1547-2003 World

Challenges
- Increased variable generation
- More bi-directional flow at distribution level
- Increased number of smart/active devices

Evolving Power System



IEEE 1547-2018 World

Content credit: Dr. Ben Kroposki, NREL

Our evolving power system context

- New inverter-based energy technologies (e.g., rooftop solar, storage)
- Increasing penetration of variable renewables
- New communications and controls (e.g., Smart Grids)
- Electrification of transportation
- Increased need for power system flexibility
- Updated standards – e.g. IEEE 1547-2018 (using DERs as grid assets)

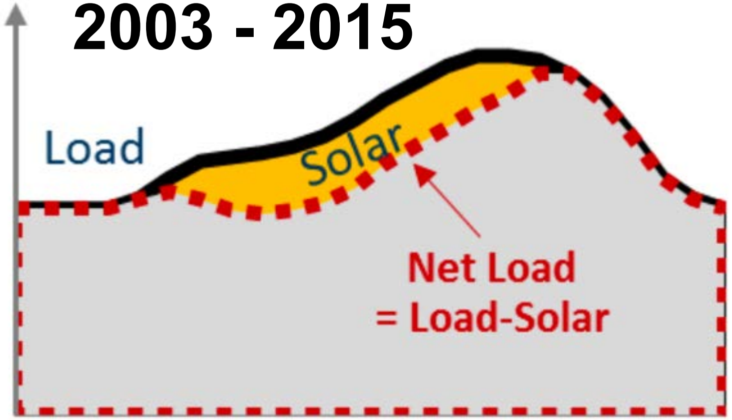
Content credit: Dr. Ben Kroposki, NREL

Role of evolving technologies and grid codes

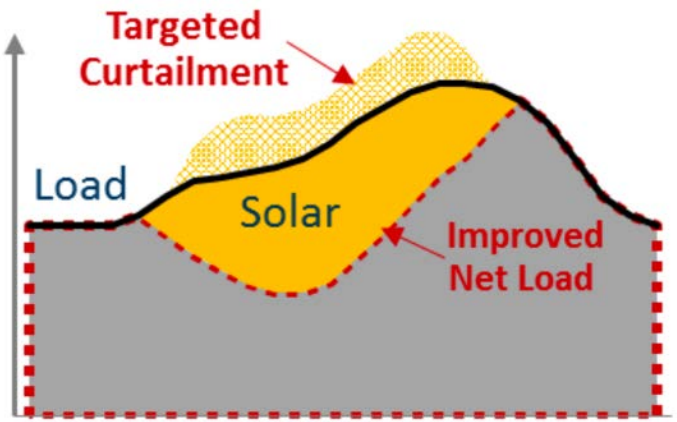
Value derived from energy

Solar is part of mid-day load, offsets peak or near-peak demand

2003 - 2015



2015 – 2017



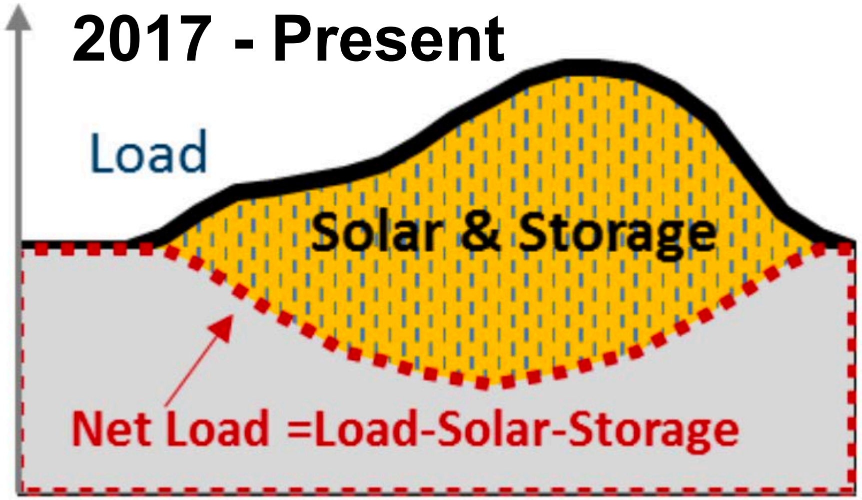
Grid services and flexibility

Solar mitigates value erosion through plant controls

Increased flexibility

Storage (hours, not days) shifts the timing of solar and makes it **dispatchable**

2017 - Present



IEEE 1547 evolution of grid support functions

IEEE 1547-2003

- Shall NOT actively regulate voltage
- Shall trip on abnormal voltage/frequency

IEEE 1547a-2014 (Amendment 1)

- **May** actively regulate voltage
- **May** ride through abnormal voltage/frequency
- **May** provide frequency response[1] (frequency-droop)

Numerous pilot studies in CA and HI

IEEE 1547-2018

- **Shall be capable of** actively regulating voltage
- **Shall** ride through abnormal voltage/frequency
- **Shall be capable of** frequency response[2]
- **May** provide inertial response[3]

Content credit: 1547-2018, Dave Narang - NREL

Key grid codes in shaping the U.S. market

California Rule 21

Hawaii Rule 14H

Essential services from solar and wind

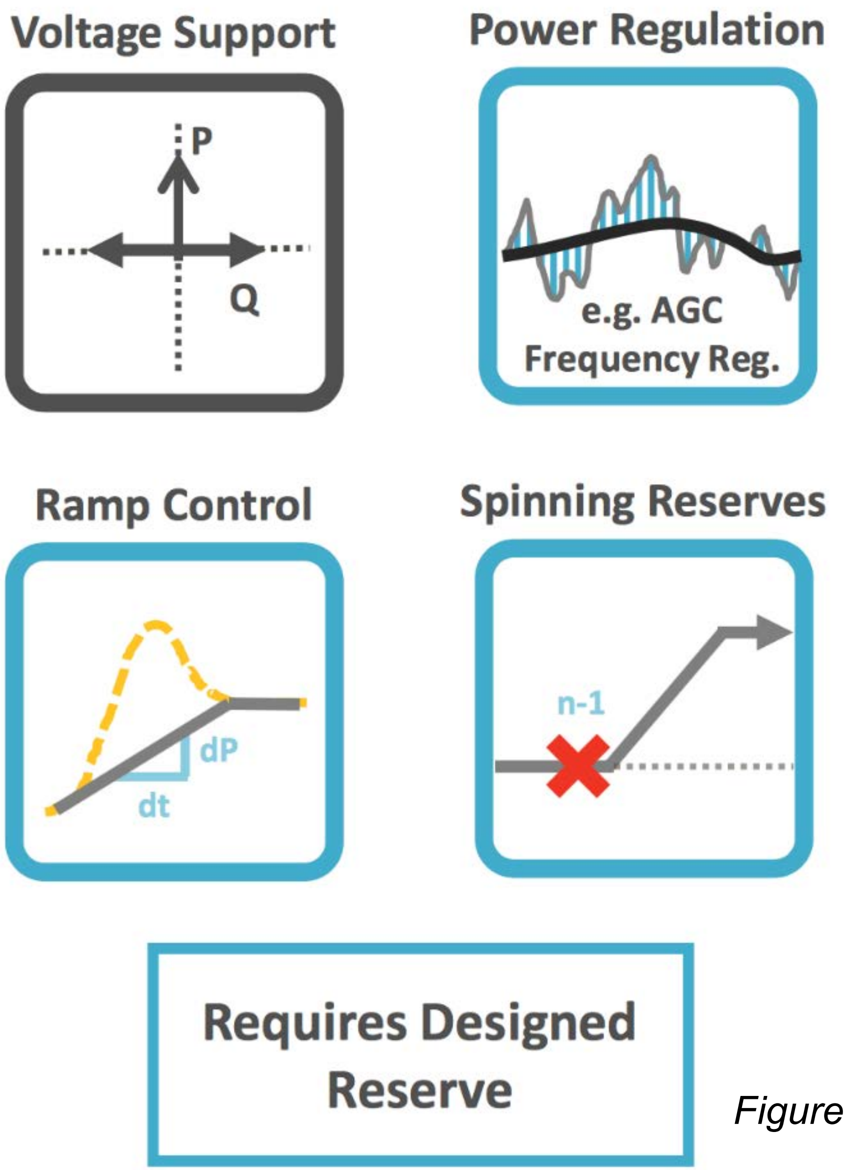


Figure credit: First Solar

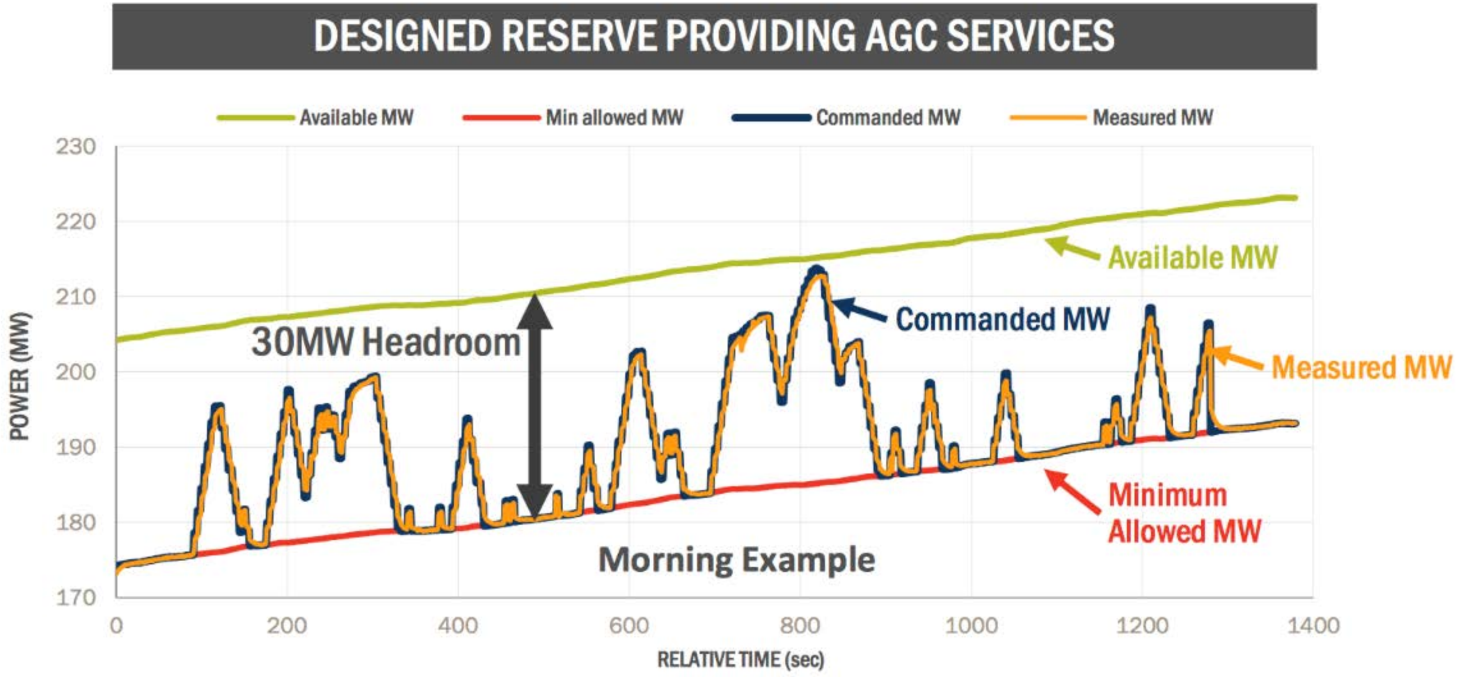


Figure credit: Vahan Gevorgian, NREL

Key Concepts and Definitions

Definitions

- **DER** stands for Distributed Energy Resources including PV , energy storage, and controllable loads that get interconnected at residential level or medium voltage level. (Typically downstream of distribution substations)
- DG stands for Distributed Generation which was previously used as proxy to describe PV
- **Distribution:** power system downstream of substations (69kV/12kV) or lower medium voltage (12kV) or lower
- **Transmission:** power system at voltages above 69kV
- **Logical connection:** data connectivity
- **Electrical connection:** grid interconnection that enables flow of electrical power to the power systems
- **Inverter System:** device that changes direct-current power to alternating-current power.

