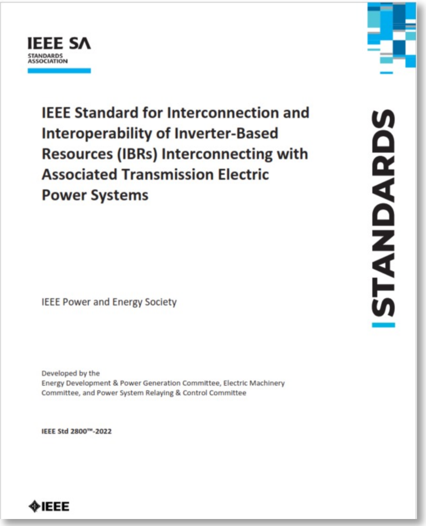
IEEE Std 2800™-2022

New IEEE Interconnection Standard for Large-Scale Solar, Wind, and Energy Storage

IEEE-ESIG-PSERC-CURENT JOINT WEBINAR

May 02, 2022



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IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems

IEEE Power and Energy Society

Developed by the
Energy Development & Power Generation Committee, Electric Machinery Committee, and Power System Relaying & Control Committee

IEEE Std 2800™-2022

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Published on Earth Day, April 22, 2022

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CURENT CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

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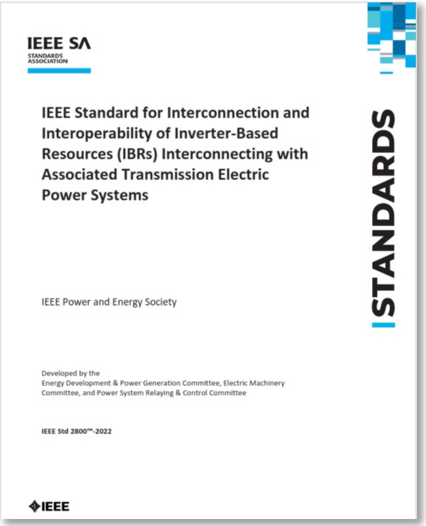

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- IEEE SA can provide information and education if an agency or body (ie, FERC or DOE) requests information on a standard and can also provide a mechanism by which they can obtain copies of standards for review.
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- Agencies/Bodies can have independent discussions outside of IEEE SA
- If a body wants to pursue “requiring” IEEE P2800 via rulings or placing the standard on their respective approved lists for use, that is up to them
- If the individual WG Chair or WG members wish to have discussions with FERC, DOE, etc. about such a required use of the standard, they can have that conversation, but they must be clear they are having that conversation as independent individuals and/or on behalf of their respective organizations---and NOT IEEE/SA.

Joint Webinars

Today:

Joint IEEE–ESIG–PSERC–CURENT Webinar for Subject Matter Experts & Academia

Tomorrow:

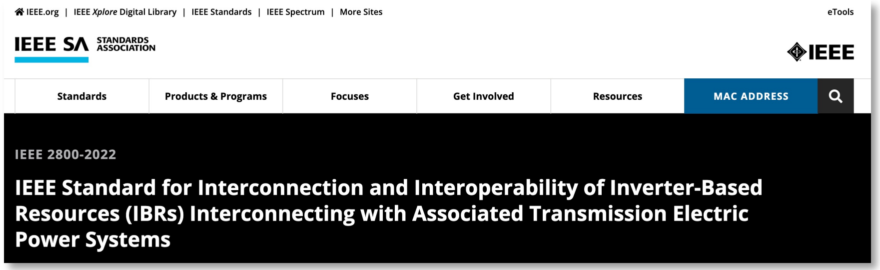
Joint NERC–NATF–NAGF–EPRI Webinar for Transmission Planners

May 3, 2022 @ 12:00pm-1:30pm ET | 9:00am-10:30pm PT | 6:00pm-7:30pm CET); no registration required, join the webinar here

TBD:

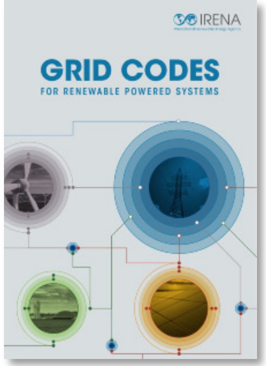
Joint SEIA–ACP (formerly AWEA) Webinar for OEMs & Developers

Resources and Media



https://standards.ieee.org/project/2800.html

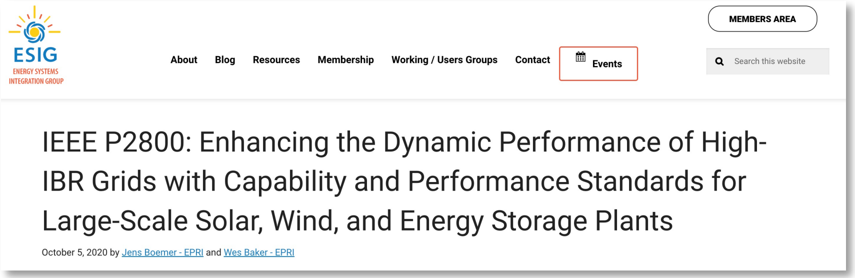
https://beyondstandards.ieee.org/addressing-grid-reliability-as-renewable-energy-integration-speeds-up/



“Grid Codes for Renewable Powered Systems” report by the International Renewable Energy Agency, published April 2022; pages 87-88:

"[IEEE 2800] will be [a] regional grid cod[e] for North America, with the main area of applicability being the United States, but [is] designed to go beyond this scope. [It] can clearly be recommended as [an] optio[n] for internationally standardised technical requirements for generators."

https://www.irena.org/publications/2022/Apr/Grid-codes-for-renewable-powered-systems



https://www.esig.energy/ieee-p2800-enhancing-the-dynamic-performance-of-high-ibr-grids/

Outline – Joint IEEE-ESIG-PSERC-CURENT Webinar – May 2, 2022

- Welcome by IEEE SA – *5 min.*
  - Rudi Schubert, IEEE SA
  - Jason MacDowell, ESIG
  - Raja Ayyanar, PSERC
  - Yilu Liu, CURENT
- Presentation by Jens C. Boemer (WG Chair) – *50 min.*
  - IEEE P2800: purpose, scope, schedule
  - High-level review of selected draft requirements
  - Potential adoption of IEEE 2800 in North America
- Comments by utilities – *5 min.*
  - Stephen Solis, ERCOT
- Q&A - *15 min.*

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For those working group members whose effort on the standard was partially or fully supported by the U.S. DOE's National Renewable Energy Laboratory, the following statement applies:

This work was supported in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office and Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

IRENA Report: Key Messages

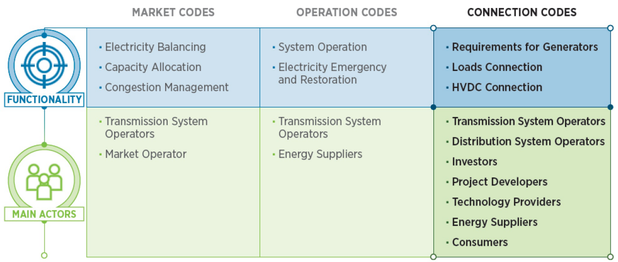
"Power system transformation towards decentralisation, digitalisation and electrification calls for ***evolving grid codes****"*

- **[Inverter-based resources, IBR] impact** the way power systems are operated
- The role of grid codes in **building trust** between different actors
- An **imperfect grid code** is, in many cases, better than no grid code at all
- Grid codes should be **technology-neutral** and should **evolve** to meet system needs
- Grid codes should **enable innovations** to connect safely to the grid
- Ensuring **compliance** with the code is key
- International **standardisation** and regional grid codes facilitate sharing of flexibility and increased economy of scale for equipment manufacturers

What does that mean for IEEE 2800-2022?

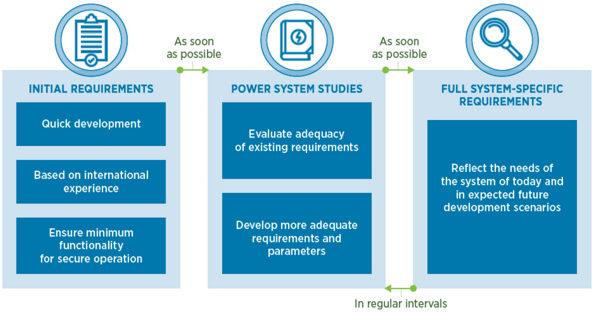
- ➢ Cornerstone in a transforming power system
- ➢ Tailored to North American context

Figure ii **Categories of grid codes in Europe, functionality and main actors**



Note: HVDC = high voltage direct current.

Figure iii **Grid code parameter development and revision process**

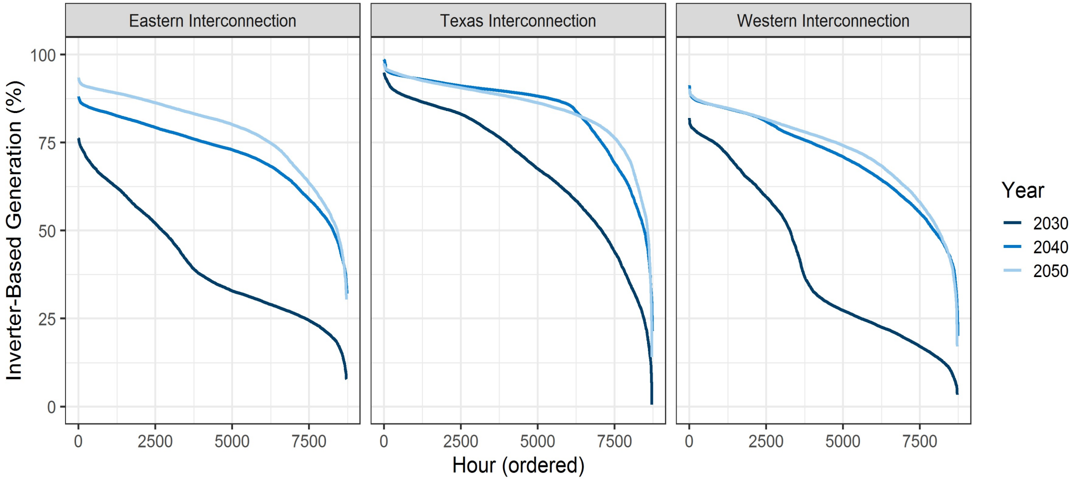


© IRENA (2022), *Grid codes for renewable powered systems*, International Renewable Energy Agency, Abu Dhabi. [Online]

Pace of IBR Interconnections

All major U.S. interconnections are expected to reach peak **instantaneous IBR levels of 75-98%** within the lifetime of IBRs being connected today.

- These plants will need to not just remain online, but contribute to system recovery and reliability.
- IEEE 2800 addresses minimum technical requirements deemed needed from IBRs.



Data from 2021 DOE/NREL Solar Futures Study: https://www.nrel.gov/analysis/solar-futures.html

IBR: inverter-based resources like wind, solar, storage

Insufficient Solar, Wind & Storage Interconnection Requirements

- Diverse & different requirements across various jurisdictions

  …requires more effort and time to address

- Inverter-based resources (IBR) are different from synchronous generators

  …higher (and sometimes lower) capability

- Requirements may not be balanced

  …some too stringent & not taking advantage of new capability

Source: https://www.natf.net/

Recurring Reliability Issues with IBRs

- Unexpected tripping, cessation of active power, oscillations, etc.
- Mis-application of IEEE 1547 standard for Transmission connected resources
- Analysis found **opportunity for standardization** of IBR performance to maintain grid reliability

Source: NERC, 2017-2022

Recurring Reliability Issues with IBRs

Causes of solar PV reduction identified by NERC

PLL Loss of Synchronism, Inverter AC Under- or Overvoltage, Inverter Under- or Overfrequency, Slow Active Power Recovery, Momentary Cessation, Inverter AC Overcurrent, Inverter DC Voltage [Ripple due to AC Voltage] Unbalance, Inverter UPS failure, etc.

NERC Recommendations

- Significant Updates and Improvements Needed to the **FERC Large Generator Interconnection Agreements (LGIA)**
- **Improvements to NERC Reliability Standards** Needed to Address Systemic Issues with Inverter-Based Resources

Source: NERC, 2017-2022

Contextualization within IBR Interconnection Process

Challenges and Opportunities for North America

Existing Step 1: Interconnection Request
Plant-Specific Interconnection Request

- **Insufficient**, diverse, or vague RTO/ISO/TP's technical interconnection requirements (**TIRs**)
- Submission of **any available models,** often **inappropriately configured**
- **Vague model 'acceptance criteria'**

Existing Step 2: Feasibility Study
Plant-Specific Interconnection Screening / Preliminary Review

Limited screening for:

- Grid strength metrics (neither conventional nor advanced)

that could help determine **what type of models and system impact studies** would be needed to reliably connect the IBR.

Existing Step 3: System Impact Study
Plant-Specific Grid Integration & Reliability Impact

- System impact studies often use **insufficient models** that may **not** be **site-specific** and **may be configured with generic** parameters
- May **not represent** IBR units, supplemental IBR devices, and **the IBR plant design** ultimately commissioned in the field

Existing Step 4: Facility Study
IBR Plant Cost Estimation and Determination of Transmission Grid Upgrades

- **No common assessment of IBR plant-level conformity** with regard to RTO/ISO/TP's technical interconnection requirements (TIRs)
- Detailed **IBR plant design may change** after Interconnection Agreement (IA) is executed

IBR Plant Construction
Installation and Building of all Equipment and Structures

- What is built in the field does often not match what had been previously studied/modeled
- **No "as-built" plant-level evaluation**

Existing Step 5: Interconnection Commissioning
Plant-Specific Commissioning & Model Validation/ Verification

- Only a (limited) set of field tests are performed to validate/verify IBR plant model.
  - Limited to small-signal disturbances.
  - Often **no verification of** large-signal disturbances such as **ride-through**

- **Limited collection of field data** to validate/verify IBR plant model.
  - Often not for large-signal disturbances.

Source: EPRI, 2021-2022

IEEE 2800-2022
IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems

&

P2800.2
Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems
Active PAR

IEEE SA: https://standards.ieee.org/ieee/2800.2/10616/
P2800.2 WG: https://sagroups.ieee.org/2800-2/

Scope of IEEE 2800 Standard

This standard establishes the recommended interconnection capability and performance criteria for inverter-based resources interconnected with transmission and sub-transmission systems. Included in this standard are recommendations on performance for reliable integration of inverter-based resources into the bulk power system, including, but not limited to, **voltage and frequency ride-through, active power control, reactive power control, dynamic active power support under abnormal frequency conditions, dynamic voltage support under abnormal voltage conditions, power quality, negative sequence current injection, and system protection**.

Applicable to IBRs like wind, solar & energy storage:

- "Type 3" wind turbines (doubly-fed induction generators) are in scope
- HVDC-VSC connected resources, e.g., onshore connection point of a HVDC-VSC tie-line interconnecting an offshore resource.

