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

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

Evolving Power System

IEEE 1547-2003 World

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

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
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.
The **total power** which is the **Apparent Power** (Lifting + Pushing) is that which is applied at the handles.
What is an inverter and what does it do?

Residential/commercial inverters


Utility-scale inverters

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

Connected at transmission level –
Fewer players and installations and better financial incentives (P2800.1)

DER – Connected at distribution level
Very large number of installations

Picture from 600MW Pavagada Solar Park:

Picture of roof-top solar installation from Hawaii
Increasing DER penetration was a major driver for revising IEEE 1547.

- Safety and reliability: Do no harm
- Anti-islanding, no interference with primary voltage regulation

- Grid performance support
- Ride-through, stabilizing frequency response, voltage support
Considerations for grid codes to manage DERs

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

Inverter vendors

- Interconnection agreements
- CA rule 21
- HECO Rule 14H
- UL 1741 SA
- IEEE 1547-2018
- NEC
- NIST
- SunSpec Alliance

Local
State law
Test compliance
Voluntary Industry standard
Safety
Communication
IEEE 1547-2018
State to Nation

As of September 8th 2017

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

<table>
<thead>
<tr>
<th>Standard Requirement</th>
<th>Category A</th>
<th>Category B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Reactive power absorption capability as % of nameplate apparent power (kVA) rating</td>
<td>25</td>
<td>44</td>
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### Categories based on Disturbance ride-through requirements

<table>
<thead>
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<th>Cat. I</th>
<th>Cat. II</th>
<th>Cat. III</th>
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<tr>
<td>Minimum ride through time when 1.10 ≤ V (p.u.) ≤ 1.15</td>
<td>0.5 second</td>
<td>1 second</td>
<td>12 seconds</td>
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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”)

The area EPS operator (utility) shall specify 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

- Nominal Voltage:
  - 110%
  - 88%

- Continuous Operation Capability

MUST TRIP
Ride through functionality after 1547-2018

![Diagram showing ride through functionality and voltage levels](image-url)
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>
<thead>
<tr>
<th>Protocol</th>
<th>Transport</th>
<th>Physical layer</th>
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<tbody>
<tr>
<td>IEEE Std 2030.5 (SEP2)</td>
<td>TCP/IP</td>
<td>Ethernet</td>
</tr>
<tr>
<td>IEEE Std 1815 (DNP3)</td>
<td>TCP/IP</td>
<td>Ethernet</td>
</tr>
<tr>
<td>SunSpec Modbus</td>
<td>TCP/IP</td>
<td>Ethernet</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>RS-485</td>
</tr>
</tbody>
</table>

- 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)

### Feed-in Management

**01/01/2009**
- Remote, temporary active power limitation of 60, 30 or 0 percent of the rated power

### Active Power Reduction in Case of Overfrequency

**01/01/2009**
- Automatic reduction of the active power output upon the power frequency exceeding 50.2 Hz

### Voltage Support through the Provision of Reactive Power

**04/01/2011**
- 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 into 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 (Measures relating to Safety and Electric Supply) Regulations

- **2010**: CEA (Technical Standards for Connectivity of the distributed generation resources) Regulations

- **2013**: Bureau of Indian Standards (BIS) Guidelines on Standards for interoperability in power system communications


- **2016**: 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

- **2018**: 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
Contact info and additional information

**Webinar Panel**

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**Greening the Grid**

greeningthegrid.org  
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Additional slides for reference
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

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

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<td>Voltage—active power (volt-watt) mode</td>
<td>Not Required</td>
<td>Mandatory</td>
</tr>
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<td>Minimum Reactive power Injection capability as % of nameplate apparent power (kVA) rating</td>
<td>44</td>
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<tr>
<td>Rate of change of frequency (ROCOF) ride-through requirements for DER</td>
<td>0.5 Hz/s</td>
<td>2.0 Hz/s</td>
<td>3.0 Hz/s</td>
</tr>
<tr>
<td>Frequency-droop (frequency-power) operation for low-frequency conditions</td>
<td>Optional</td>
<td>Mandatory</td>
<td>Mandatory</td>
</tr>
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</table>
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
### 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

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