Source: Definitions based on IEEE 1547-2018, Rule 14H and Rule 21

Reactive power and active power curtailment

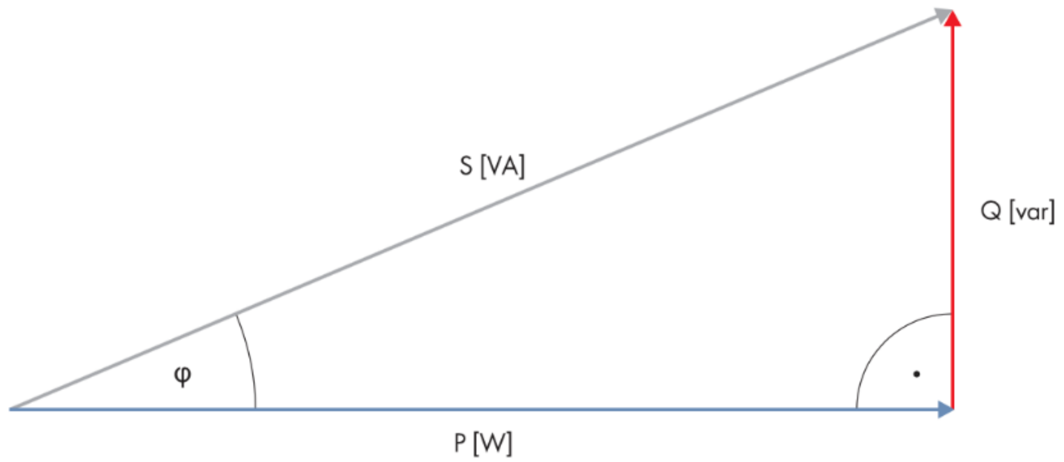
Active power (Watt):
Real electrical resistance power consumption in circuit. Typically effective for frequency control

Reactive power (var): Inductive and capacitive power consumption in circuit. Typically effective for voltage control.

Apparent power (VA):
Combination of active power and reactive power. This is the total power.

Power Factor (no unit):
Ratio between active power and apparent power. Reactive power is generated as a fixed percentage of active power.

Identification	Symbol	Unit
Apparent power	S	[VA]
Active power	P	[W]
Reactive power	Q	[var]
Displacement power factor	$\cos(\varphi)_{leading\,/\,lagging}$	Factor without unit



$S^2 = P^2 + Q^2$ (Pythagorean theorem for right-angled triangles)

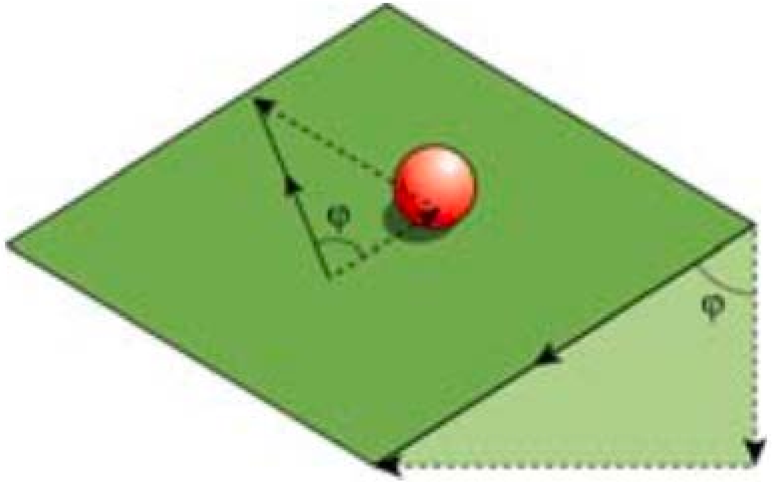
$S = \sqrt{P^2 + Q^2}$ $\quad S = \frac{P}{\cos(\varphi)}$ $\quad P = S \cdot \cos(\varphi)$ $\quad Q = \sqrt{S^2 - P^2}$

Illustrations to depict reactive power

Illustration 1

The **total power** which is the **Apparent Power** (Lifting + Pushing) is that which is applied at the handles

Illustration 2



Inclined-plane analogy

What is an inverter and what does it do?

Residential/commercial inverters

Image source: SMA-America. https://www.sma-america.com/products/solarinverters.html

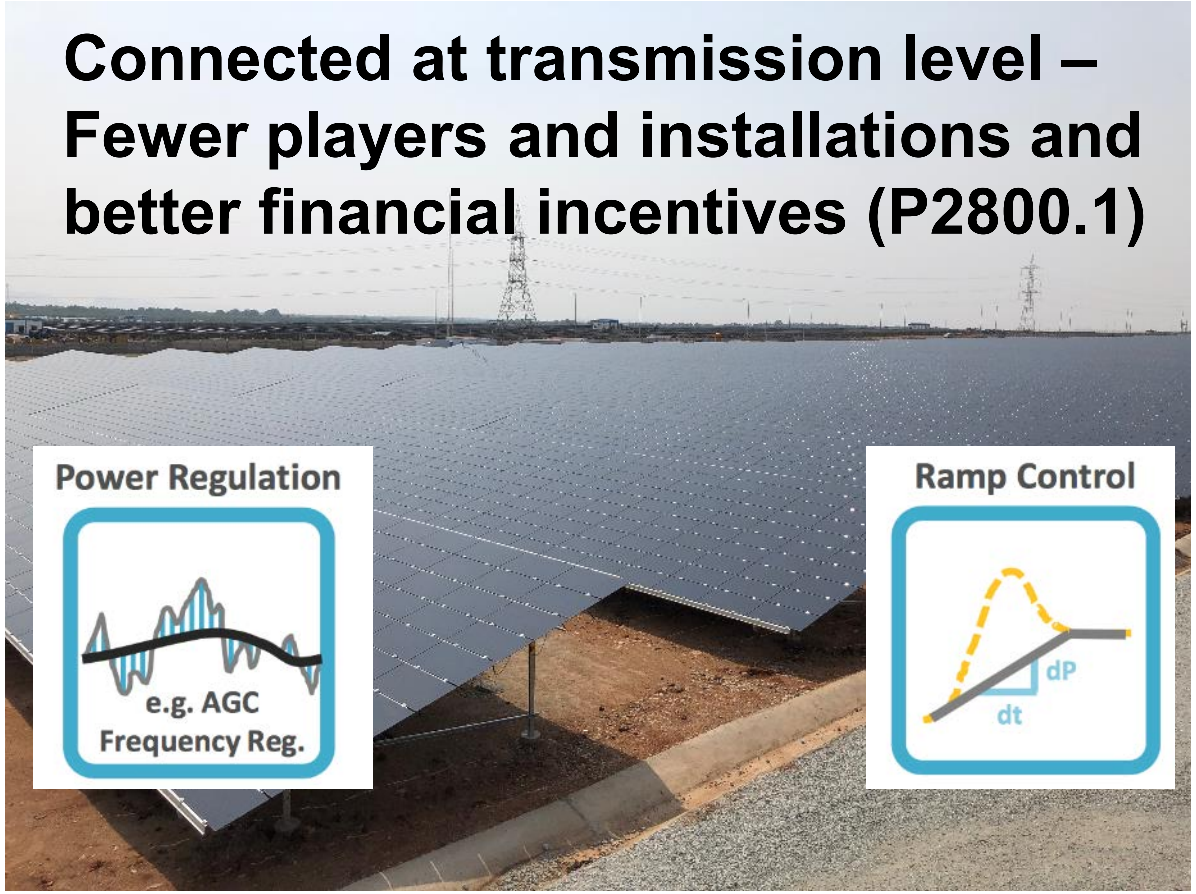
Utility-scale inverters

Image source: GTM. https://www.greentechmedia.com/articles/read/sungrow-designing-solar-inverters-for-different-markets

Evolving landscape

Large-scale and roof-top solar/storage growth comparison

DER – Connected at distribution level
Very large number of installations

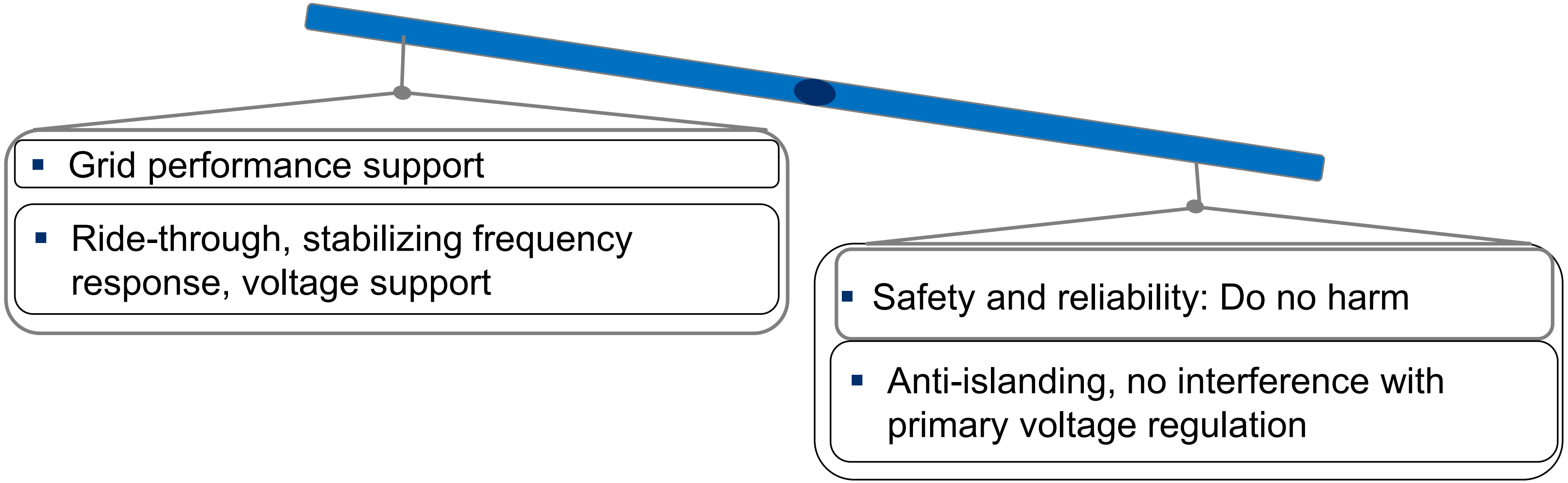


Picture from 600MW Pavagada Solar Park:
https://en.wikipedia.org/wiki/Pavagada_Solar_Park

Picture of roof-top solar installation from Hawaii

Solving Grid Planning and Operation Challenges using DER

Increasing DER penetration was a major driver for revising IEEE 1547.