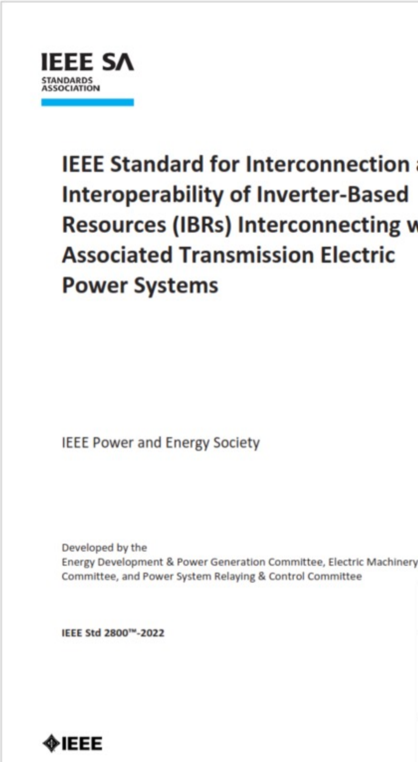
Summary of IEEE 2800 Standard

- The standard **harmonizes** Interconnection Requirements for Large Solar, Wind and Storage Plants

- It is a **consensus-based** standard developed by over ~175 Working Group participants from utilities, system operators, transmission planners, & OEMs over 2 years

- It has successfully passed the IEEE SA ballot among 466 SA balloters **(>94% approval)**, >90% response rate)

- **Published on April 22, 2022 (Earth Day)**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Complementing North American Reliability Standards

Authority	Scope	Performance	Test & Verification & Model Validation
FERC / NERC?	**Transmission**	• FERC Orders • NERC Reliability Standards & Guidelines	• NERC compliance monitoring & enforcement
NARUC / State PUCs?	**Sub-Transmission**	• Not available	• Not available
NARUC / State PUCs?	**Distribution** (for DER)	• IEEE Std 1547-2018 • IEEE Std 1547a-2020 ✓	• IEEE 1547.1-2020 • Ul 1741 (SB) • IEEE ICAP ✓

IEEE 2800-2022

IEEE P2800.2

DER: Distributed Energy Resources

Source: EPRI, 2021

Only when <u>adopted</u> by the appropriate authorities, IEEE standards become mandatory

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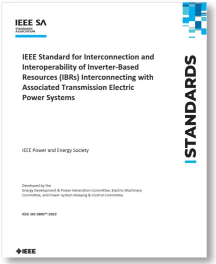
IEEE Standards Classification and Consensus Building

IEEE 1547

IEEE 1547.1

Standards
documents specifying mandatory requirements (***shall***)

IEEE 2800



Recommended Practices
documents in which procedures and positions preferred are presented (***should***)

IEEE P2800.10

IEEE P1547.2

IEEE P1547.3

IEEE P1547.9

Guides
documents that furnish information – e.g., provide alternative approaches for good practice, suggestions stated but no clear-cut recommendations are made (***may***)

IEEE P2800.1

What to expect from IEEE 2800-2022?

- **Provides Value**
  - widely-accepted, unified technical minimum requirements for IBRs
  - simplifies and speeds-up technical interconnection negotiations
  - flexibility for IBR developers & OEMs ➔ not an equipment design standard
- **Specifies**
  - performance and functional capabilities *and not* utilization & services
  - functional default settings and ranges of available settings
  - performance monitoring and model validation
  - type of tests, plant-level evaluations, and other verifications means, but not detailed procedures (➔ *IEEE P2800.2)*
- **Scope**
  - Limited to all transmission and sub-transmission connected, large-scale wind, solar, energy storage and HVDC-VSC

What *not* to expect from IEEE 2800?

- **No exhaustive requirements for evolving IBR technology solutions**
  - IEEE 2800 applies to all IBRs (including grid-forming ones), but was designed with conventional grid-following IBRs in mind
  - Considers synchronous condensers as ”supplemental IBR devices” but allows for exceptions when used in IBR plants
- **No definition of an interconnection process**
  - This is up to transmission system owners and their stakeholders and regulators
  - IEEE 2800 may be used as *part* of such a process
- **No procedures to verify that IBRs comply with requirements**
  - **Procedures are currently being developed in IEEE P2800.2:**

P2800.2

Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems

Active PAR

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P2800.2 WG: https://sagroups.ieee.org/2800-2/

Capability versus Utilization

Capability:

"Ability to Perform"

- Functions
- Ranges of available settings
- Minimum performance specifications

<u>Examples</u>

- Frequency Response
  - Frequency Droop Response
  - Ramp rate limitations
- Ride-Through
  - Voltage ride-through
  - Current injection during ride-through
  - Consecutive voltage ride-through
  - Frequency ride-through
  - ROCOF ride-through
  - Phase angle jump ride-through

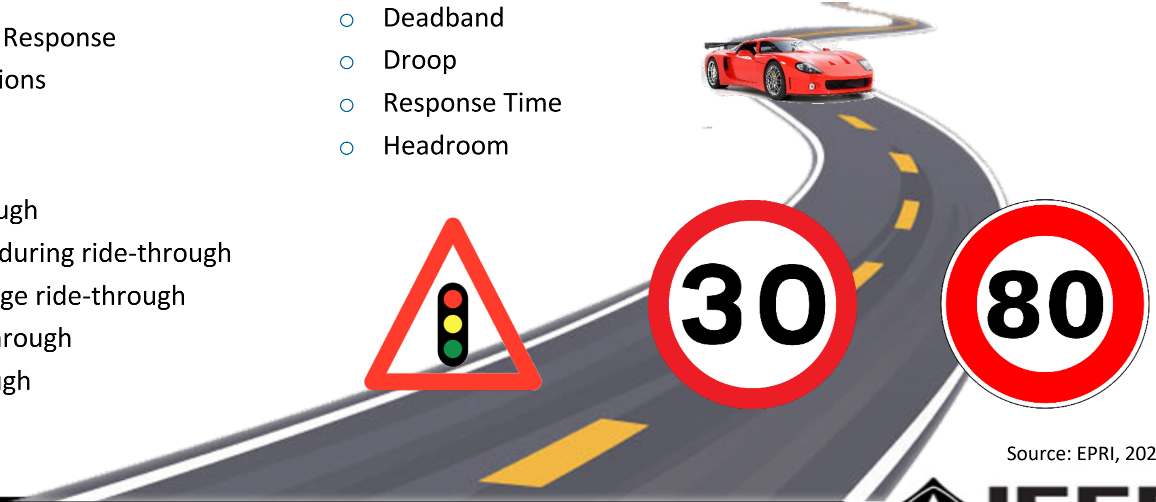
Utilization of Capability:

"Delivery of Performance"

- Enable/disable functions
- Functional settings / configured parameters
- Operate accordingly (e.g., maintain headroom, if applicable)

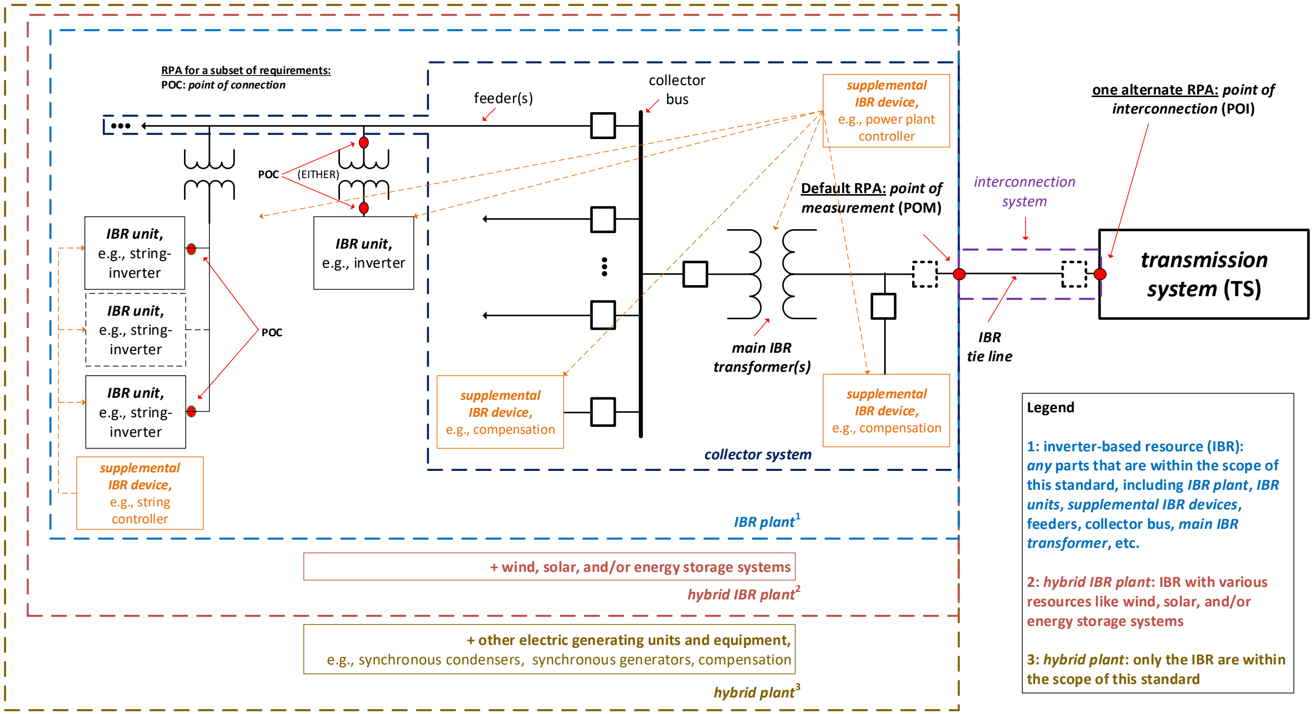
<u>Examples</u>

- Deadband
- Droop
- Response Time
- Headroom

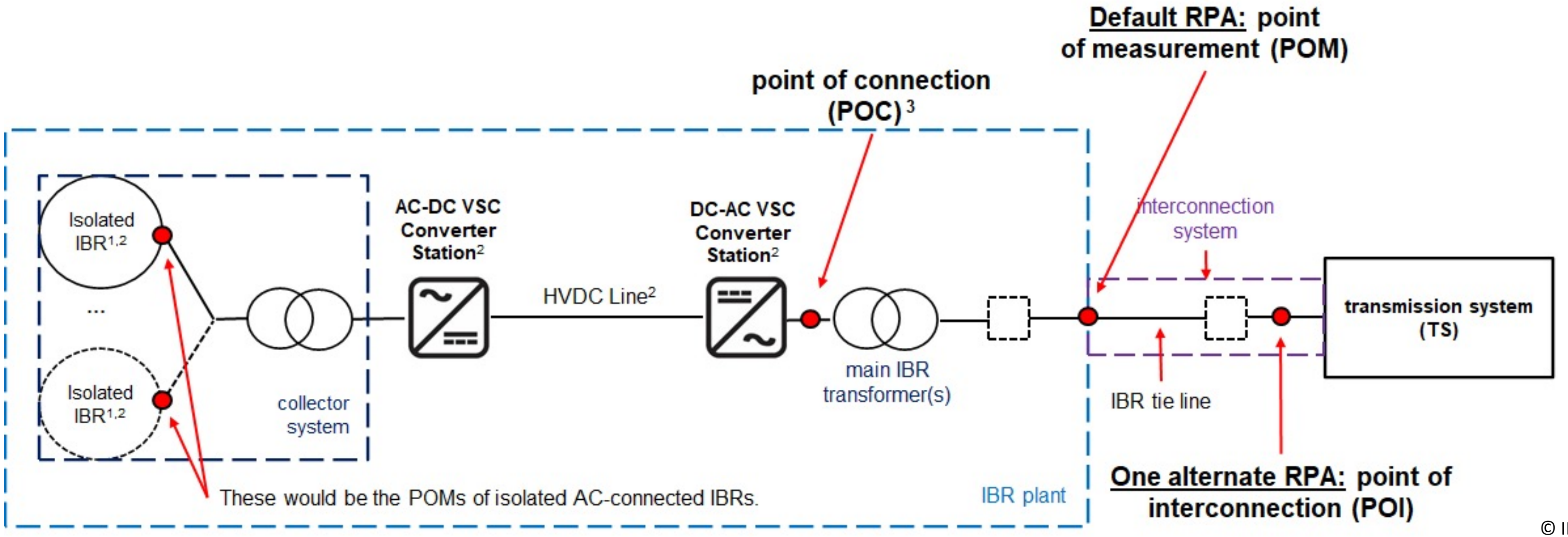


Source: EPRI, 2021

Reference Point of Applicability – Example 1



Reference Point of Applicability – Example 2

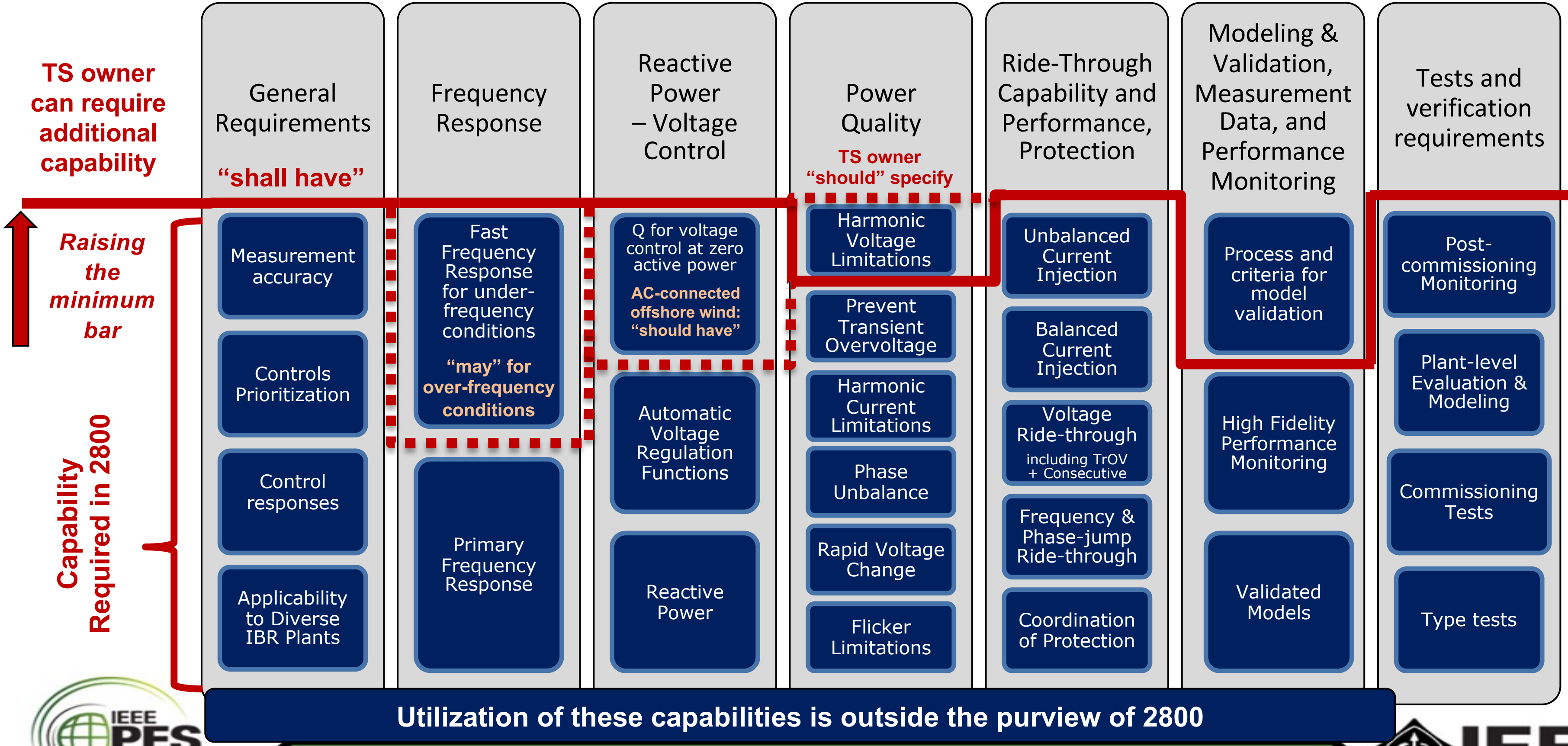


[1] Includes IBR units like type IV wind turbine generators

[2] May serve as a supplemental IBR device that is necessary for the IBR plant with VSC-HVDC to meet the requirements of this standard at the RPA

[3] Depending on design, the POC may be on the TS side of the main IBR transformer.