Slide credit: IEEE 1547-2018

Considerations for grid codes to manage DERs

- Mutually agreeable voltage support modes during continuous operation
- Mutually agreeable voltage/frequency support modes during abnormal grid conditions
- Safety: Fails safely and provides adequate fire protection
- Ability to communicate and complies with existing standards
  - Support acceptable communication protocols
  - Support well known data object models (speaks same language)
- Interoperability: Plug-n-play for DER

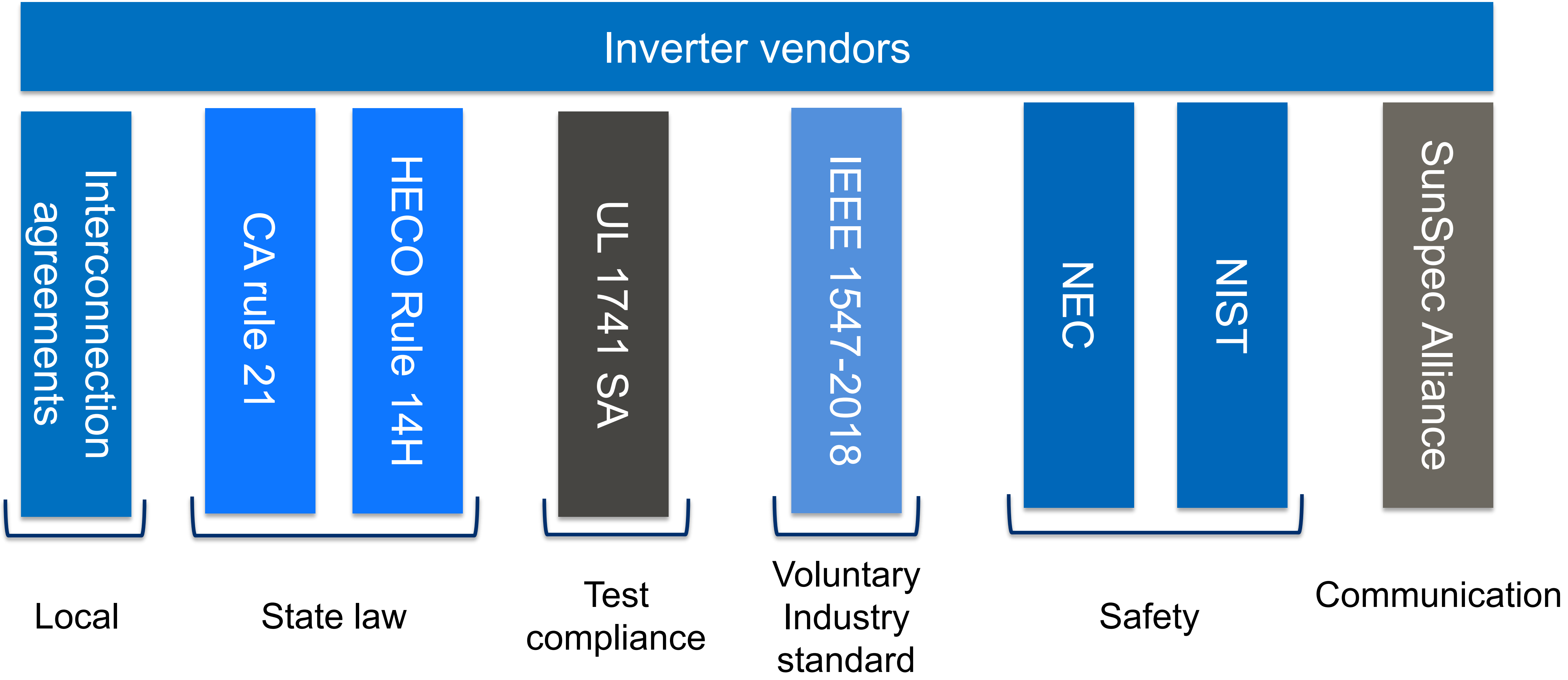
Stakeholders in grid code formation

- Inverter manufacturers
- Distribution utilities
- State governments
- Public utility commissions
- Voluntary organizations (IEEE, NIST, NEC, UL, SEPA)
- Utility customers or residential owners
- National laboratories
- Universities
- Private organizations
- Legal firms

Example: SIWG has over 200 organizations from all major stakeholder groups including utilities, inverter manufacturers, integrators, customer groups, investors and interested parties.

Inverter vendors manufacturers are key

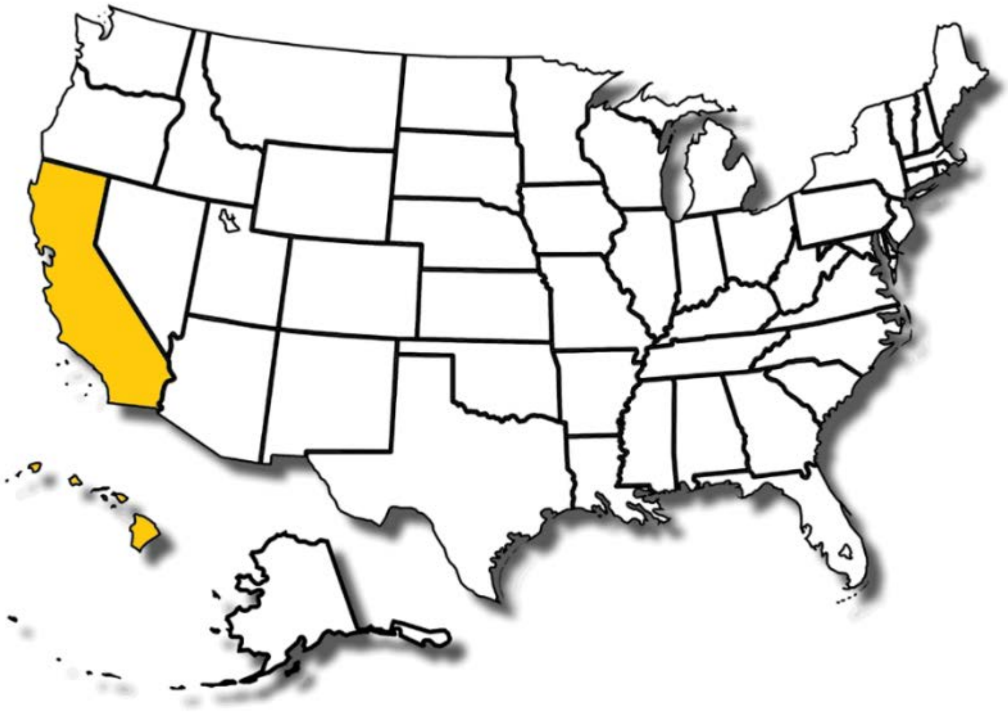
Advanced Inverter Technical Working Group (AITWG) from Hawaii,
Smart Inverter Working Group (SIWG) from CA

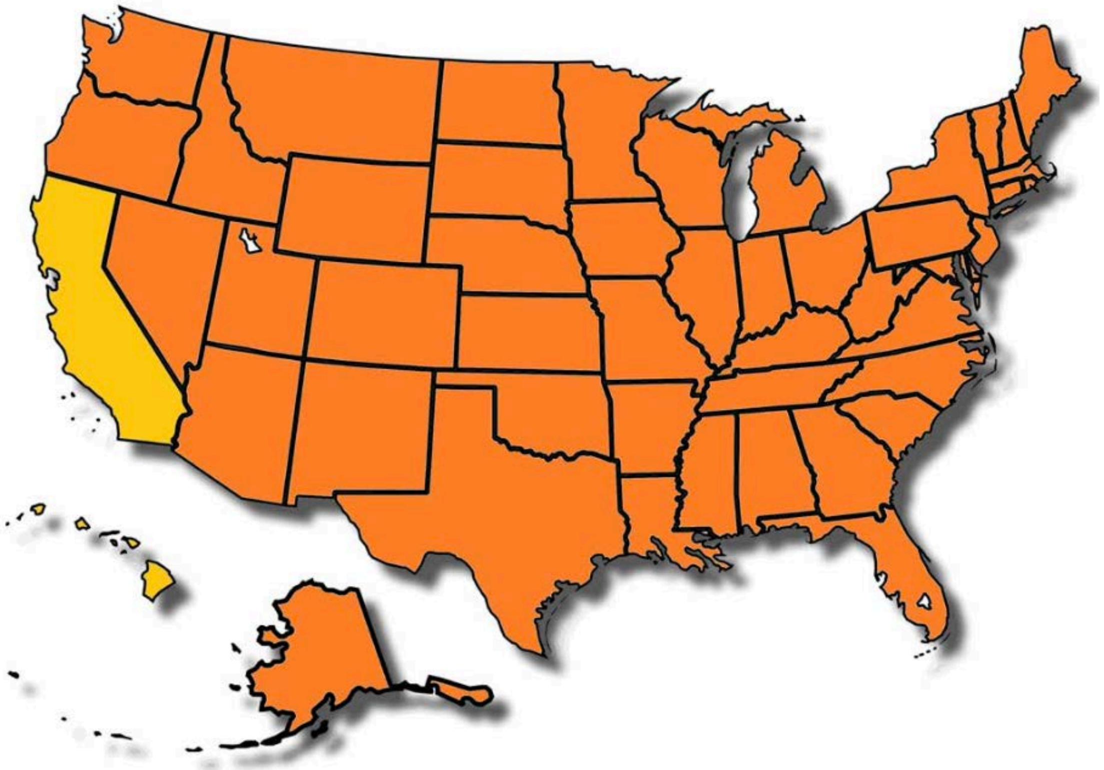


IEEE 1547-2018

State to Nation

As of April 2018 1547-2018 advanced grid support functions are required nationally



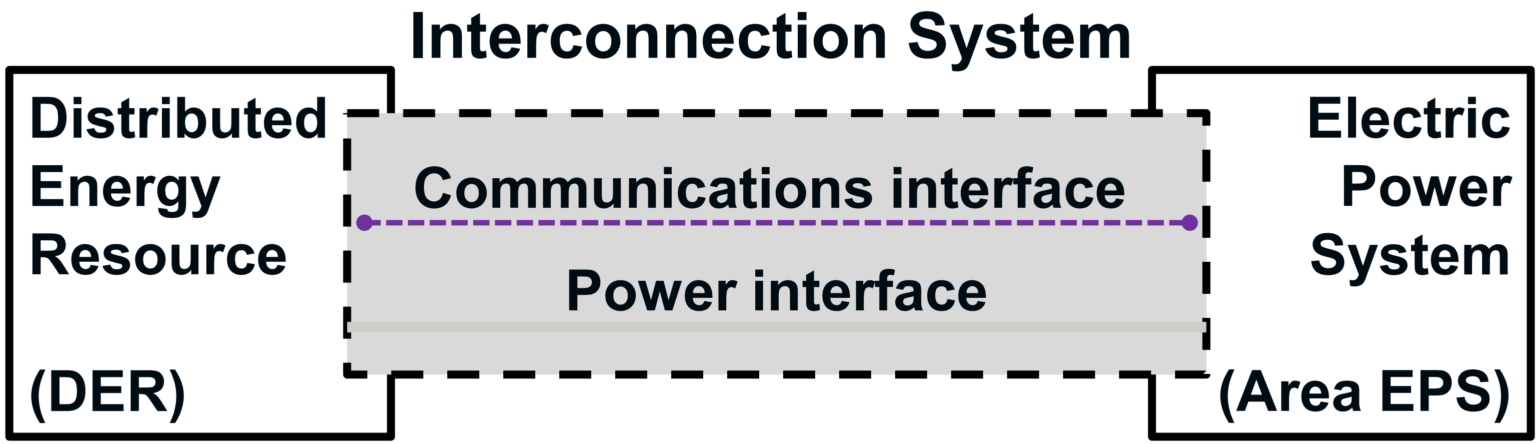


As of September 8th 2017

IEEE 1547 Scope and Purpose

Title: *Standard for **Interconnection** and **Interoperability** of Distributed Energy Resources with Associated **Electric Power Systems Interfaces***

Scope: *This standard establishes criteria and requirements for interconnection of distributed energy resources (DER) with electric power systems (EPS), and associated interfaces.*



Purpose*: This document provides a uniform standard for the interconnection and interoperability of distributed energy resources (DER) with electric power systems (EPS). It provides requirements relevant to the interconnection and interoperability performance, operation, and testing, and, safety, maintenance and security considerations.*

1547 IS

- A technical standard—functional requirements
- A single (whole) document of mandatory, uniform, universal, requirements apply at PCC or PoC
- Technology neutral—i.e., it does not specify particular equipment or type

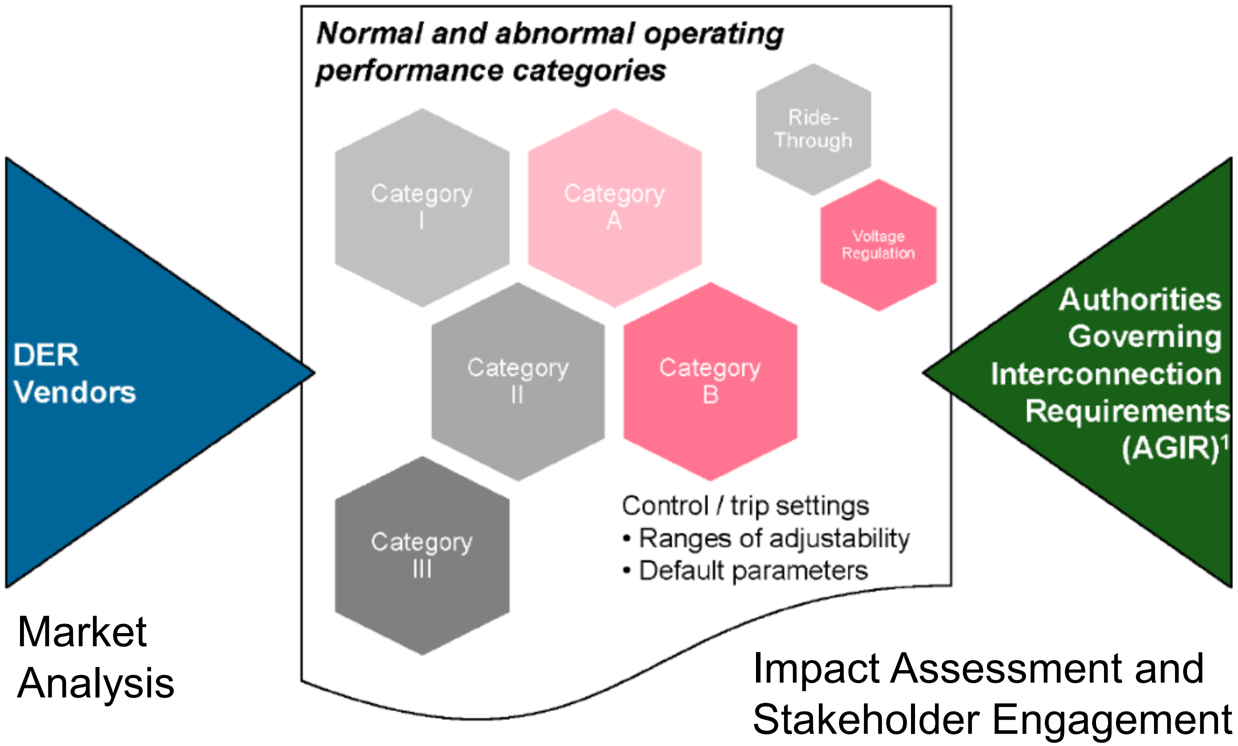
1547 is NOT

- **A design handbook**
- An application guide (see IEEE 1547.2)
- **An interconnection agreement**
- **Prescriptive**—i.e., it does not prescribe other important functions and requirements such as cyber-physical security, planning, designing, operating, or maintaining the area EPS with DER

General Remarks and Limitations

- IEEE 1547 is applicable to all DERs connected at typical primary or secondary distribution voltage levels.
  - Removed the 10 MVA limit from previous versions.
  - BUT: Not applicable for transmission or networked sub-transmission connected resources.
- Does not address planning, designing, operating, or maintaining the Area EPS (grid) with DER.
- Emergency and standby DER are exempt from certain requirements of this standard.
  - E.g., voltage and frequency ride-through, interoperability and communications.
- Gives precedence to synchronous generator (SG) design standards for DER with SG units rated 10 MVA and greater.
  - E.g., IEEE Std C50.12, IEEE Std C50.13.
- Consensus standard – 120+ industry experts in Working Group, 4-year effort
- Robust public balloting – 389-member public ballot pool, 1500+ comments resolved
- 93% Approval (75% required)

IEEE 1547-2018 Performance based categories



Categories based on voltage regulation performance and reactive power capability requirements		
Standard Requirement	**Category A**	**Category B**
Minimum Reactive power Absorption capability as % of nameplate apparent power (kVA) rating	25	44

Categories based on Disturbance ride-through requirements			
Standard Requirement	**Cat. I**	**Cat. II**	**Cat. III**
Minimum ride through time when 1.10 ≤ V (p.u.) ≤1.15	0.5 second	1 second	12 seconds

Figure credit: IEEE 1547-2018

Active Voltage Regulation Capabilities

“The DER shall provide voltage regulation capability by changes of reactive power. The approval of the Area EPS Operator shall be required for the DER to actively participate in voltage regulation.”

Capability required for all DER – (Cat A, B)

- Constant power factor mode
- Constant reactive power mode
- Voltage-reactive power mode (“volt-var”) □

“State-of the art” DER – Cat B

- Active power-reactive power mode (“watt-var”)
- Voltage-active power mode (“volt-watt”)

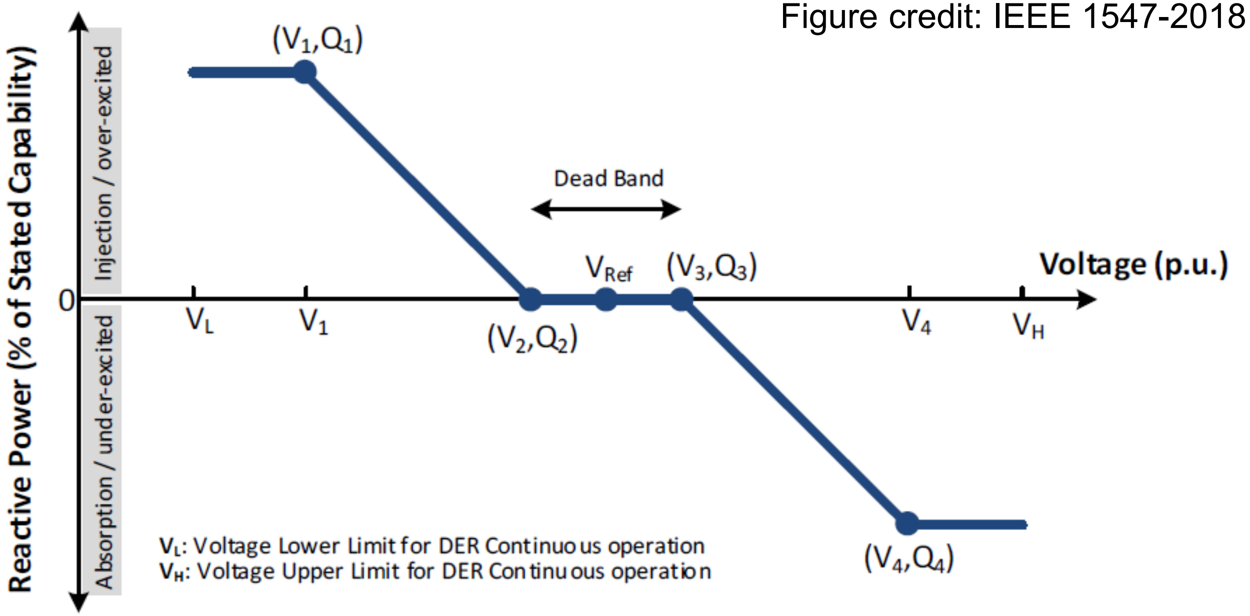
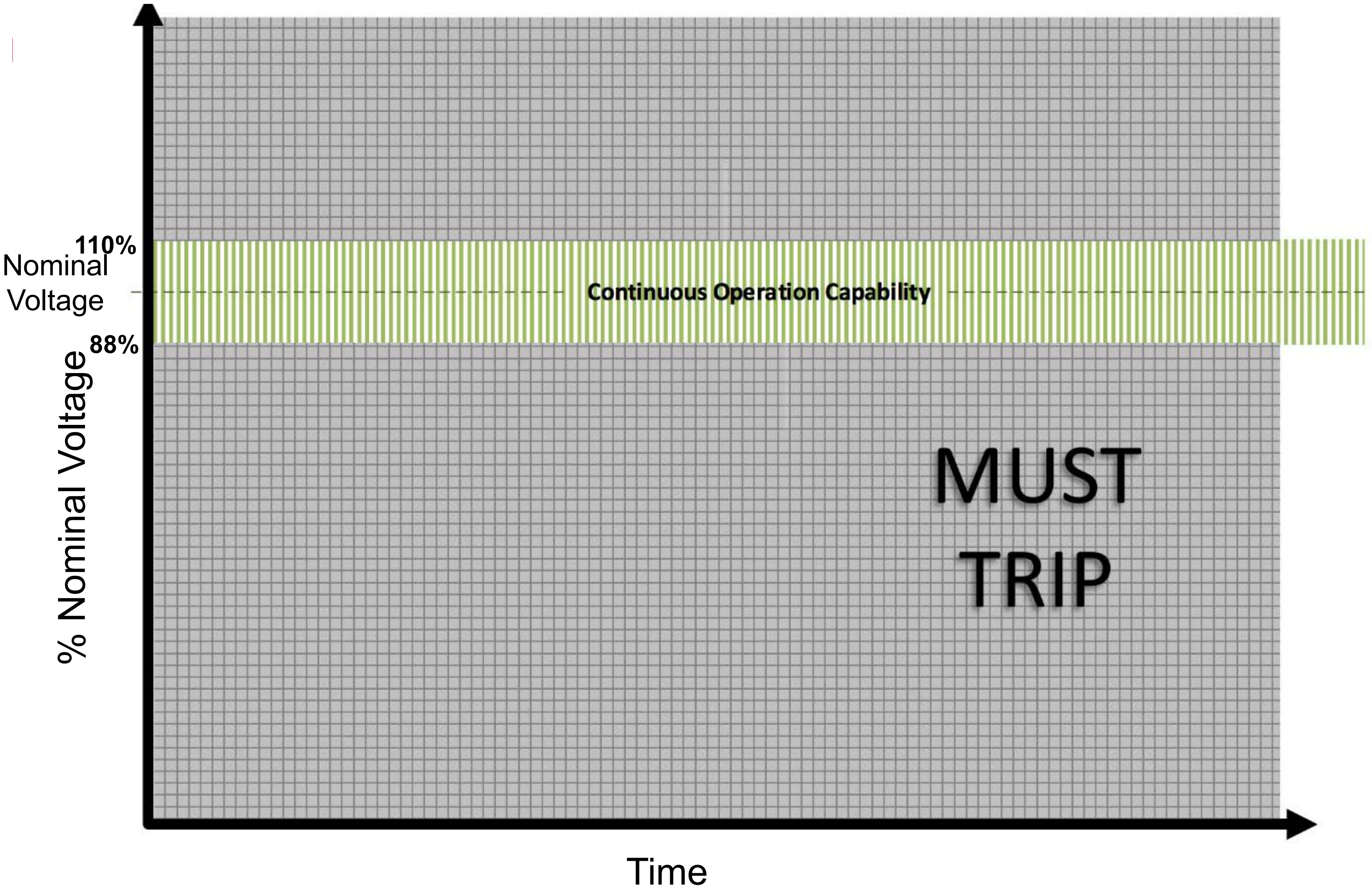