IEEE 2800-2022 Technical Minimum Capability Requirements



Source: EPRI, 2021

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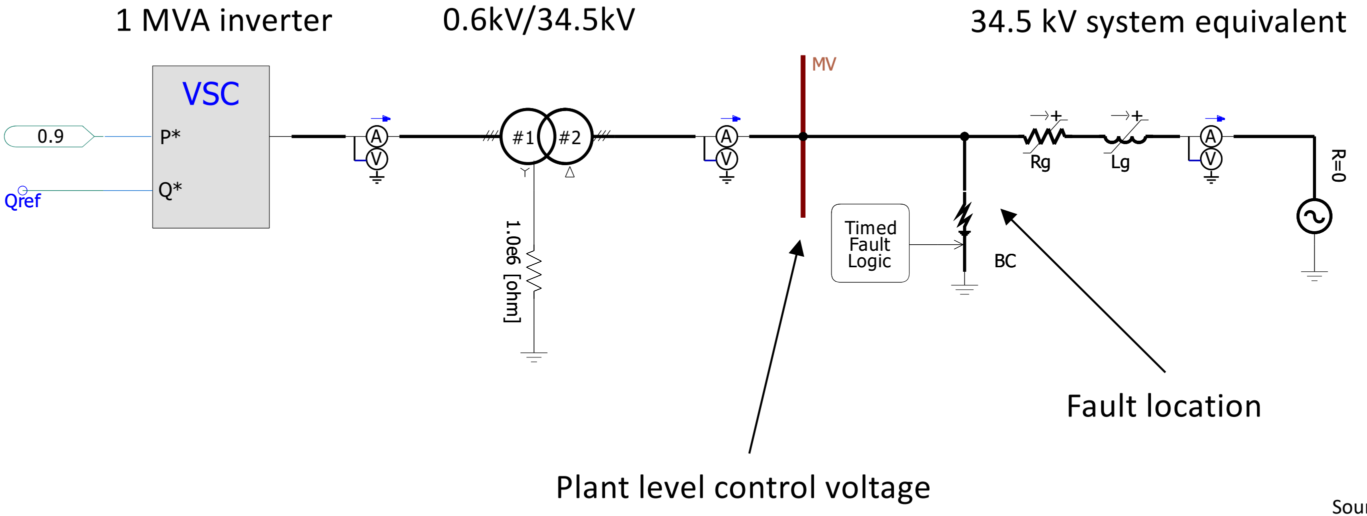
IBR Plant Modeling Examples

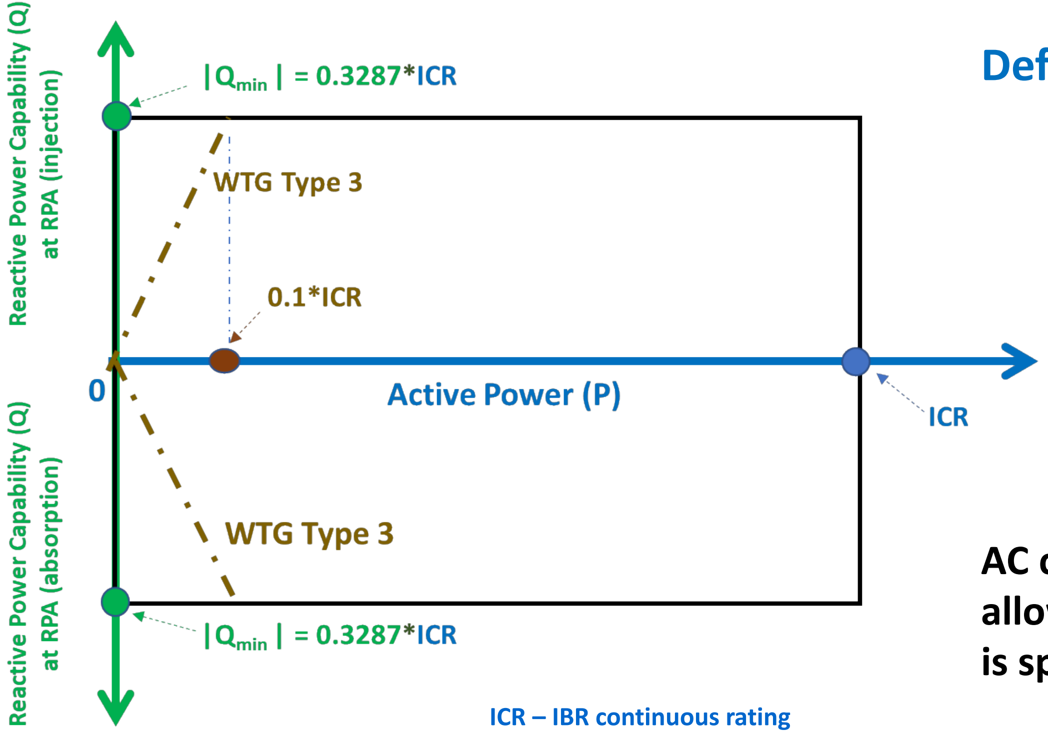
Infinite Bus simulations



Source: EPRI, 2022

MINIMUM REACTIVE POWER CAPABILITY REQUIREMENTS

Min. Reactive Power Capability vs Active Power Injection



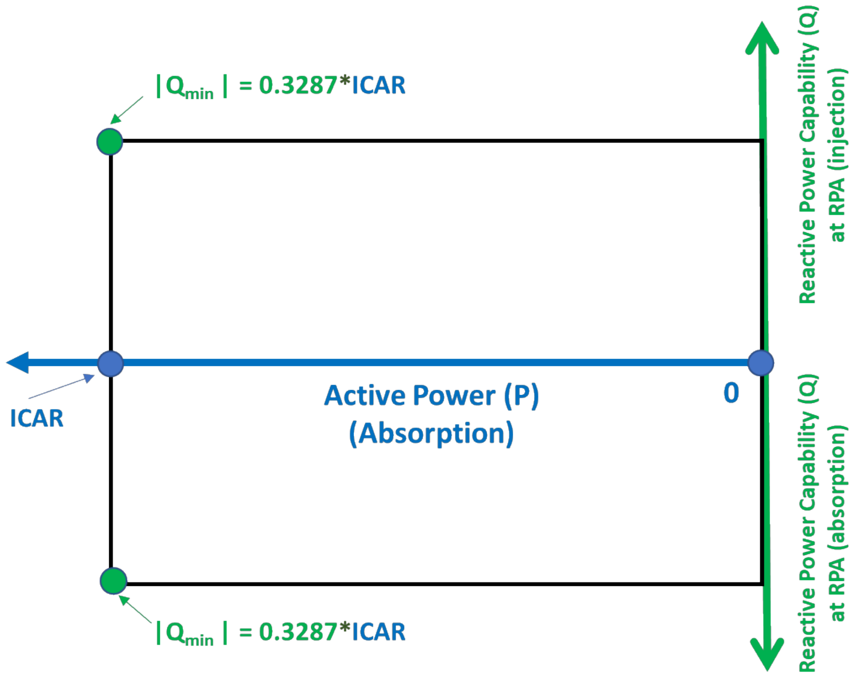
Default RPA: Point of Measurement

AC connected off-shore plant: exception allowed but shall not require capability than is specified for type III WTG-based IBR Plant.

ICR – IBR continuous rating
Q_{min} – minimum reactive power capability

Min. Reactive Power Capability vs Active Power Absorption

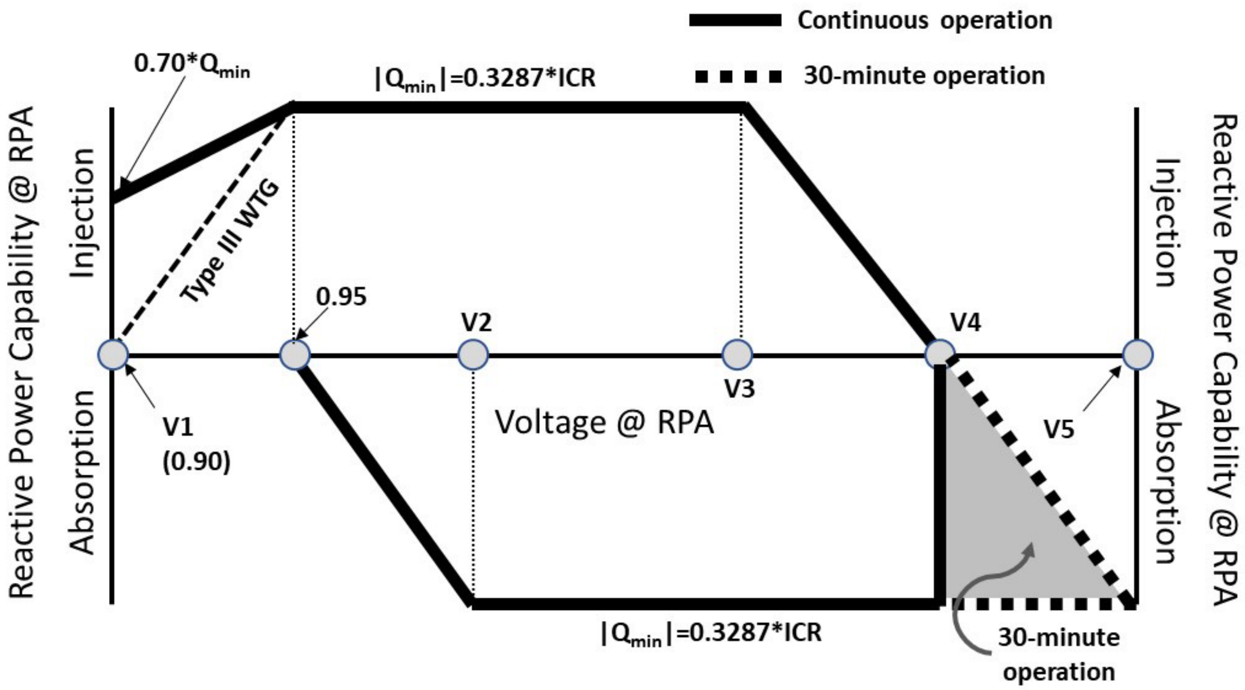
Default RPA: Point of Measurement



ICAR – IBR continuous absorption rating

Q_{min} – minimum reactive power capability

Min. Reactive Power Capability at RPA vs Voltage



TS Nominal Voltage at RPA	V1 (p.u.)	V2 (p.u.)	V3 (p.u.)	V4 (p.u.)	V5 (p.u.)
< 200 kV	0.90	0.99	1.03	1.05	1.10
>= 200 kV except 500 kV and 735 kV as below	0.90	1.00	1.04	1.05	1.10
500 kV	0.90	1.02	1.06	1.10	1.10
735 kV	0.90	1.02	1.06	1.088	1.10
TS Owner/Operator may specify different values/thresholds.					

Voltage and Reactive Power Control Modes

The *IBR plant* shall provide the following mutually exclusive modes of reactive power control functions:

— RPA voltage control mode
— Power factor control mode
— Reactive power set point control mode

RPA voltage control

Closed-loop automatic control to regulate the voltage at the RPA

Capable of reactive power droop to ensure a stable and coordinated response

Any switched shunts or LTC transformer tap change operation needed to restore the dynamic reactive power capability shall respond within 60 s.

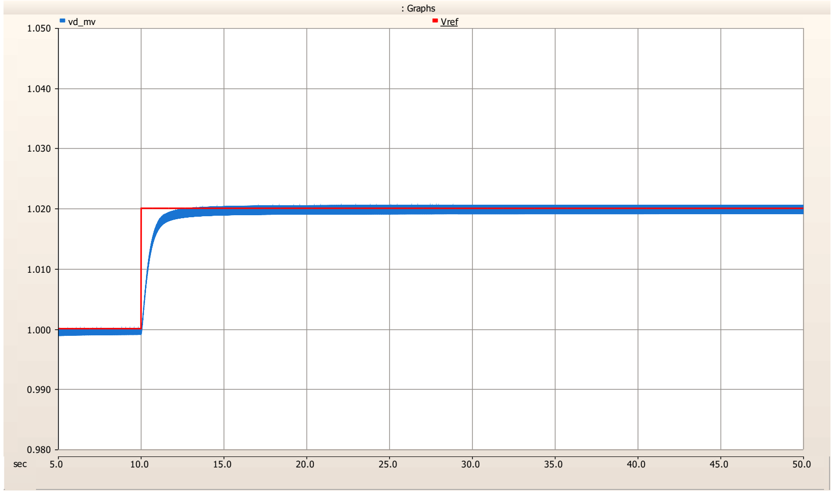
Parameter	**Performance target**	**Notes**
Reaction time	< 200 ms	
Max. *step response time*	As required by the *TS operator*	Typical *step response time* ranges between 1 s and 30 s.
Damping	Damping ratio of 0.3 or higher	Damping ratio, indicative of control stability, depends on grid strength.