Figure credit: IEEE 1547-2018

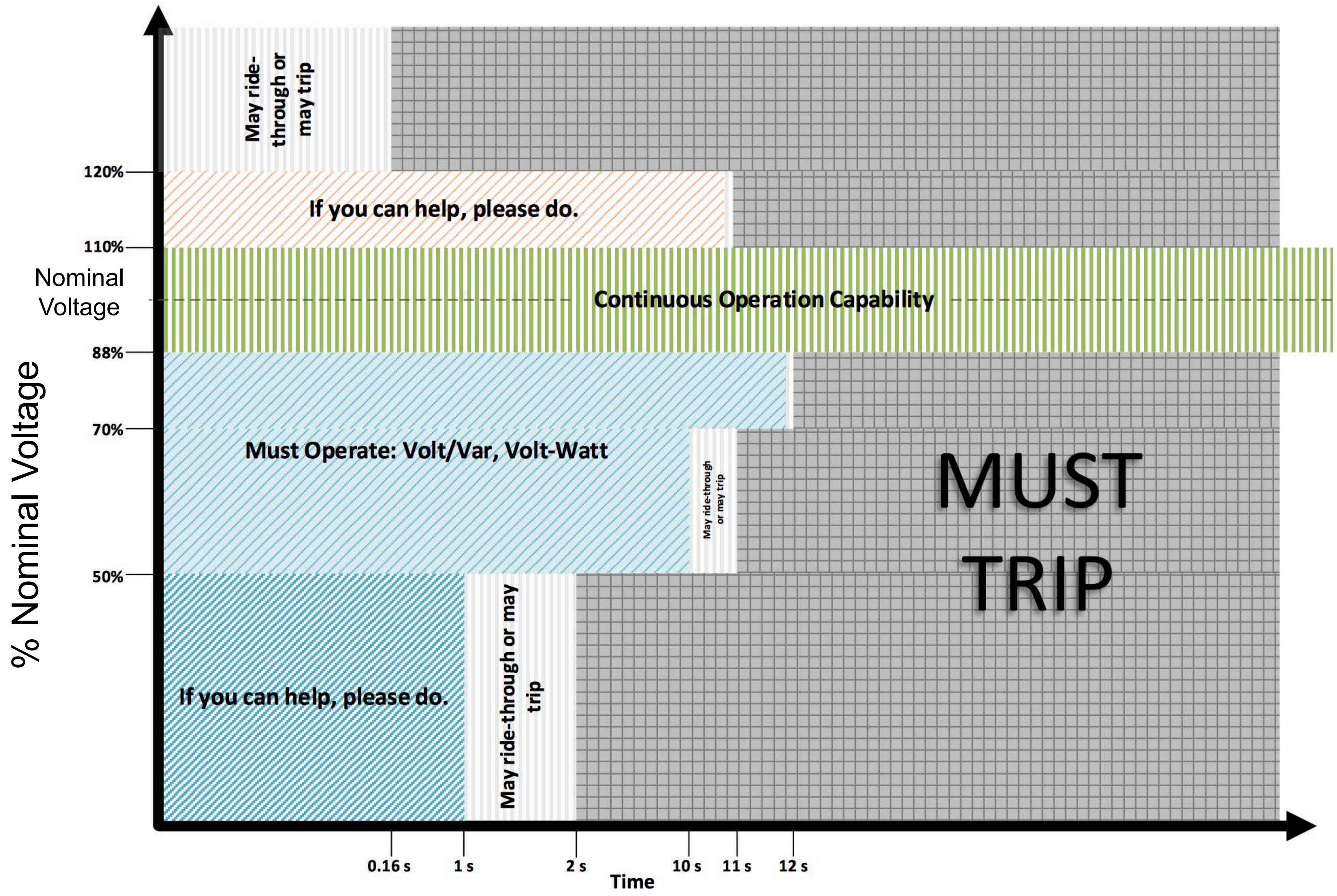
The <u>area EPS operator (utility) shall specify</u> the required voltage regulation control modes and the corresponding parameter settings. Modifications of the settings and mode selected by the EPS operator shall be implemented by the DER operator.

Settings can be adjusted locally or remotely

Ride through functionality prior to 1547-2018



Ride through functionality after 1547-2018



IEEE 1547-2018 Communications Protocols

IEEE 1547-2018 excerpt:

The DER shall support at least one of the protocols specified in Table 41. The protocol to be utilized may be specified by the Area EPS operator. Additional protocols, including proprietary protocols, may be allowed under mutual agreement between Area EPS operator and DER operator. Additional physical layers may be supported along with those specified in the table.

Table 41 —List of eligible protocols

Protocol	Transport	Physical layer
IEEE Std 2030.5 (SEP2)	TCP/IP	Ethernet
IEEE Std 1815 (DNP3)	TCP/IP	Ethernet
SunSpec Modbus	TCP/IP	Ethernet
	N/A	RS-485

- 2030.5: Contains security provisions, but no DERs natively speak it today
- DNP3: Widely used for utility SCADA, but not implemented in most DERs
- SunSpec Modbus: Used by most new DERs, but contains little/no security

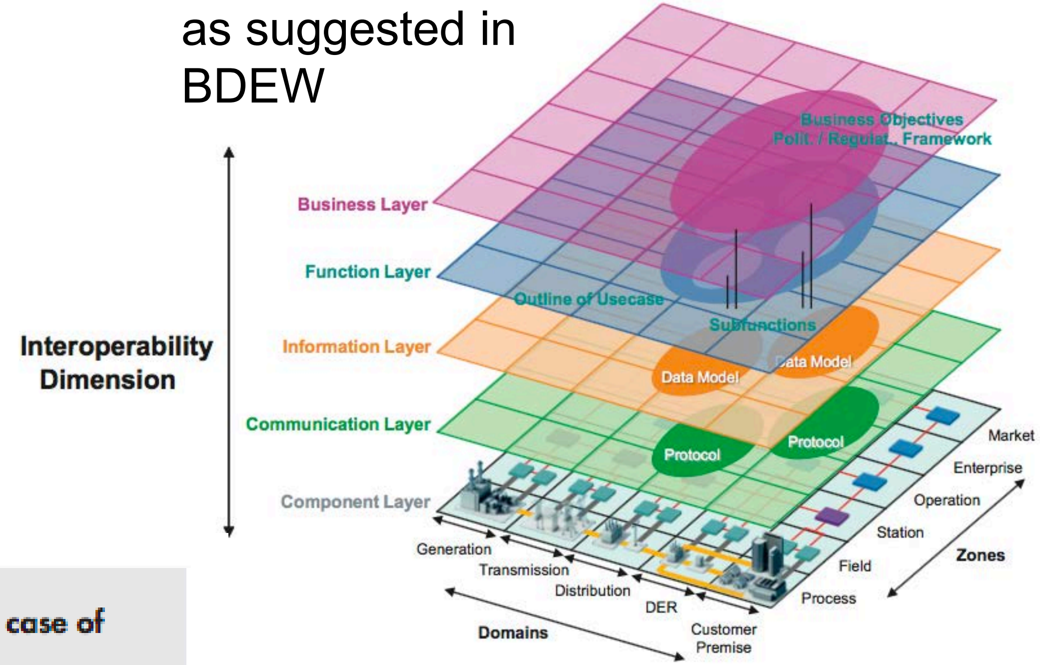
Europe: Germany, Italy, Spain

International grid codes development

BDEW/VDE 4105 key guidelines

- Feed-in management
- Active power reduction during over frequency
- Provision for reactive power
- Dynamic grid support (fault ride through)

Grid architecture as suggested in BDEW



01/01/2009	**Feed-in management** Remote, temporary active power limitation of 60, 30 or 0 percent of the rated power	**Active power reduction in case of overfrequency** Automatic reduction of the active power output upon the power frequency exceeding 50.2 Hz

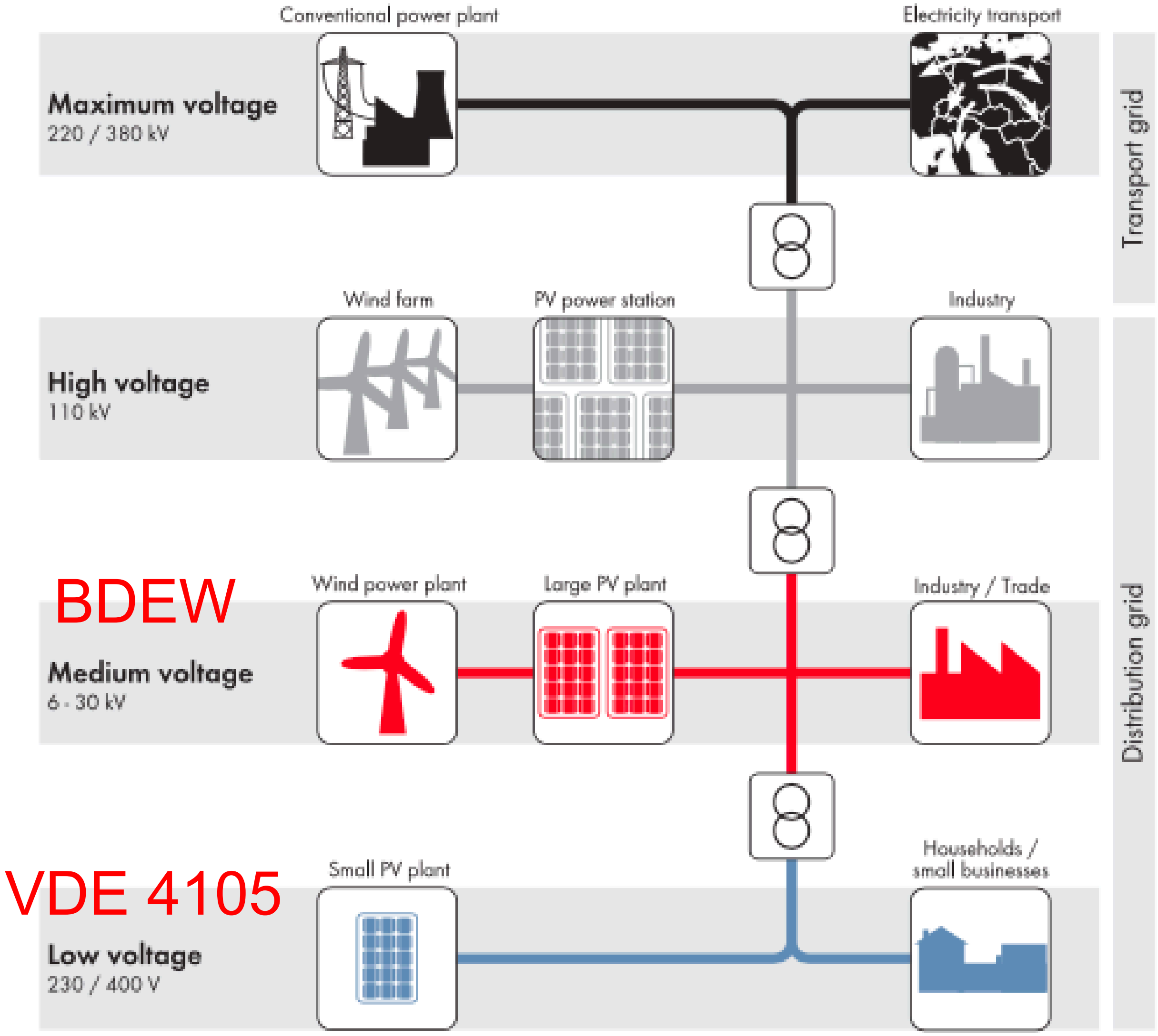
04/01/2011	**Voltage support through the provision of reactive power**		
	Fixed specification of reactive power values by the grid operator	Remote setting of various reactive power values	Automatic regulation of the reactive power as a function of grid parameters measured on-site
	Dynamic grid support Feed-in of reactive current during brief voltage drops		**Certification** Unit and/or plant certificates are mandatory

BDEW: Effective from Jan. 1 2009 and generation greater than 100kW

VDE 4105: Effective from Jan 1 2012 for low voltage grid

BDEW and VDE 4105 disambiguation

- Jan 1 2012 fundamental new connection regulations for PV interconnection came into effect
- BDEW : Medium voltage
- VDE 4105: Low voltage
- The VDE 4105 since August 1, 2011
  - Binding since January 1, 2012
  - Affects all PV plants that feed in to the low-voltage grid



PV interconnection outside Germany

- European level: European Network of Transmission System Operators for Electricity (ENTSO-E)
- Italy: CEI 0-21 standard governing the connection of power generation and consumption plants in the low-voltage grid was published in Italy in December 2011 also AEEG 084-12 from March 8, 2012
- Spain: Royal decree RD 1565/2010, dynamic grid support is already mandatory for all PV plants exceeding two megawatts in Spain today.

India

International grid codes development

Indian Grid codes timeline

2007

CEA* (Technical Standards for connectivity to the grid) Regulations

2010

CEA (Measures relating to Safety and Electric Supply) Regulations

2013

CEA (Technical Standards for Connectivity of the distributed generation resources) Regulations

CEA (Technical Standards for connectivity to the grid) Amendment Regulations

2014

Bureau of Indian Standards (BIS) Guidelines on Standards for interoperability in power system communications

2016

Best Practices Guide, Implementation of State-Level Solar Rooftop Photovoltaic Programs in India, MNRE**

CEA (Technical Standards for connectivity to the grid) Amendment 2

2018

To incorporate provisions pertaining to charging of Electric Vehicles following were amended:

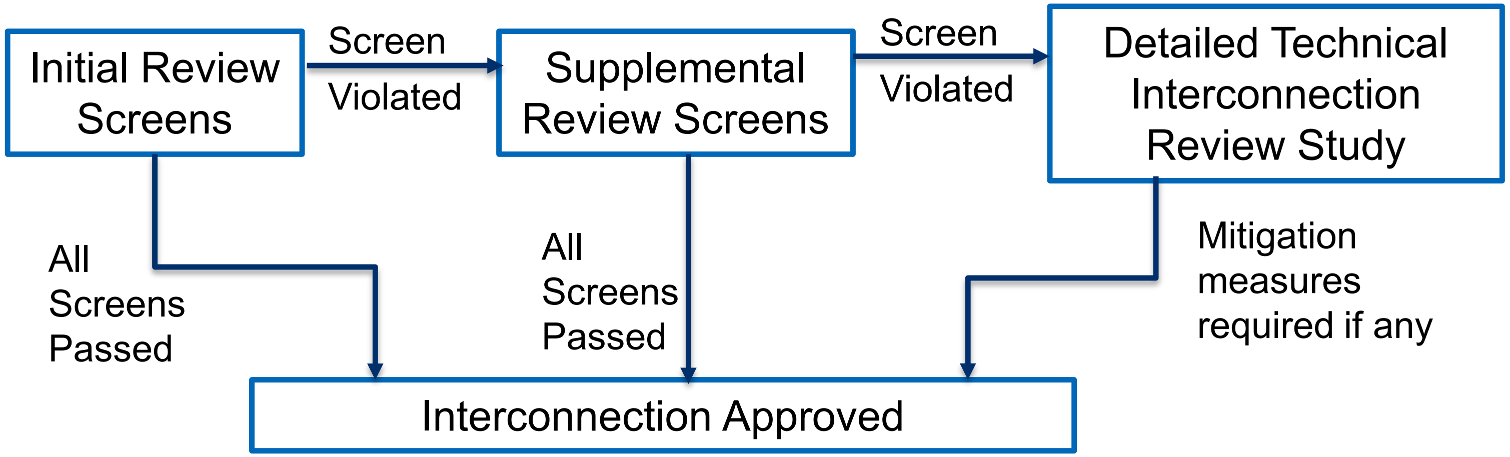
- CEA (Technical Standards for Connectivity of the distributed generation resources) Regulations
- CEA (Measures relating to Safety and Electric Supply) Regulations

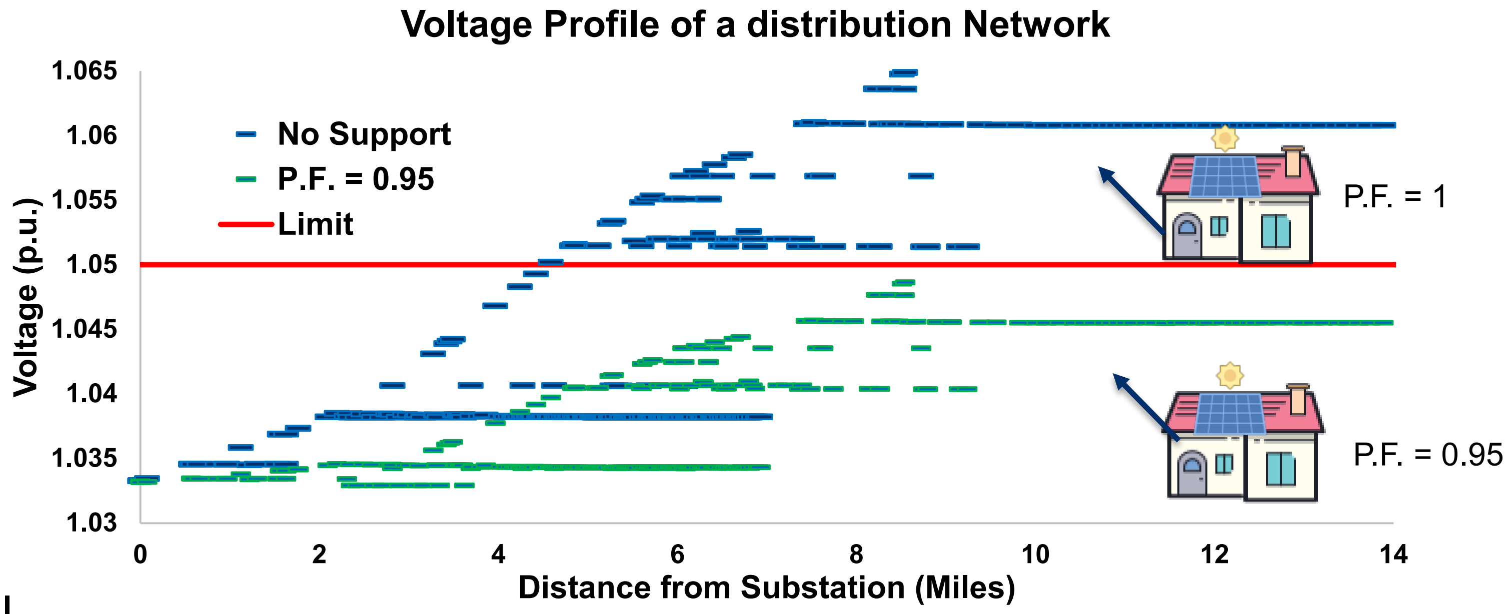
CEA (Technical Standards for Communication system in power sector) Regulations

*CEA: Central Electricity Authority, ** Ministry of New and Renewable Energy

Good Practices for DER Interconnection from Rule 21 and 14H

- Managing DER interconnection requests for distribution utilities is overwhelming
- Categorizing interconnection requests to Initial and Supplemental Review can help
- Reactive power support from DERs can help in mitigating possible adverse grid integration impacts





https://www.nrel.gov/grid/precise-tool.html

Summary and conclusions

- Transmission connected inverter interfaced energy technologies (PV, Wind, storage) are handled case-by-case and primarily used for frequency support
- P2800.1 - NERC and IEEE are developing standards on generators connected to bulk energy systems
- IEEE 1547-2018 govern distribution connected DER’s
- Stand on the shoulders of giants: Grid codes and best practices are well developed all over the world
- Leveraging distribution connected DER’s utilities and transmission systems with better power factor and additional benefits

Thank you

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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Greening the Grid