Plant level voltage control

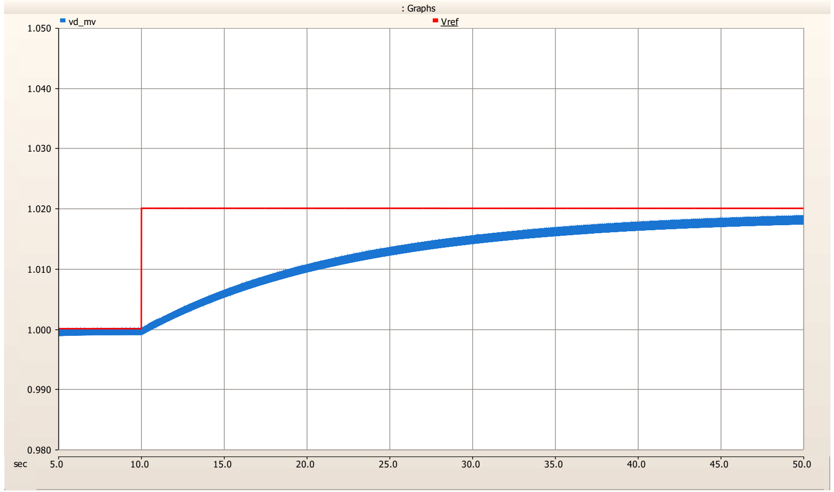
rise time = 1.0 sec vs 30.0 seconds

Red trace is the plant controller voltage setpoint (pu)

Blue trace is the measured 34.5 kV voltage (pu)



1 second rise time



30 second rise time

Source: EPRI, 2022

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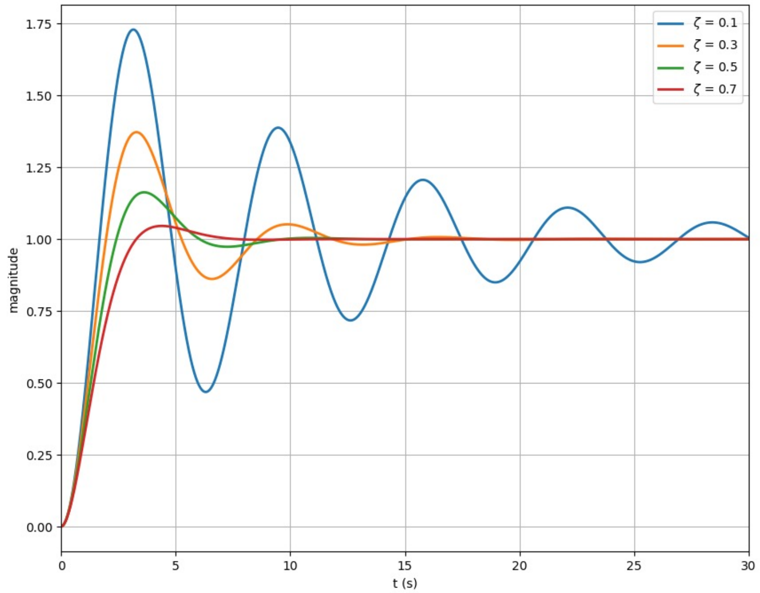
Plant level voltage control response damping > 0.3



Source: EPRI, 2022

FREQUENCY DISTURBANCE RIDE-THROUGH CAPABILITY AND PERFORMANCE REQUIREMENTS

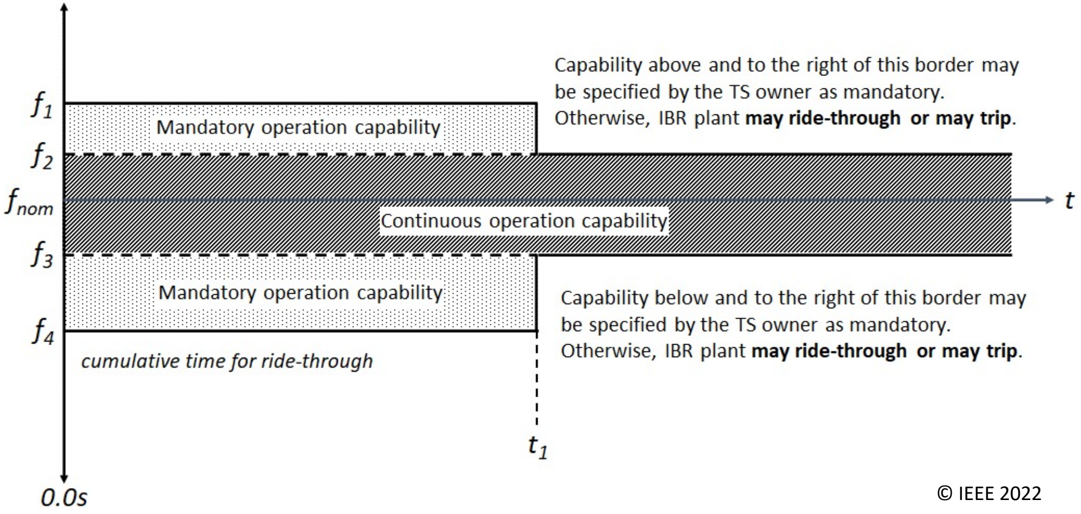
Frequency Disturbance Ride-Through Capability Requirements

The IBR plant shall be capable to ride-through and:

- maintain **synchronism** with the TS.
- meet **active power** requirements of **PFR and/or FFR** as applicable or **maintain pre-disturbance active power** output
- maintain its **reactive power** output. **Adjustment allowed** to stay in V/Hz limit

Exception

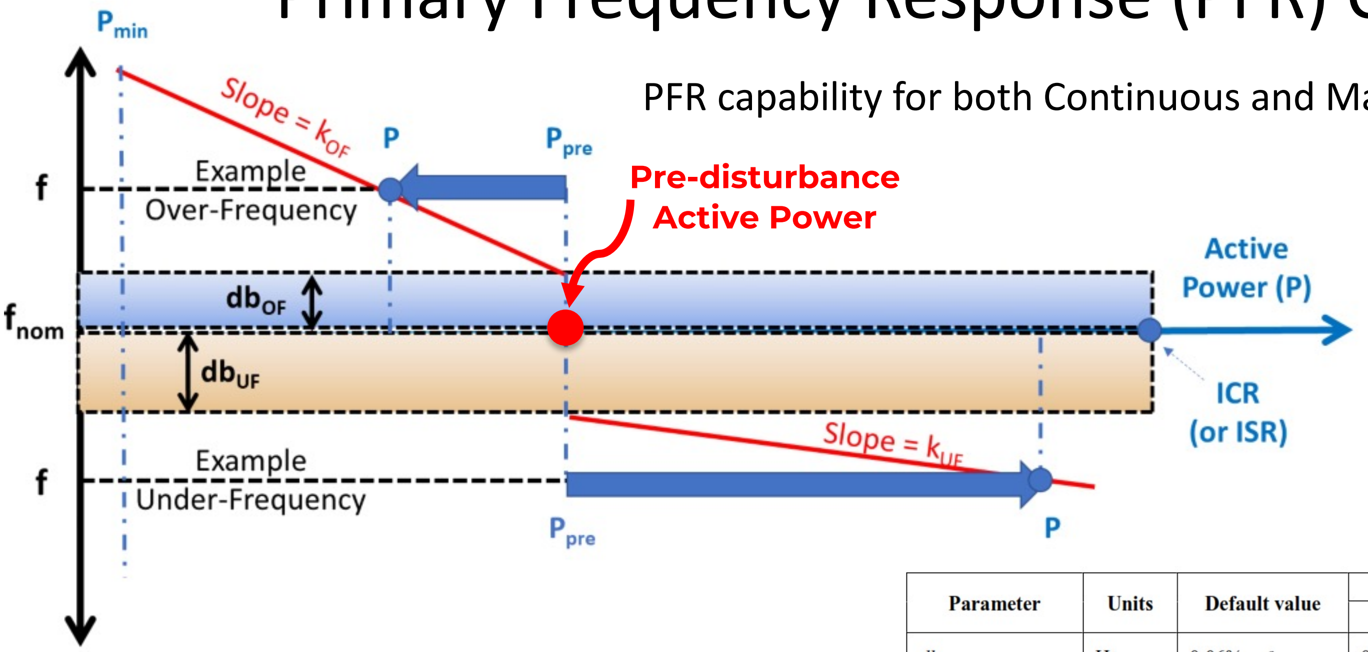
- Within **V/Hz capability** of IBR units, transformers & supplemental IBR devices.



Frequency range (Hz)	Percent from f_{nom}	Minimum time (s) (design criteria)	Operation
f_1, f_4	+3, −5	299.0 (t_1)	Mandatory operation
f_2, f_3	+2, −2	∞	Continuous operation

Primary Frequency Response (PFR) Capability

PFR capability for both Continuous and Mandatory Operation Regions



ICR: IBR Continuous Rating
ISR: IBR Short-Term Rating

Parameter	Units	Default value	*Ranges of available settings*	
			Minimum	Maximum
db_{UF}	Hz	0.06% × f_{nom}	0.025% × f_{nom}	1.6% × f_{nom}
db_{OF}	Hz	0.06% × f_{nom}	0.025% × f_{nom}	1.6% × f_{nom}
k_{UF}[68]		5%	2%[69]	5%
k_{OF}		5%	2%	5%

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Primary Frequency Response (PFR) Dynamic Performance

Parameter	Units	Default value	Ranges of available settings	
			Minimum	Maximum
Reaction time	Seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	Seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	Seconds	10.0	10	30
Damping ratio	Unitless	0.3	0.2	1.0
Settling band	% of change	Max (2.5% of change or 0.5% of ICR)	1	5

Stable and damped response shall take precedence over *rise time* and *settling time*.

Fast Frequency Response (FFR) *Capability* Requirements

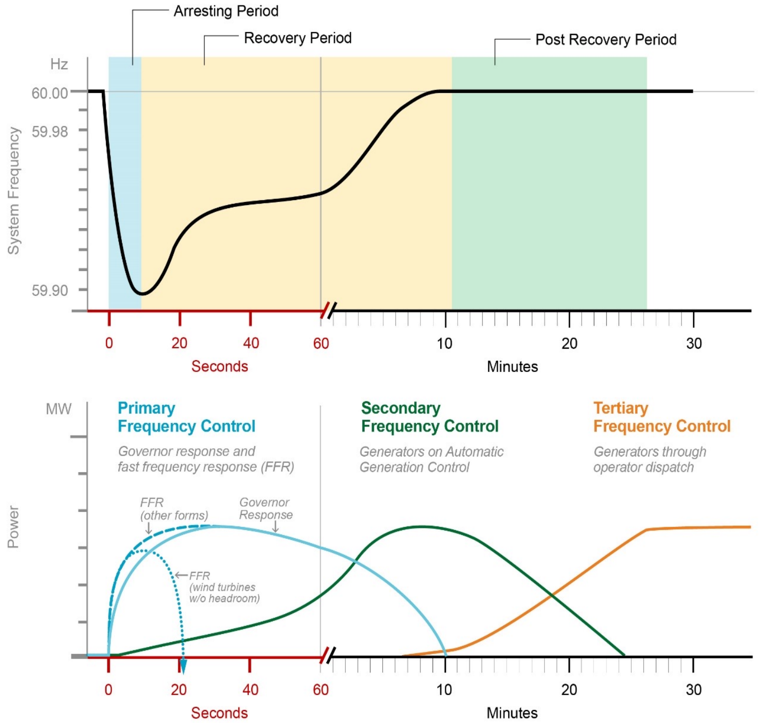
Inertial Response is also known as FFR in North America

Definition of FFR

*active power injected to the grid **in response to changes in measured or observed frequency** during the arresting period of a frequency excursion event **to improve the frequency nadir or initial rate-of-change of frequency***

Requirements for FFR from IBR

- *Capability* required for under-frequency conditions
- *Utilization* of FFR capability of IBR plant shall not be enabled by default
- FFR capability may be deployed for the purposes of ancillary service offering



Source: LBNL 2020

FFR Performance Requirements (General)

- FFR capability shall be an autonomous function
- The FFR response time capability, shall be adjustable to no greater than 1 second, including the reaction time for triggering FFR
- The response shall be stable and any oscillations shall be positively damped with a damping ratio of 0.3 or better
- Stable and damped response shall take precedence over response time
- *IBR plant* shall be capable of sustaining FFR for as long as the *IBR plant* energy resource is available or until supplanted by primary, secondary or tertiary frequency response, whichever is less
- Active power response during FFR actuation may temporarily exceed the *IBR continuous rating* (ICR) but shall not exceed the *IBR short-term rating* (ISR)
- FFR and PFR may actuate independently from each other or may complement each other

FFR is an evolving functional and performance capability

FFR Performance Requirements

FFR1: FFR proportional to frequency deviation

$$p_{FFR1} = \min\left\{ p_{avl}, p_{pre} + \max\left(0, \frac{f_{UF,FFR1} - f}{f_{nom} \times k_{UF,FFR1}} \right) \right\}$$

	Units	Default value	*Ranges of available settings*	
			Minimum	Maximum
$f_{UF,FFR1}$	Hz	99.94% of f_{nom}	99.17% of f_{nom}	99.94% of f_{nom}
$k_{UF,FFR1}$	%	1%	1%	5%

Other variants of FFR (Informative Annex K)

- FFR2: FFR proportional to df/dt
- FFR3: Fixed magnitude FFR with frequency trigger
- FFR4: Fixed magnitude FFR with df/dt trigger

Dynamic performance

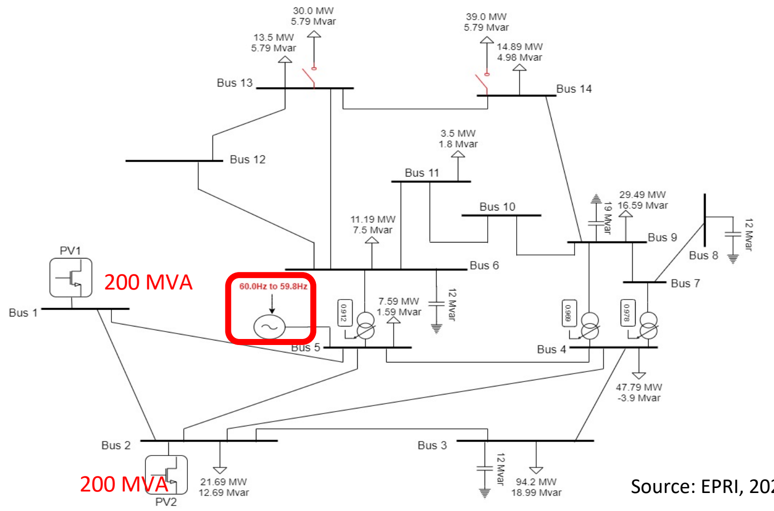
- applicable parameters such as reaction and response time
- tuning of these parameters to be carefully studied on a case-by-case basis to avoid instable IBR plant operation

In many cases, FFR is just "a faster PFR"