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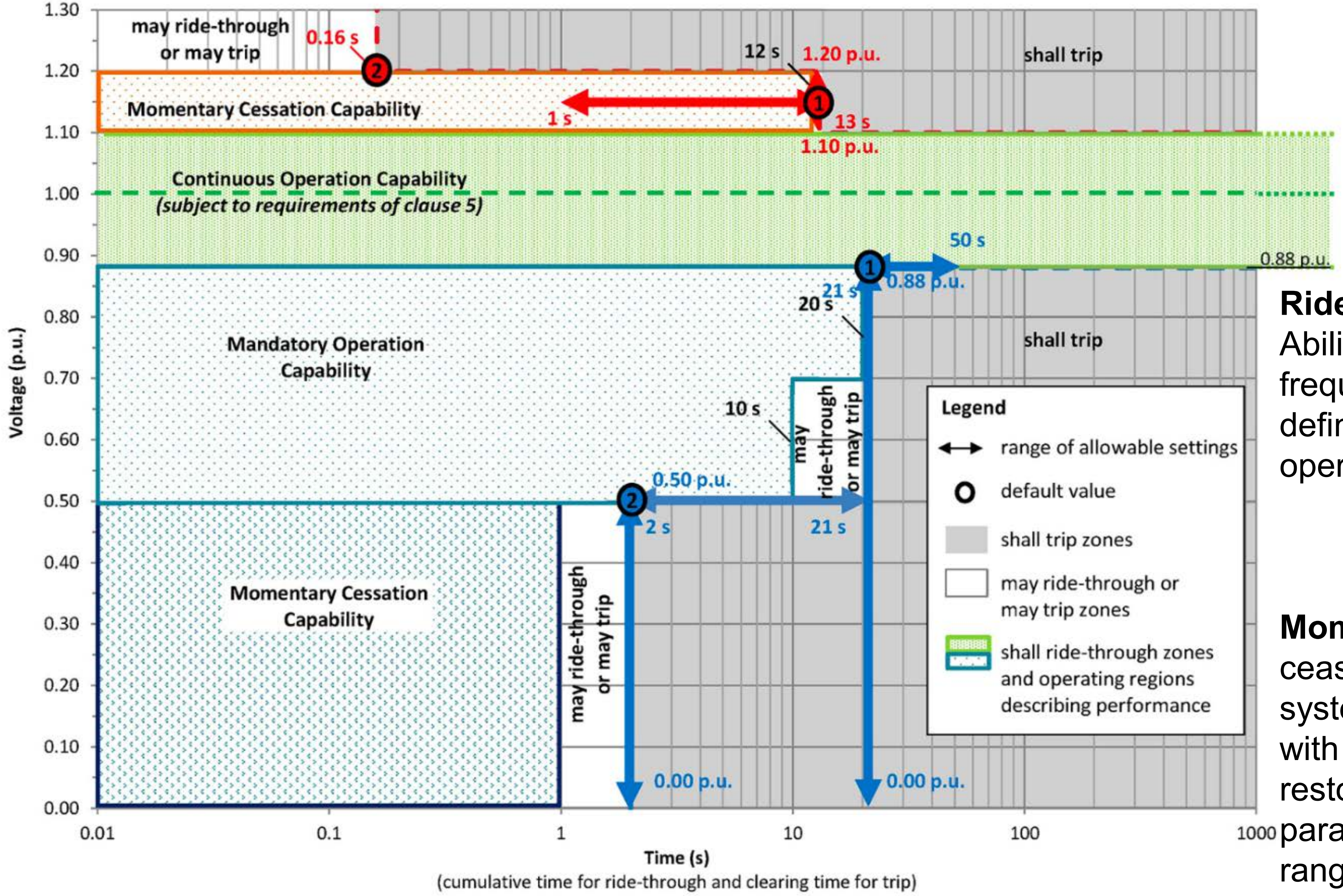
Additional slides for reference

Category III : DER response to abnormal grid conditions



Based on practices in CA and HI

Ride-through:
Ability to withstand voltage or frequency disturbances inside defined limits and to continue operating as specified.

Momentary Cessation: Temporarily cease to energize an electric power system in response to a disturbance, with the capability to immediately restore output when system parameters return to within defined ranges

UL 1741 SA

- UL 1741 SA is the test standard by which we certify that our inverters
  - Meet HECO Rule 14H Requirements
  - Meet CA Rule 21 Requirements

UL 1741 SA	HECO Rule 14H	CA Rule 21
Anti-Islanding Protection	X	X
L/HVRT Low and High Voltage Ride Through	X	X
L/HFRT Low and High Frequency Ride Through	X	X
Volt/VAR Mode	X	X
SPF – Specified Power Factor	X	X
RR- Normal Ramp Rate and SS- Soft Start Ramp Rate	X	X
Frequency-Watt (Optional)	X	
Volt –Watt (Optional)	X	

HECO Specific Function	HECO Rule 14H
Remote Connect/Disconnect	X

Key takeaway:
As more PV is installed on electrical grids, grid operators need flexible tools to help ensure stability and reliability

VDE: Provision of reactive power

Set values for the G/P protection:

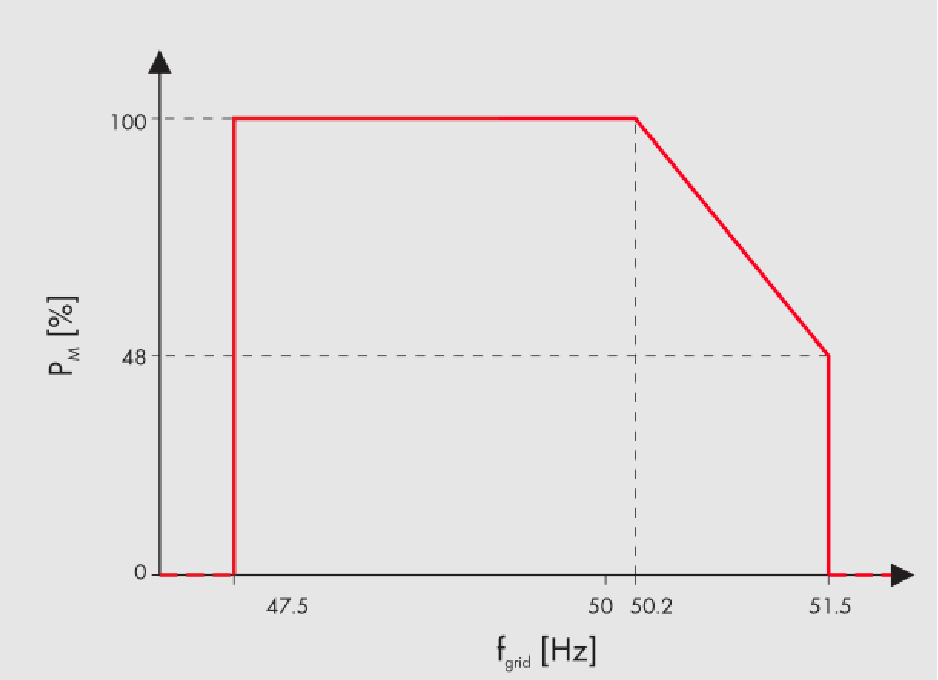
Deactivation limits:

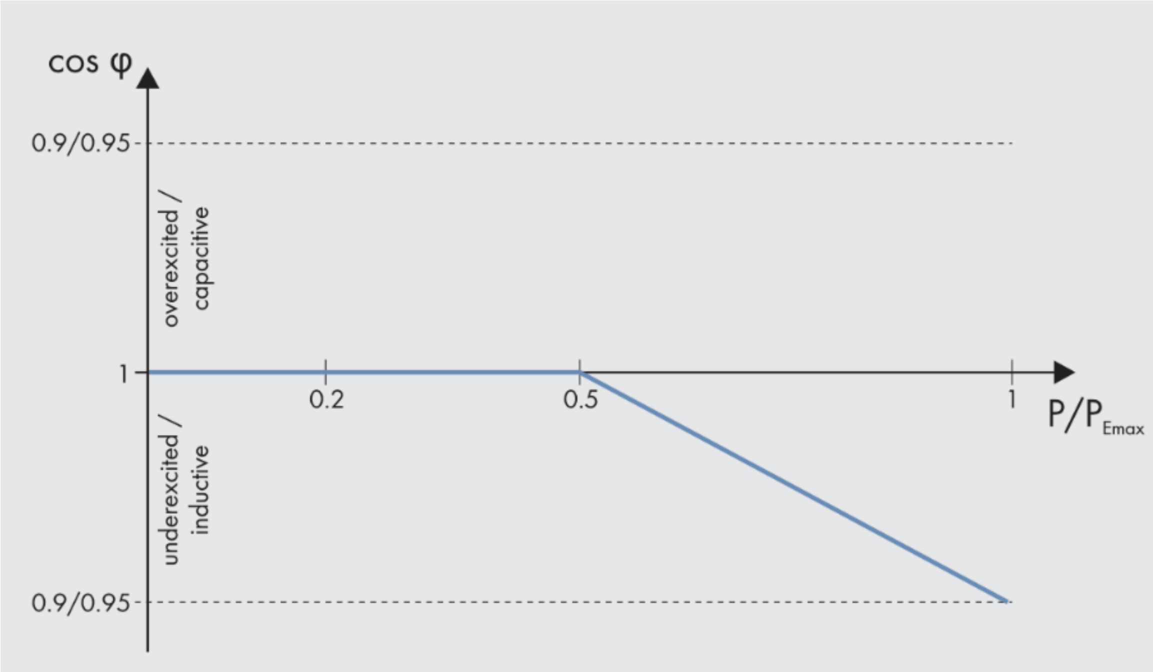
Voltage drop protection (U <)	< 184 V
Voltage increase protection (U >)	> 253 V
Voltage increase protection (U >>)	> 264.5 V
Frequency drop protection (f <)	< 47.5 Hz
Frequency increase protection (f >)	> 51.5 Hz

Reconnection limits:

Voltage greater than 195.5 V and less than 253 V

Frequency greater than 47.5 Hz and less than 50.05 Hz





IEEE 1547-2018 Performance based categories

Categories based on voltage regulation performance and reactive power capability requirements		
Standard Requirements	**Category A**	**Category B**
Voltage—active power (volt-watt) mode	Not Required	Mandatory
Minimum Reactive power Injection capability as % of nameplate apparent power (kVA) rating	44	44
Minimum Reactive power Absorption capability as % of nameplate apparent power (kVA) rating	25	44

Categories based on Disturbance ride-through requirements			
Standard Requirements	**Category I**	**Category II**	**Category III**
Minimum ride through time when $1.10 \leq V$ (p.u.) ≤ 1.15	0.5 seconds	1 second	12 seconds
Rate of change of frequency (ROCOF) ride-through requirements for DER	0.5 Hz/s	2.0 Hz/s	3.0 Hz/s
Frequency-droop (frequency-power) operation for low-frequency conditions	Optional	Mandatory	Mandatory

Organizations referred in this slide deck

- BDEW: Directive of German Association of Energy and Water Industries for the connection and parallel operation of power generation plants in medium-voltage grid
- CPUC: California Public Utilities Commission regulates privately owned electric, natural gas, telecommunications, water, railroad, rail transit, and passenger transportation companies, in addition to authorizing video franchises
- EPRI: Electric Power Research Institute (EPRI) is a nonprofit organization involved in public interest energy and environmental research
- IEEE: Institute of Electrical and Electronics Engineers, technical professional organization dedicated to advancing technology for the benefit of humanity
- SEPA: Smart Electric Power Alliance is a non-profit organization dedicated to the growth and utilization of smart energy
- SIWG: Smart Inverter Working Group, identified the development of advanced inverter functionality as an important strategy to mitigate the impact of high penetrations of distributed energy resources (DERs)
- UL LLC, formerly Underwriters Laboratories, is a global safety and certification company (wikipedia)
- VDE-AR-N 4105: Standard guiding generators connected to the low-voltage distribution network

Updates in CA - SIWG

Phase I (Autonomous Functions)