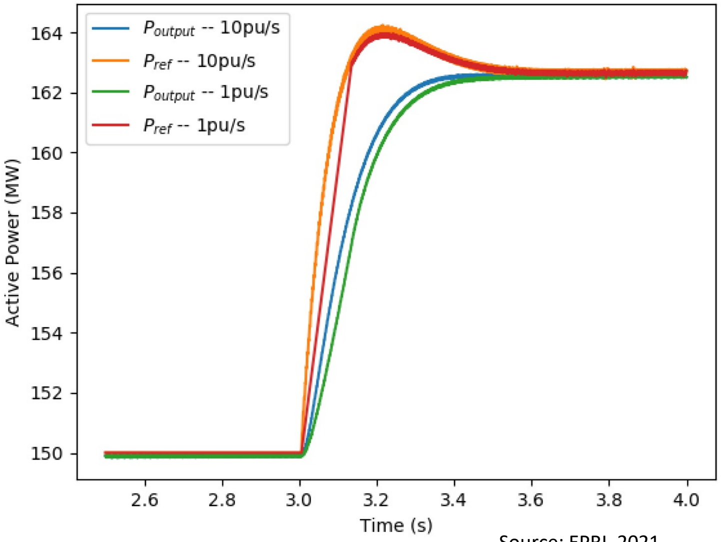
FFR Performance Requirements – WTG Based IBR Plant

- **adjustable** frequency threshold **dead band** from -0.1 Hz to -1.0 Hz
- temporary increase of active power output, **provided wind resource is available**:
  - equal to at least 5% of rated power of each WTG in service when operating at or above 25% of rated power
  - for the duration from 5 s to 10 s
- limit **rise time** to reach maximum temporary increase of active power output to **1.5 s or less**.
- limit **decrease in active power output** during energy recovery to a **maximum of 20%** of pre-disturbance active power output.
  - energy recovery extend as long as possible to minimize the magnitude of the initial decrease of active power
- capability to **operate repeatedly** in FFR mode with a 2 minutes delay after the end of the recovery period
- **FFR shall take precedence over PFR** and **PFR shall be activated at the end of** energy recovery period following **FFR support**

Example: Two PV plants in an existing strong network



Source: EPRI, 2021



Source: EPRI, 2021

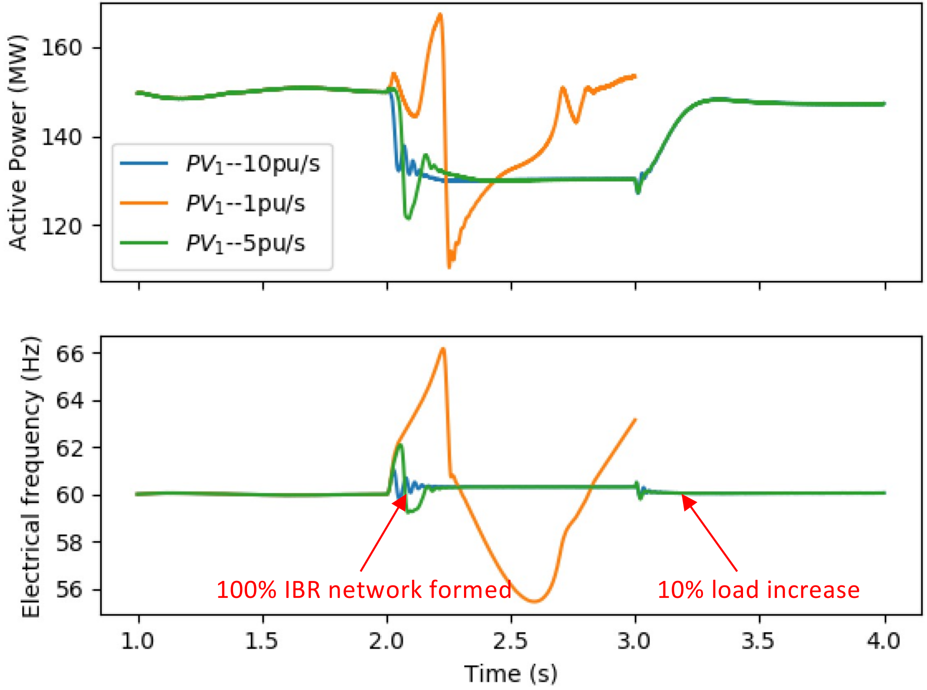
- Each 200 MVA PV plant is a full switching model[1]
- Frequency control with 17mHz dead band and 5% droop at inverter level
  - Comparison with 1pu/s and 10pu/s ramp rate on active power command

Both ramp rates meet requirements mentioned in IEEE P2800 Draft Standard

[1] https://www.pscad.com/knowledge-base/article/521

Source behind resource may influence delivery of response

- A low inertia power network needs fast injection of current to mitigate imbalances.
- Suitable choice of ramp rate limit can bring about a stable response



Source: EPRI, 2021

- 100% IBR network created at t=2.0s
- Load increase at t=3.0s

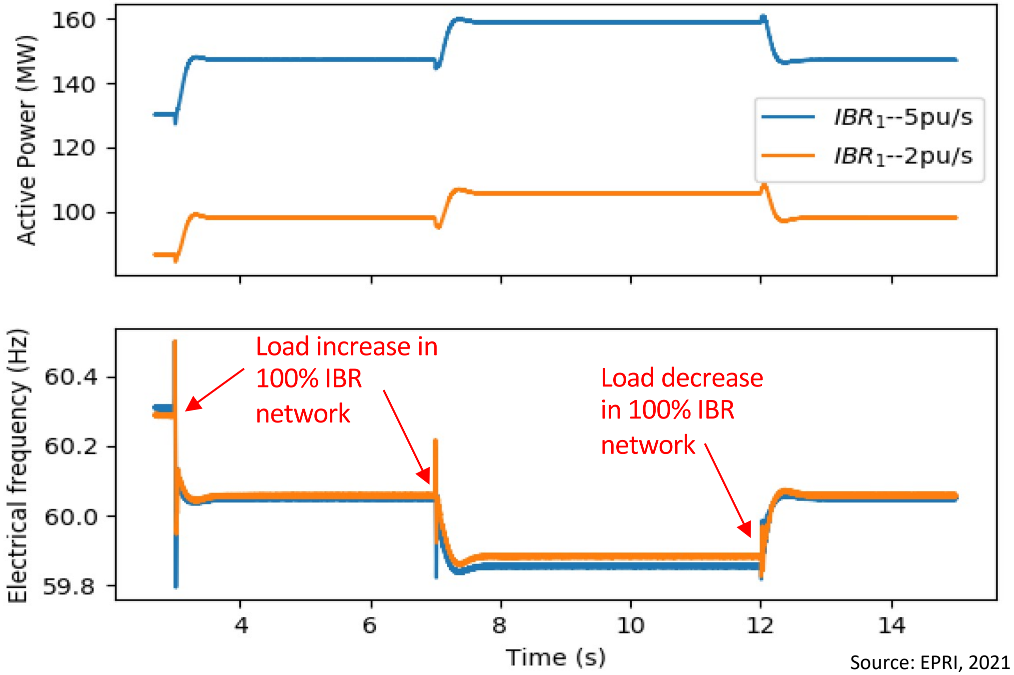
Maximum ramp rate **influenced by source behind the inverter**

Batteries can tolerate higher ramp rates as opposed to wind turbines

Lower ramp rate requires more responsive resources

- Possible to obtain stable frequency **control in a 100% IBR network**, with lower ramp rates
- Requires more **resources to share** the change in energy **burden**
- Any form of IBR device/control can have inherent ramp rate limits

Important to recognize this if newer IBRs have to additionally support older IBRs



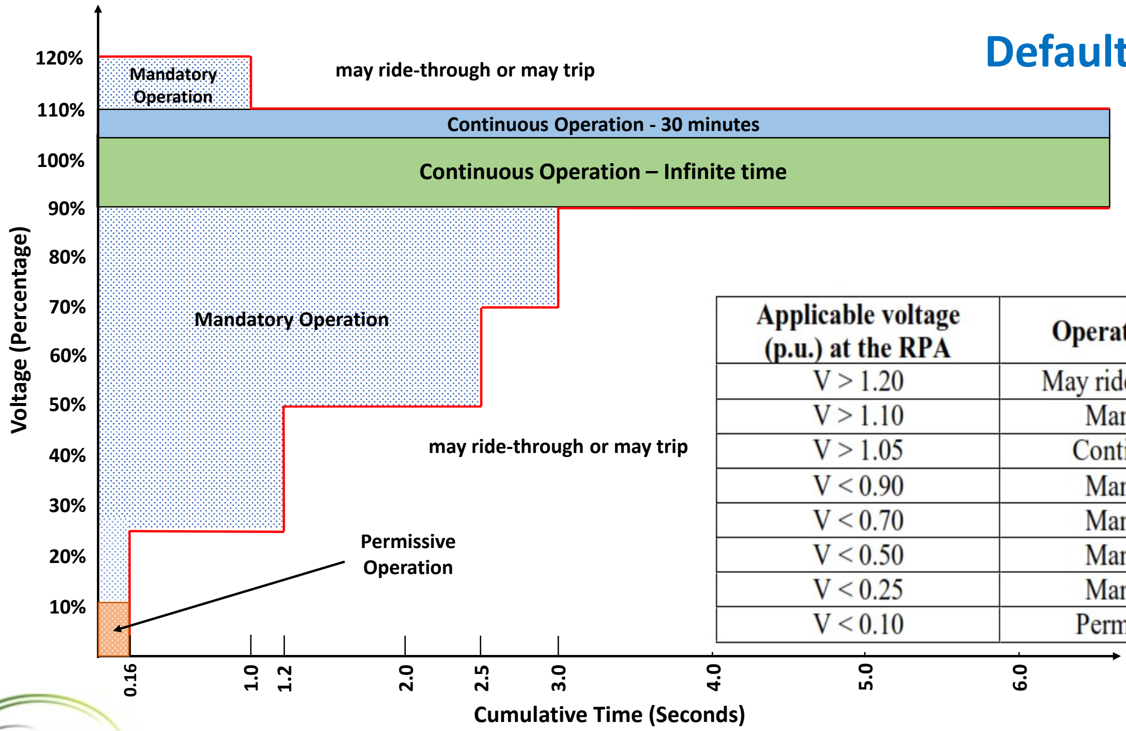
Source: EPRI, 2021

5pu/s – Two PV plants of 200 MVA each
2pu/s – Three PV plants of 100 MVA each

VOLTAGE DISTURBANCE RIDE-THROUGH CAPABILITY AND PERFORMANCE REQUIREMENTS

Voltage Ride-Through Capability – Plants with Aux. Load limitations, i.e., Wind Plant

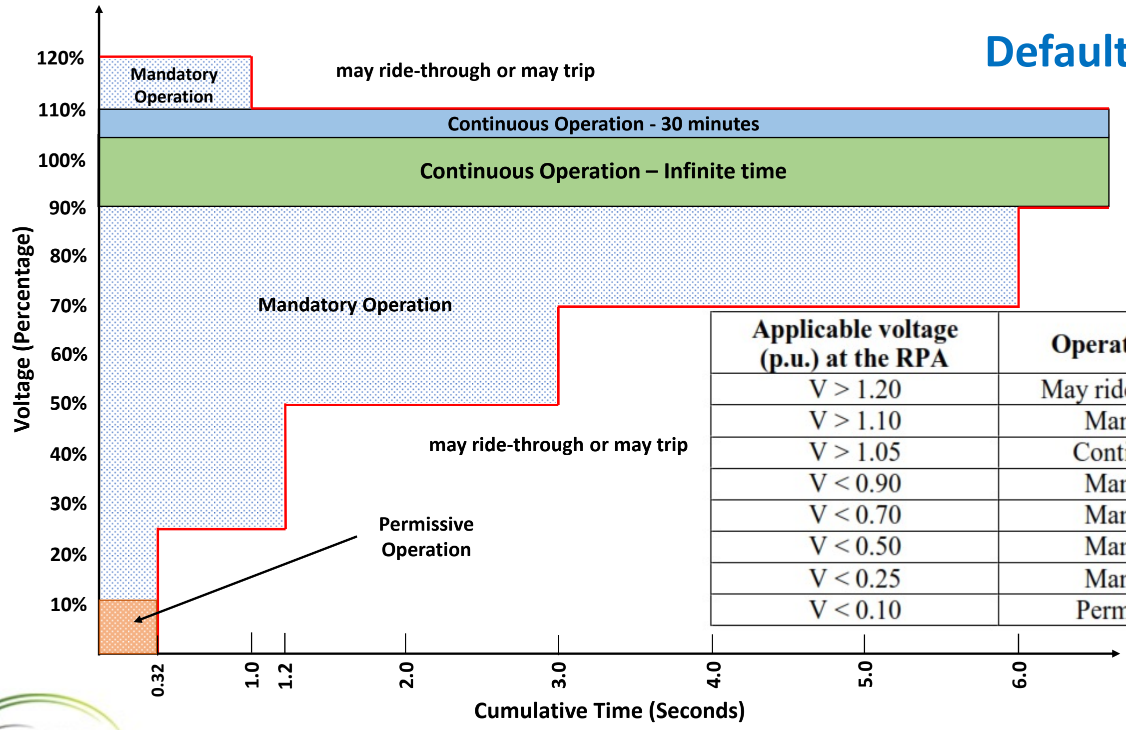
Default RPA: Point of Measurement



Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
V > 1.20	May ride-through or may trip	NA
V > 1.10	Mandatory operation	1.0
V > 1.05	Continuous operation[90]	1800
V < 0.90	Mandatory operation	3.00
V < 0.70	Mandatory operation	2.50
V < 0.50	Mandatory operation	1.20
V < 0.25	Mandatory operation	0.16
V < 0.10	Permissive operation[91]	0.16

Voltage Ride-Through Capability – Plants without Aux. Load limitations, i.e., Solar Plant

Default RPA: Point of Measurement



Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
V > 1.20	May ride-through or may trip	NA
V > 1.10	Mandatory operation	1.0
V > 1.05	Continuous operation[90]	1800
V < 0.90	Mandatory operation	6.00
V < 0.70	Mandatory operation	3.00
V < 0.50	Mandatory operation	1.20
V < 0.25	Mandatory operation	0.32
V < 0.10	Permissive operation[91]	0.32

Clarification of Voltage Ride-Through Capability Req.

Three possible understanding:

- Voltage versus Time curve: For a given voltage, IBR plant shall not trip until the duration at this voltage exceeds ride-through curve capability.
    - ✓Correct understanding

- Voltage Deviation *times* Time *Area*: Area between a nominal voltage (100%) and either a low or high voltage ride-through boundary.

- Voltage versus Time Envelope: Ride-through curves define an envelope to lay as a template over a voltage versus time trajectory.

Exceptions from Voltage Ride-Through Capability Req.

Continuous Operation Region

The *IBR plant* may trip if **V2** of the *applicable voltages* in % of nominal voltage is

> 3% for greater than 10 s, OR
> 2% for greater than 300 s OR
> 6.7% for a duration specified by the TS owner,

provided that the voltage unbalance is **neither caused nor aggravated** by the *IBR plant*.

Mandatory Operation Region

For a voltage disturbance that reduces the *applicable voltage* at the **RPA to < 50% of nominal**, the *IBR plant* shall be considered compliant with this standard if **the post-disturbance apparent current of the *IBR plant* is not less than 90% of the pre-disturbance apparent current**.

When **Tripping of the *IBR plant*** is required to **clear faults** either internal to the *IBR plant*, on the *interconnection system* (*IBR tie line*) or any portion of the TS which may provide sole connectivity between the *IBR plant* and the TS

Voltage Ride-Through Performance

No specification of current magnitude

The 1-cycle time required for DFT (to derive phasor quantities) is included in specified response/settling time.

	Type III WTGs	All other IBR Units
Step Response Time	NA[1]	≤ 2.5 cycles
Settling Time	≤ 6 cycles	≤ 4 cycles
Settling Band	Max of (±10% of required change or ±2.5% of IBR unit maximum current)	Max of (±10% of required change or ±2.5% of IBR unit maximum current)

Note 1: Initial response is driven by machine characteristics, & not the control system.

Slower response/settling time is permitted with mutual agreement between TS owner and IBR owner.

Voltage Ride-Through Performance Requirements

- During a ride-through mode including fault conditions -
  - Type & Magnitude of current injection shall be **dependent** on voltage at inverter (IBR unit) terminals. ← **RPA: Point of Connection**
  - System Disturbance/Balanced Faults:
    - Capability to operate in **active or reactive current priority mode**
    - In reactive current priority mode: increased injection of reactive current
  - Unbalanced faults:
    - Requirements for injection of **negative sequence reactive current**.
  - Injection of current from IBR units shall be at the **same frequency** as of the terminal voltage with following **exceptions**:
    - Close-in faults (PLL fails to track system frequency, type III WTG where control of rotor current is lost
    - Transients, transformer inrushes etc….

Illustration of VRT Performance Requirements

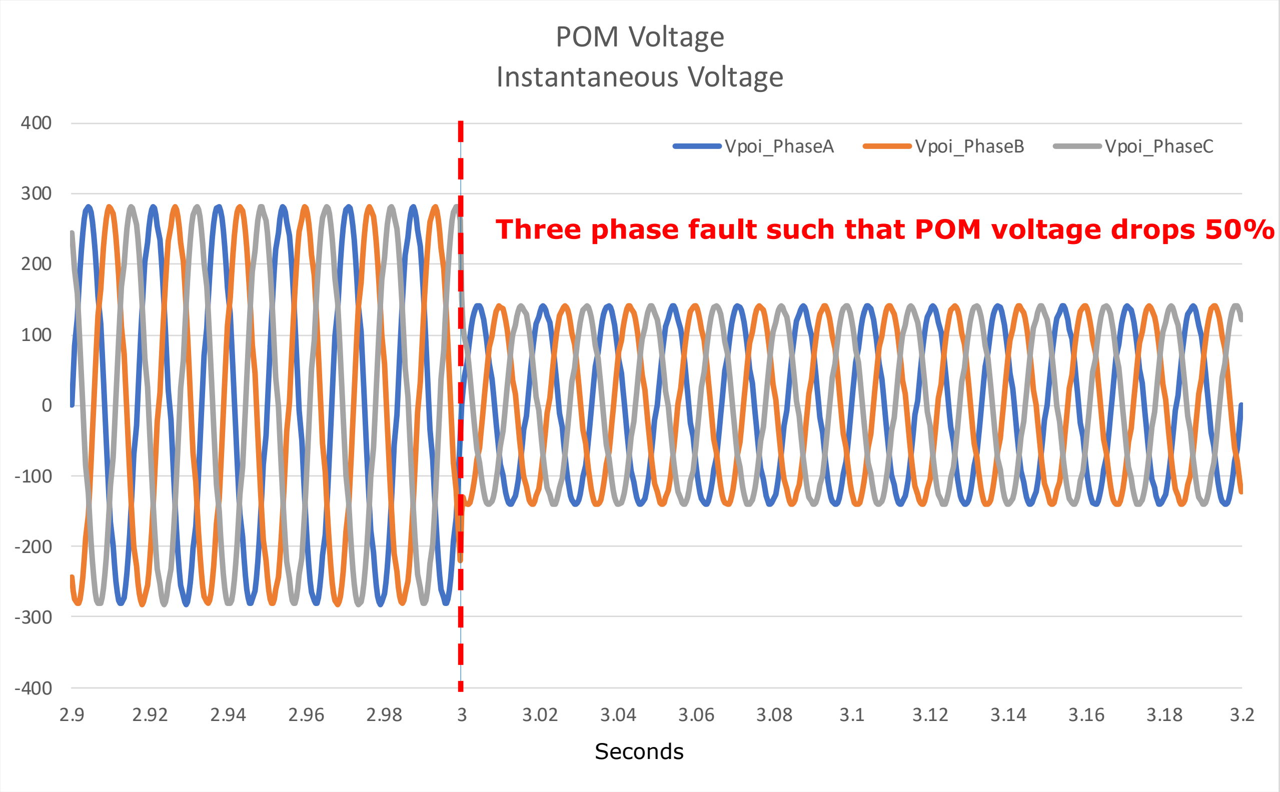


Illustration of VRT Performance Requirements

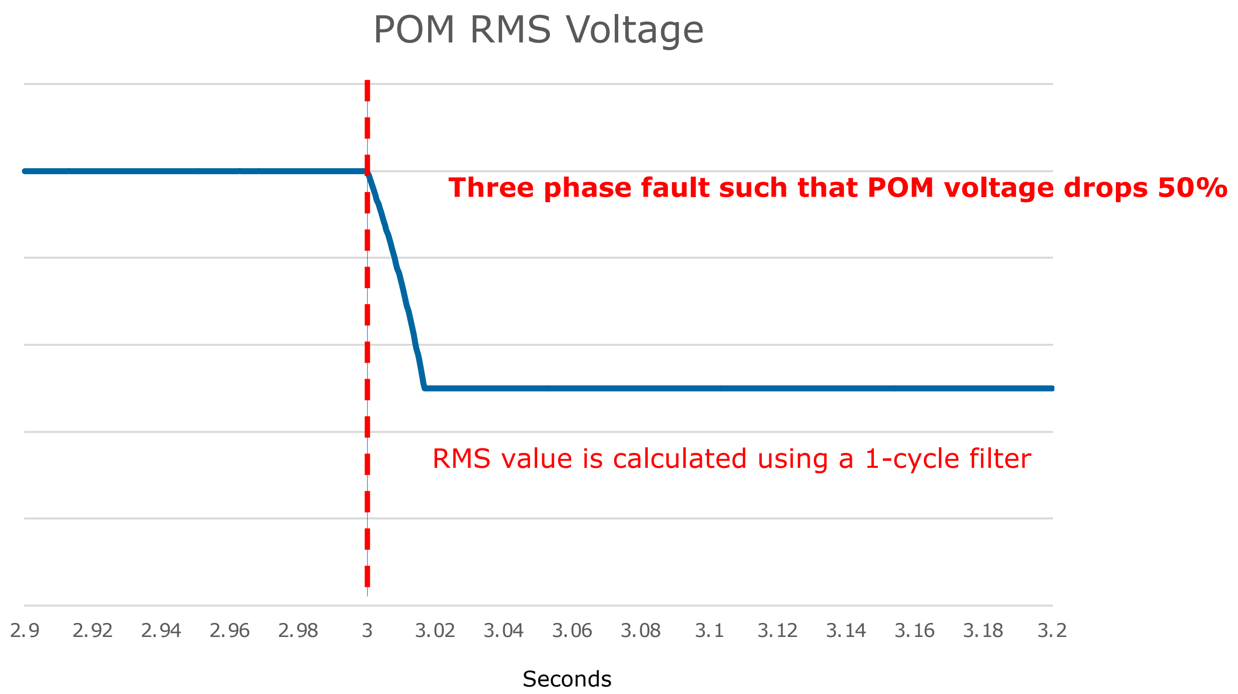


Illustration of VRT Performance Requirements

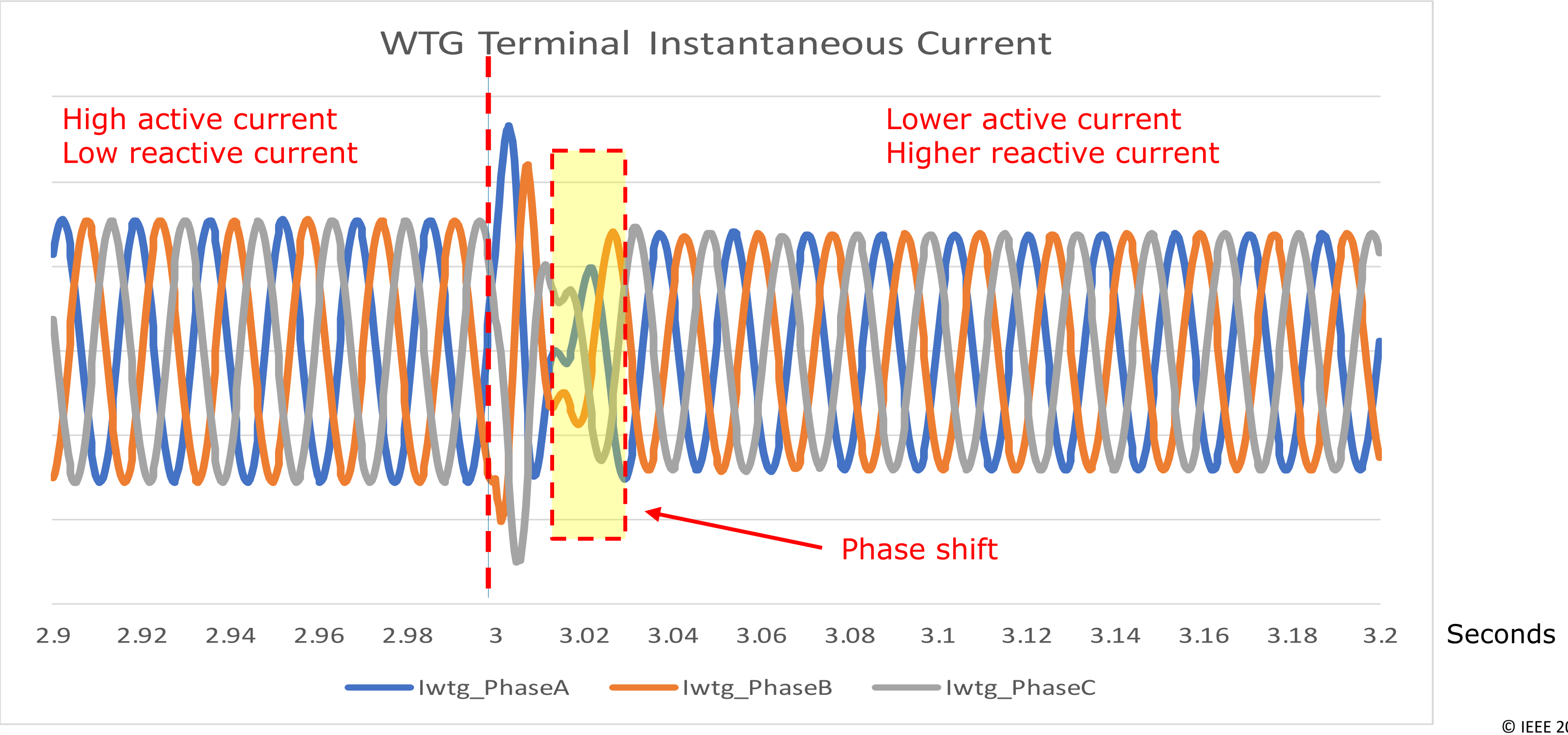
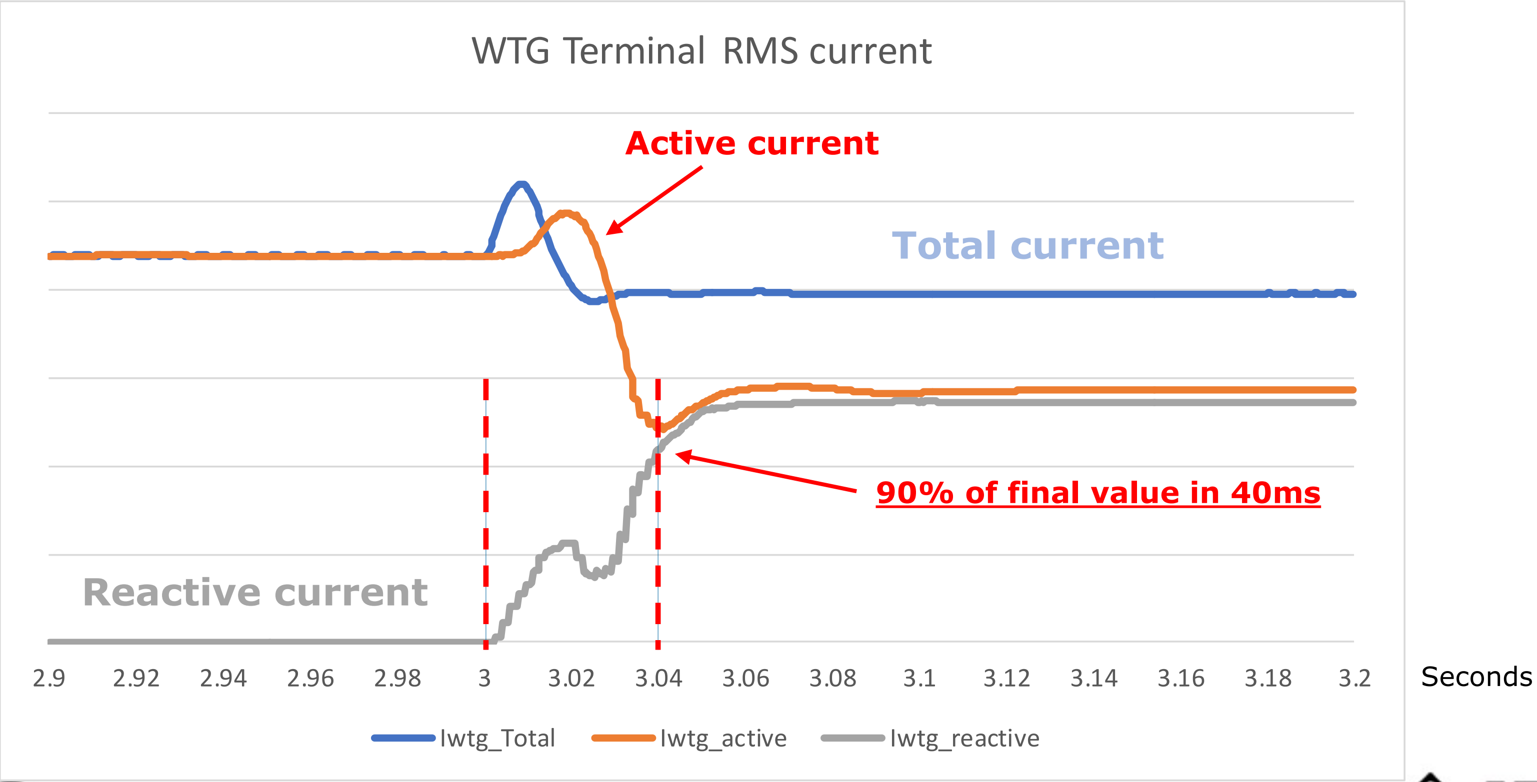