- **Low/High Voltage Ride Through**
- **Low/High Frequency Ride Through**
- **Dynamic Volt/Var Operation**
  - ***Reactive Power Priority***
- **Ramp Rate Controls**
- **Reconnect by "Soft Start"**
- **Fixed Power Factor**
- **Anti - islanding**

Phase II (Communications)

- **Establishes communication capabilities requirements between Generating Facilities and Distribution Provider**
- **Three methods available**
  - **DP to Direct to Generator**
  - **Through GFEMS**
  - **Through Aggregator**
- **Defaults the use of IEEE2030.5**

Phase III (Advanced Functions)

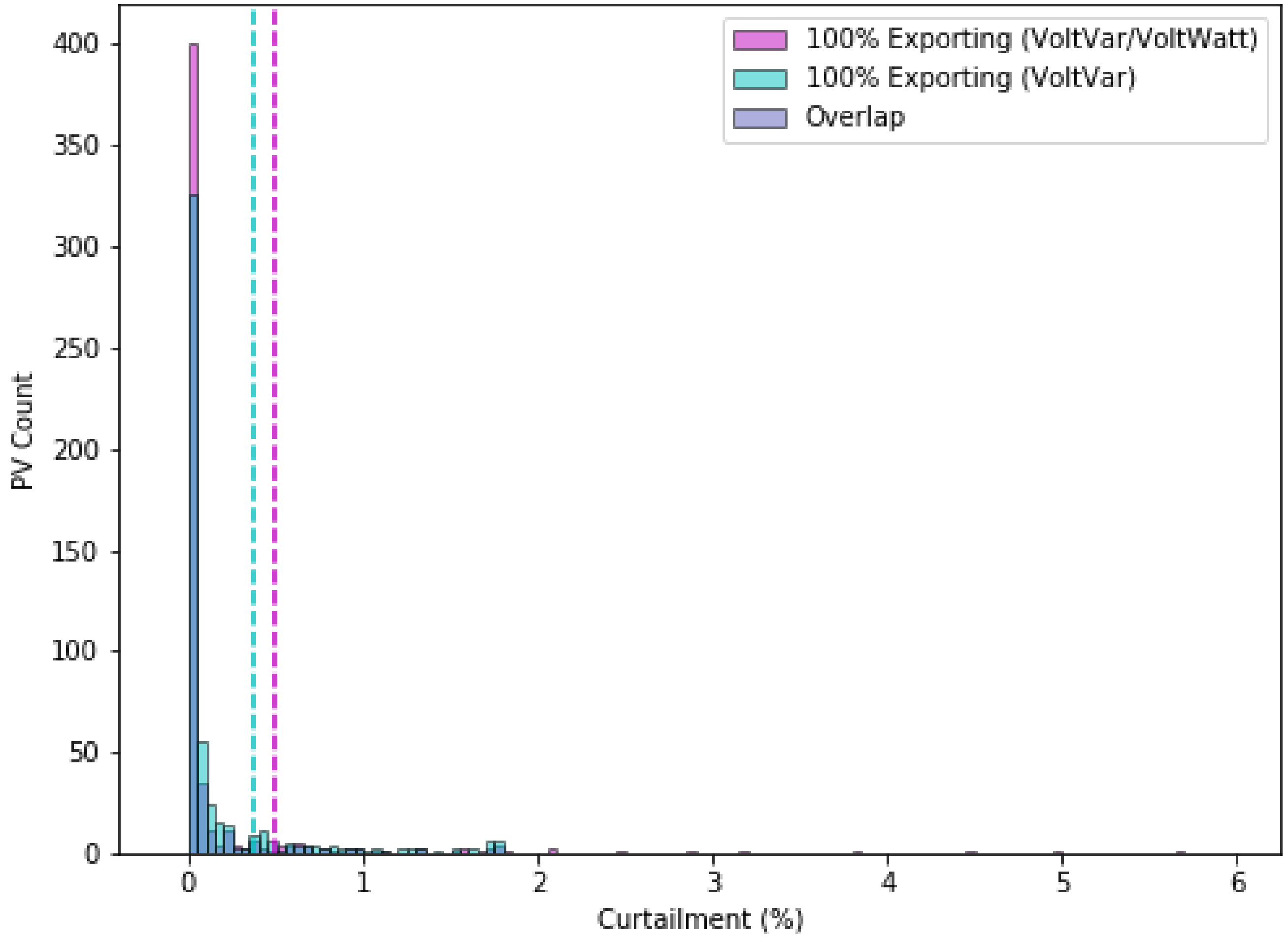
- **Monitor Key DER data**
- **DER Disconnect and Reconnect Commands**
- **Limit Maximum Active Power Mode**
- **Set Active Power Mode**
- **Frequency Watt Mode**
- **Volt Watt Mode**
- **Dynamic Reactive Support**
- **Scheduling Power Values and Modes**

NREL participation in grid code updates: Impact of reactive power support on active power curtailment

- Curtailment for a very high-PV penetration case in an Oahu 12 kV feeder

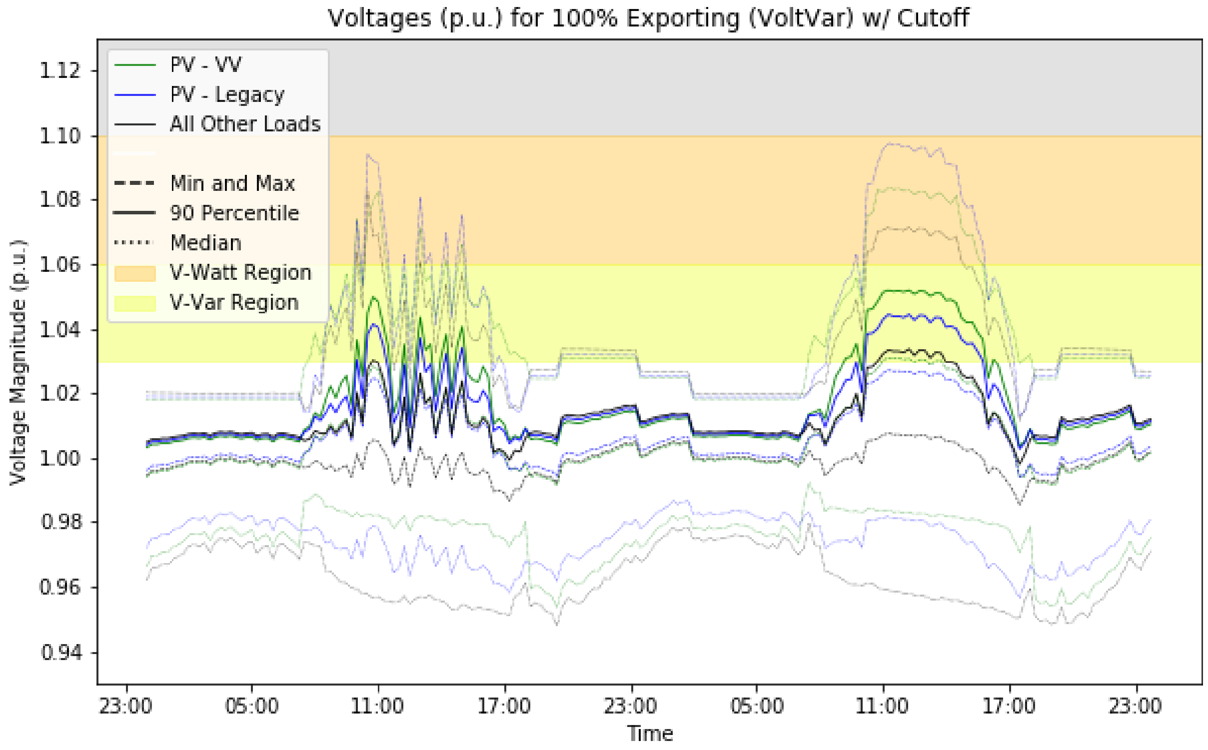
- >650% PV penetration of Gross Day Time Minimum Load

- Outlier customers (curt. > 2%) have worst case secondary assumptions of being 200ft apart on 1/0 conductors

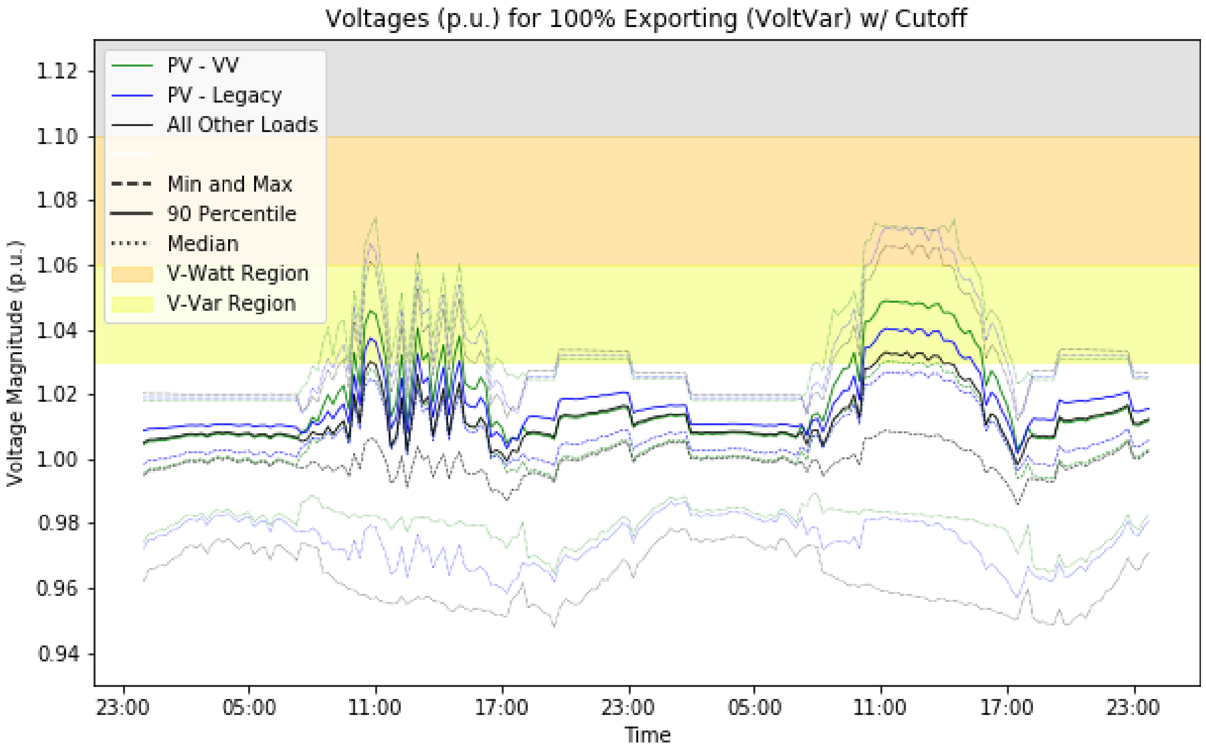


Example simulation result from HECO-NREL collaboration

PVs Disconnect > 1.1 pu & No-Upgrades



PVs Disconnect > 1.1 pu & Secondary Upgrades



Main finding: volt-var and volt-watt control reduce voltage violations with minimal impact to customer and minimal negative impact to grid.