Illustration of VRT Performance Requirements

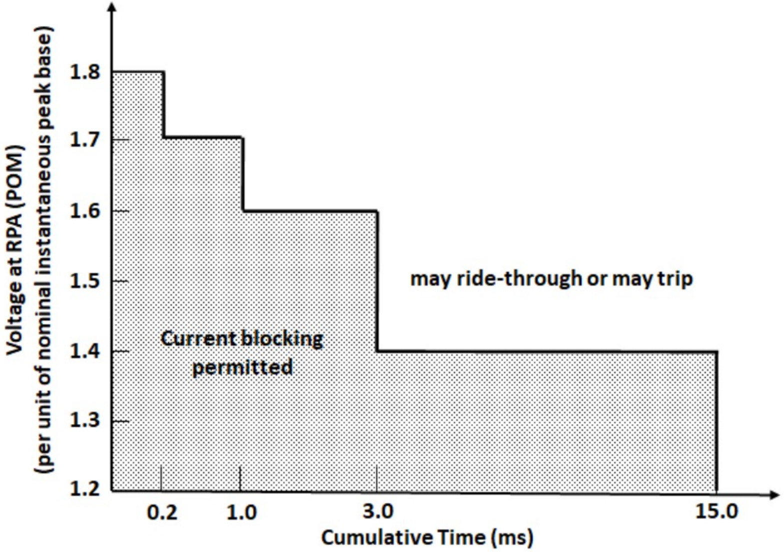


Transient overvoltage ride-through requirements

Default RPA: Point of Measurement

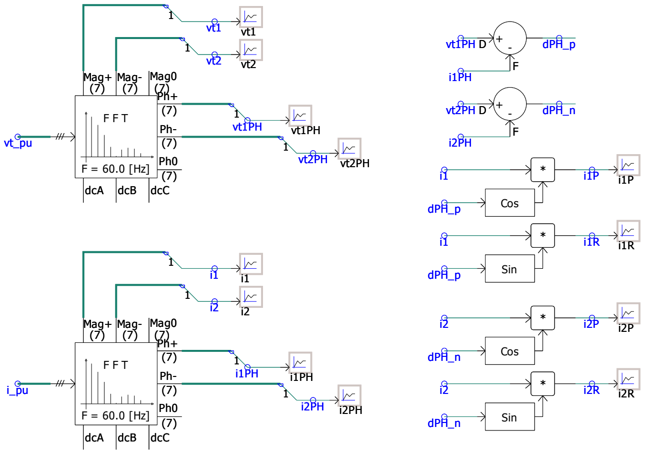
Voltage[c] (p.u.) at the RPA	Minimum ride-through time (ms)[d] (design criteria)[b]
V > 1.80	See footnote[a]
V > 1.70	0.2
V > 1.60	1.0
V > 1.40	3.0
V > 1.20	15.0

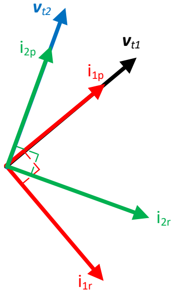
[a] Appropriate surge protection shall be applied at the RPA as well as within the *IBR plant*, including *IBR unit* terminals (POC), as necessary.
[b] The minimum ride-through times specified in Table 14 apply to both 50 Hz and 60 Hz systems.
[c] Specified voltage magnitudes are the residual voltages with surge arresters applied.
[d] Cumulative time over a 1-min time window.



The ***IBR unit*****'s TOV ride-through capability may differ from the *****IBR plant*****'s TOV ride-through requirement** specified in this subclause. The *IBR plant* design should coordinate an *IBR unit*'s TOV ride-through capability with surge protection implemented within the *IBR plant* to allow the *IBR plant* to meet specified TOV ride-through requirements.

Nomenclature of fundamental frequency signals





Positive sequence fundamental frequency

$$i1P = |i1|\cos(\angle vt1PH - \angle i1PH)$$
$$i1R = |i1|\,sin(\angle vt1PH - \angle i1PH)$$

Negative sequence fundamental frequency

$$i2P = |i2|\cos(\angle vt2PH - \angle i2PH)$$
$$i2R = |i2|\,sin(\angle vt2PH - \angle i2PH)$$

Based on this nomenclature, during unbalanced faults, we expect:

positive sequence current lags positive sequence voltage

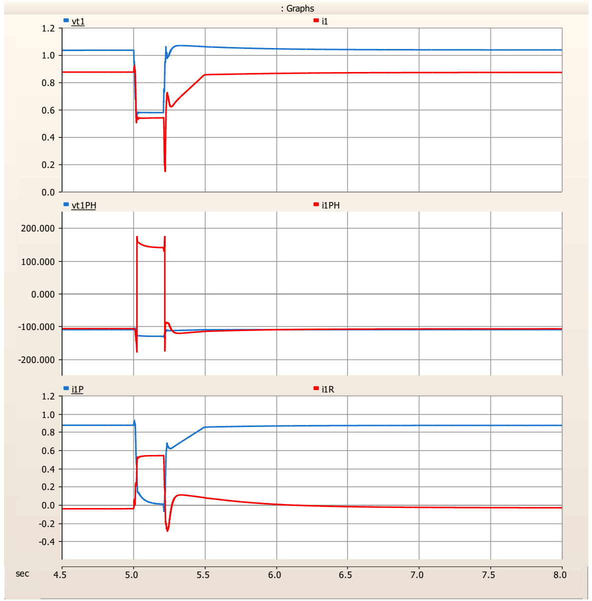
$$i1R > 0$$

negative sequence current leads negative sequence voltage

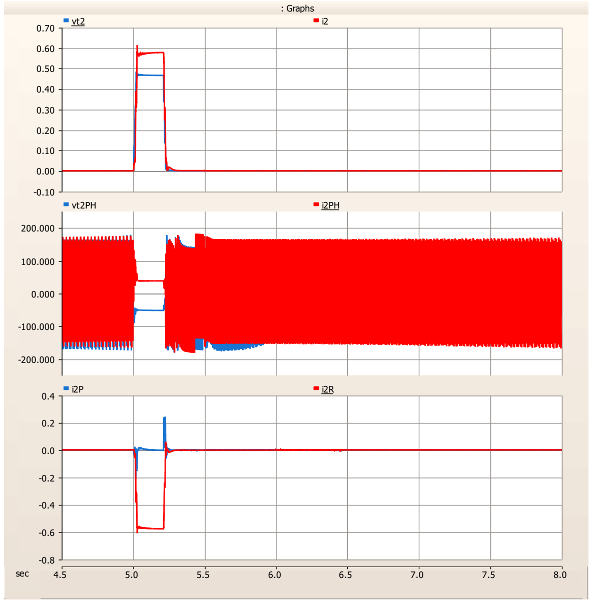
$$i2R < 0$$

Source: EPRI, 2022

Inverter response to B-C fault at the 34.5 kV bus
Negative sequence current injection enabled



$k_{qv1} = 2.0$

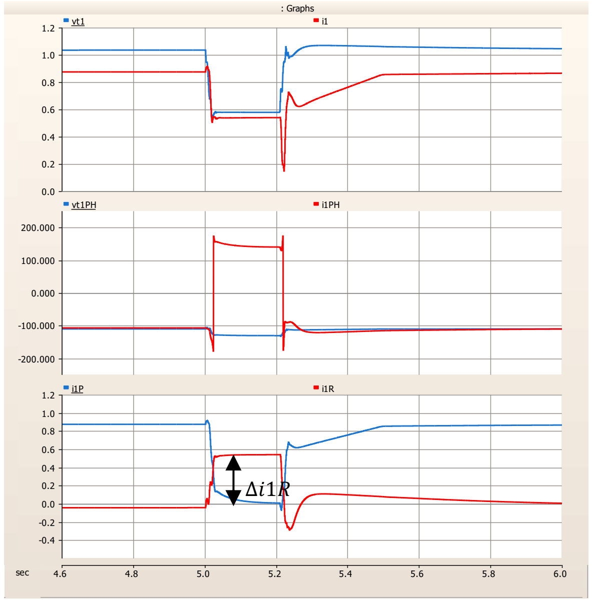


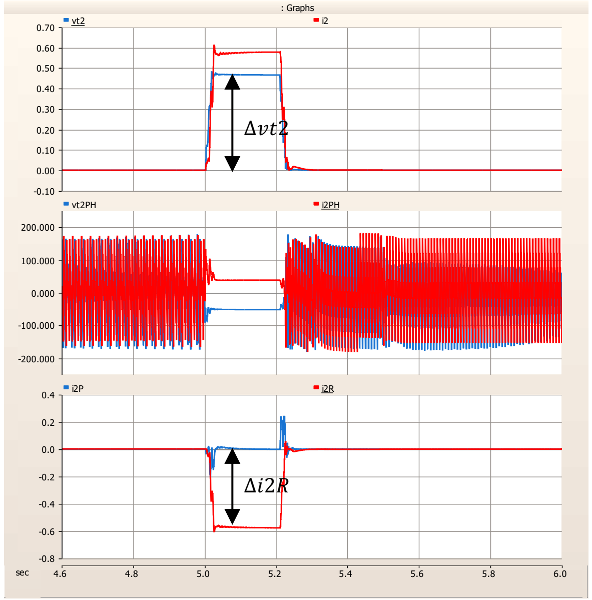
$k_{qv2} = 2.0$

Source: EPRI, 2022

Inverter response to B-C fault at the 34.5 kV bus

Negative sequence current injection enabled (fault period)



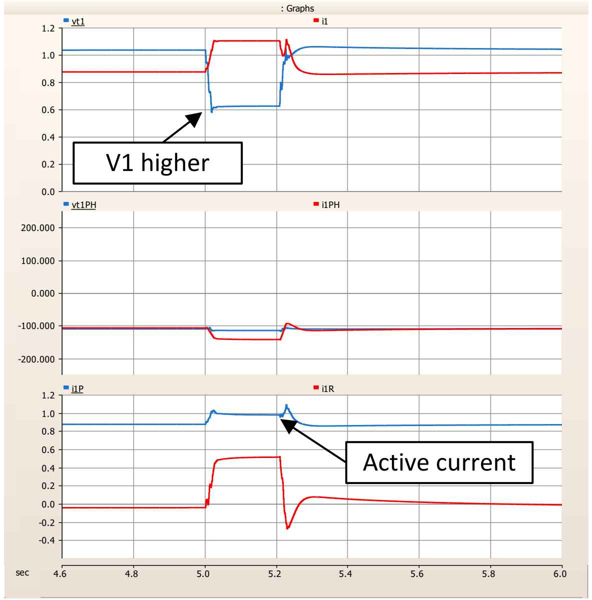


$k_{qv1} = 2.0$

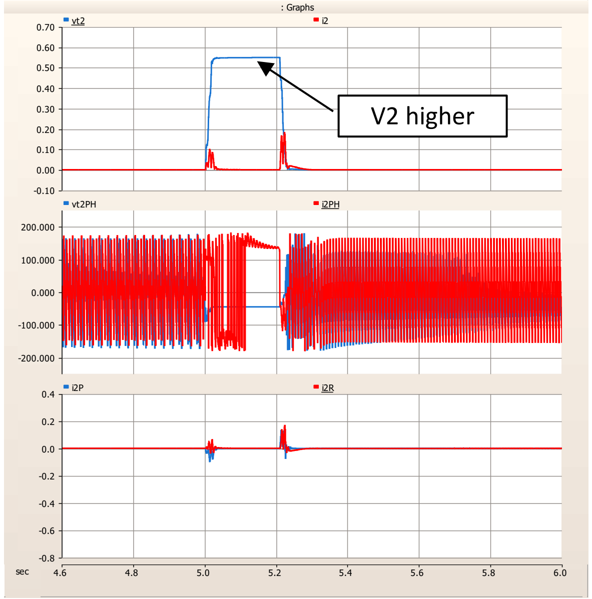
$k_{qv2} = 2.0$

Source: EPRI, 2022

Inverter response to B-C fault at the 34.5 kV bus
Negative sequence current injection disabled (fault period)



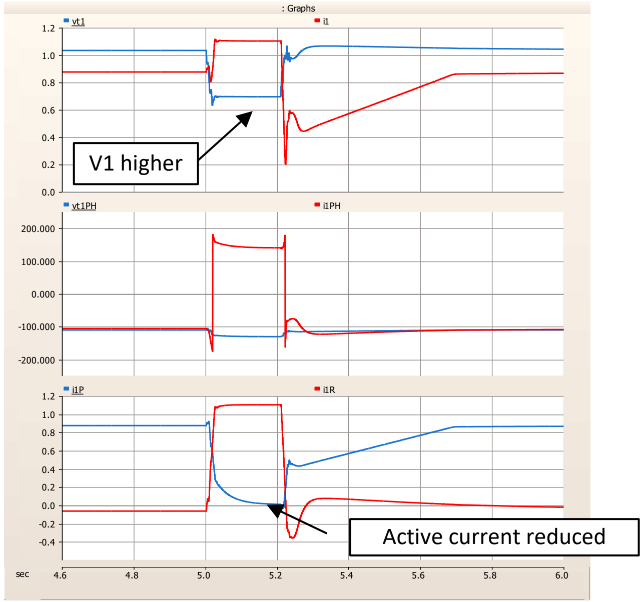
$k_{qv1} = 2.0$



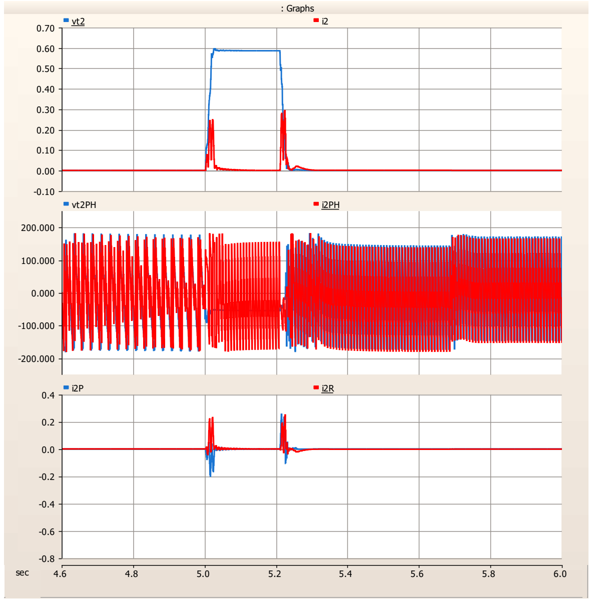
$k_{qv2} = 0.0$

Source: EPRI, 2022

Inverter response to B-C fault at the 34.5 kV bus
Negative sequence current injection disabled (fault period)



$k_{qv1} = 6.0$



$k_{qv2} = 0.0$

Source: EPRI, 2022

OTHER REQUIREMENTS

Other Capability/Performance Requirements

- **Consecutive voltage dip ride-through**

  Capability to ride-through specified combination of successive voltage dips

- **Phase angle jump ride-through**

  shall ride through positive-sequence phase angle changes in sub-cycle-to-cycle time frame ≤ 25 electrical degrees

- **Rate of change of frequency ride-through**

  Capability to ride through an absolute ROCOF magnitude that is less than or equal to 5.0 Hz/s

- **Restore active power output after voltage disturbance**

  Capability to restore active power output to 100% of pre-disturbance level at an average rate equal to 100% of ICR divided by specified active power recovery time. The default active power recovery time shall be 1.0 s.

Power Quality Requirements

- **Voltage fluctuations** induced by IBR Plant
  - Limits for frequent/infrequent rapid voltage changes & Flicker are specified
- **Harmonic distortion**
  - Limits for current harmonic limits are specified
  - Limits for voltage harmonic limits are <u>not</u> specified. TS owner <u>should</u> specify voltage harmonic limits
- **Overvoltage contribution** by IBR Plant
  - Limits for instantaneous as well as over fundamental frequency period overvoltage are specified

Protection Requirements

- Standard does not require specific type of protection to be applied within IBR Plant.
- If protection is applied (including on auxiliary load), shall allow IBR plant to meets its ride-through requirements
- Some requirements for frequency, ROCOF, overvoltage, overcurrent protection.
- **Unintentional Islanding** protection

  if not permitted by TS owner, protection shall be implemented in accordance with requirements of TS owner
- **Interconnection System** protection

  shall be in accordance with requirements of TS owner

Modeling Data

- Some specified requirements **cannot** be verified based on tests (type, commissioning etc.)
- Verification of such requirements is **done using models and simulations**
- IBR owner is **required** to provide **verified models** to TS owner/operator

  such as, power flow, stability dynamic model, short-circuit, EMT, harmonics etc
- Development of verified models is outside the scope of this standard; however, some guidance is provided.
- **Annex G** provides recommended practice for modeling data

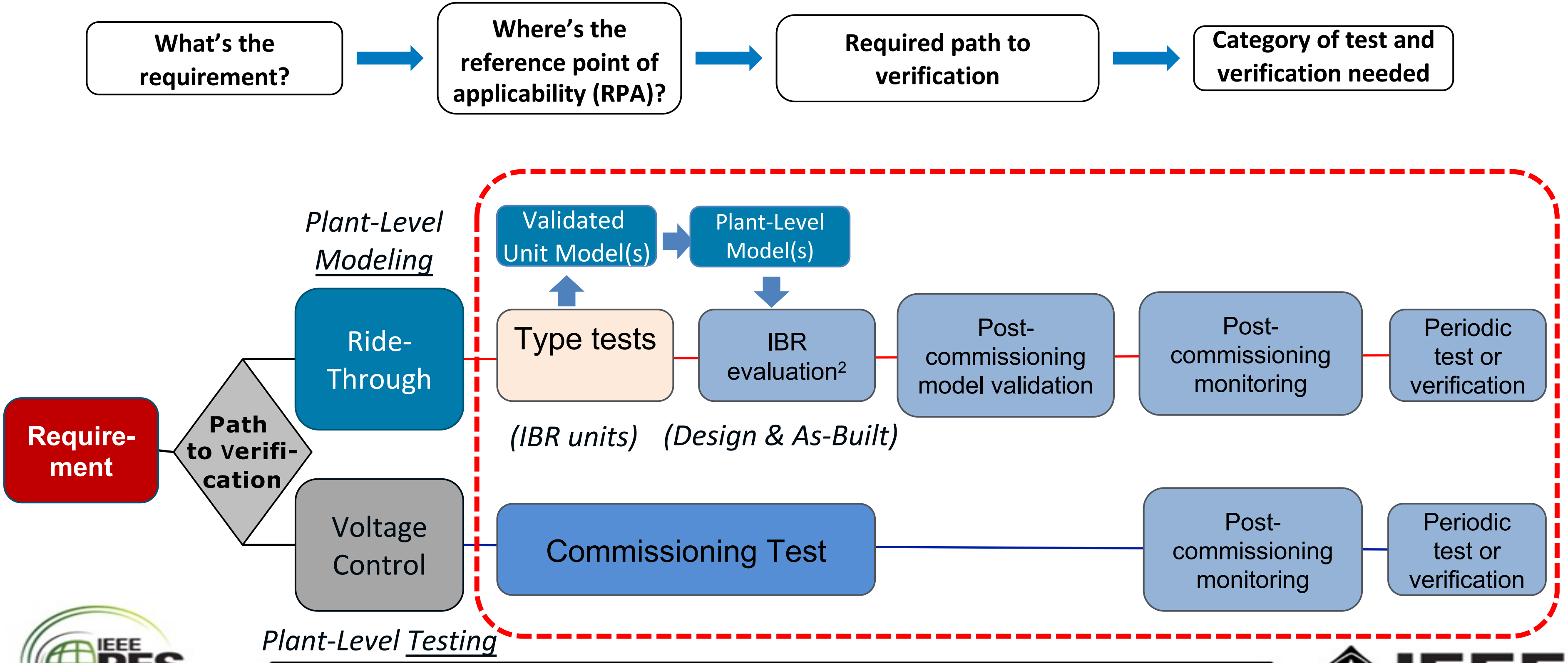
  i.e., details in each type of model

Measurements for Performance Monitoring/Model Validation

IBR plant is required to take measurements at specified points throughout the resource, from individual IBR units to the POM, using various technologies

Data Type	Data Points	Recording Rate	Retention	Duration
Plant SCADA Data	Voltage, frequency, P, Q, etc.	One record per second	One year	One year
Plant Equipment Status Log	Breakers, shunt devices, LTCs, collector system, IBR units, etc.	Static, as changed	One year	NA
Sequence of Event Recordings	Date/Time stamp, type of event, sequence number etc.	Static, as changed	One year	NA
Digital Fault Recordings	Each L-G voltage, phase & neutral currents, etc.	>128 samples/cycle, triggered	90 days	5 second data
Dynamic Disturbance Recordings	Voltage, current, frequency, calculated P and Q	Input: ≥ 960 samples/second Output: ≥ 60 times/second; continuous	One year	NA
IBR Unit Data	Fault & alarm codes, PLL loss of synchronism, dc/ac voltage and current etc.	Many kHz, triggered	90 days	5 second data

Test and Verification Framework



Thoughts on Adoption of IEEE 2800

- **Gap Analysis** – comparing existing IC requirements with IEEE 2800 requirements
- Adoption of IEEE 2800 is not contingent upon publication/adoption of IEEE P2800.2 (recommended practice for test & verification procedures)
- Needs consideration of **enforcement date, grandfathering/flexibility** for IBR Plants being built at the time of adoption
- Possible Adoption methods
  - **Full adoption** by simple reference
  - **Full or partial adoption**, clause-by-clause reference, additional requirements

IEEE P2800.2 Motivation

- IEEE 2800 contains performance requirements for IBRs, and a <u>table of methods to verify each requirement</u>
  - Details of verification methods not included

- **P2800.2** will develop details through “individual standard” process (like 2800, 1547, 1547.1, etc)

Requirement	RPA at which requirement applies	*IBR unit*-level tests (at the POC)	*IBR plant*-level verifications (at the RPA)						
		Type tests[157]	Design evaluation (including modeling)	As-built installation evaluation	Commissioning tests	Post-commissioning model validation	Post-commissioning monitoring	Periodic tests	Periodic Verification
		Responsible Entity							
		IBR Manufacturer	Developer /TS owner/TS operator	Developer /TS owner/TS operator	Developer /TS owner/TS operator	Developer / IBR Operator /TS owner/TS operator	IBR Operator /TS owner/TS operator	IBR operator /TS owner/TS operator	IBR operator /TS owner/TS operator
6.1 Primary Frequency Response (PFR)	POC & POM	NR[158]	R	R	R	R	D	D	D
6.2 Fast Frequency Response (FFR)	POC & POM	R[159]	R	R	R	R	D	D	D
Clause 7 Response to TS abnormal conditions									
7.2.2 Voltage disturbance ride-through requirements	POC[160] & POM[161]	R	R	R	NR	R	R	D	D
7.2.3 Transient overvoltage ride-through requirements	POM	R	R	R	NR	R	R	D	D
7.3.2 Frequency disturbance ride-through requirements	POM	R	R	R	NR	R	R	D	D
7.4 Return to service after IBR plant trip	POM	refer to line entries for 4.10 (Enter service)							

Anticipated Timeline, and What Comes Next?

	Jan 2019-Dec 2020	Q1-Q2/2021	Q2-Q4/2021	Q4/2021	Q1-Q2/2022	2022	2023	2024
2800	WG Drafting in Parallel SubGroups	Initial Sponsor Ballot	Recirculation	Submit to RevCom	**Publication**			
P2800.1 *entity project*							P2800.1 entity project is **inactive**	
P2800.2 *individual project**					Kick-Off Jan 18, 2022	WG Drafting in Parallel SubGroups	Balloting	Publication
Related activities	IEEE 1547.1 is published		NERC IRPWG Guidelines	…	IEEE P2882	**Potential 2800 Adoption**	➔	**Potential P2800.2 Adoption**

*Project authorization request (PAR) approved by NesCom on May 21, 2021 (https://development.standards.ieee.org/myproject-web/app#viewpar/12623/9133); contact andy.hoke@nrel.gov and sign up for P2800.2 Working Group and Task/Project on IEEE SA myProject at https://development.standards.ieee.org/myproject-web/app#interests

Now that IEEE 2800 has been published, the drafting of conformance procedures has commenced under IEEE P2800.2

Summary & Conclusion

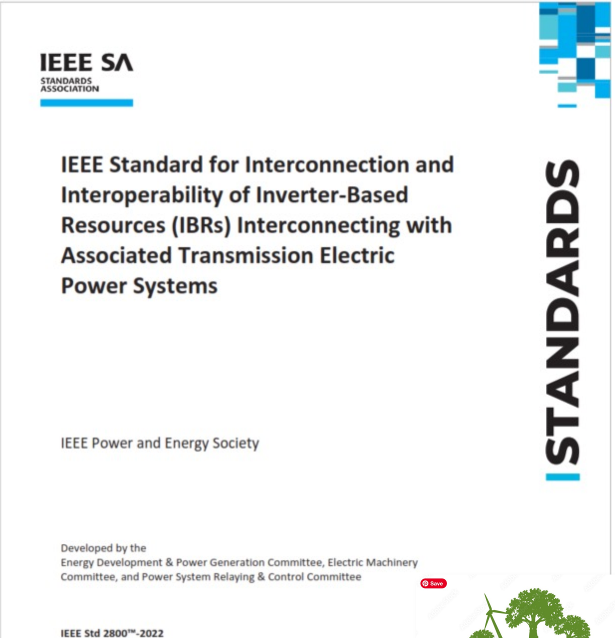
- ❑ IEEE Std 2800™ **harmonizes** minimum Interconnection Requirements for Large Solar, Wind and Storage Plants
  - ❑ Expected to mitigate most reliability issues identified by NERC
- ❑ As a voluntary IEEE standard, it **requires adoption** by the appropriate authorities to become mandatory
  - ❑ Adoption is not contingent on IEEE P2800.2
- ❑ Drafting of **conformance procedures** has commenced under IEEE P2800.2
  - ❑ ***Get involved:***

P2800.2

Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems

Active PAR

IEEE SA: https://standards.ieee.org/ieee/2800.2/10616/
P2800.2 WG: https://sagroups.ieee.org/2800-2/


IEEE SA
STANDARDS ASSOCIATION

IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems

IEEE Power and Energy Society

Developed by the
Energy Development & Power Generation Committee, Electric Machinery Committee, and Power System Relaying & Control Committee

IEEE Std 2800™-2022

STANDARDS

IEEE

Available from IEEE at https://standards.ieee.org/project/2800.html
and via IEEExplore: https://ieeexplore.ieee.org/document/9762253/

Contacts

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https://sagroups.ieee.org/2800-2/

IEEE 2800-2022

Available from IEEE at https://standards.ieee.org/project/2800.html
and via IEEExplore: https://ieeexplore.ieee.org/document/9762253/

Outline – Joint IEEE-ESIG-PSERC-CURENT Webinar – May 2, 2022

- Welcome by IEEE SA – *5 min.*
  - Rudi Schubert, IEEE SA
  - Jason MacDowell, ESIG
  - Raja Ayyanar, PSERC
  - Yilu Liu, CURENT
- Presentation by Jens C. Boemer (WG Chair) – *50 min.*
  - IEEE P2800: purpose, scope, schedule
  - High-level review of selected draft requirements
  - Potential adoption of IEEE 2800 in North America
- Comments by utilities – *5 min.*
  - Stephen Solis, ERCOT
- Q&A - *15 min.*

Adoption by ERCOT Inverter-Based Resources Task Force (IBRTF)
Objective, Approach, and Timeline

Objective

Inform strategic ERCOT decision on IEEE 2800 adoption method:

- General reference (‘wholesale adoption’)
- Detailed reference (‘piecemeal adoption – per reference’)
- Full specification (‘piecemeal adoption – own language’)

Timeline by Priority

- Wholesale or High: June – Dec 2022
- Medium: Oct 2022 – Dec 2023
- Low: 2024

Approach

1) Working with EPRI for gap analysis
   a. High-level gap analysis: identify where ERCOT has no requirements but IEEE 2800 does
   b. Detailed gap analysis: identify where ERCOT and IEEE 2800 both specify requirements and
      Where IEEE 2800 are more specific or more stringent than ERCOT requirements (“<”)
      ii. Where ERCOT requirements and P2800 already align in stringency and level of specificity (“~“)
      Where ERCOT requirements exceed IEEE 2800 either in stringency or specificity (“>“)
2) Stakeholder discussion in ERCOT’s Inverter-Based Resources Task Force (IBRTF)

Adoption by ERCOT Inverter-Based Resources Task Force (IBRTF)

Comparison Basis and Remarks

ERCOT

1. ERCOT Nodal Protocols (NPs) – applicable Sections available at https://www.ercot.com/mktrules/nprotocols/current and published on or prior to February 11, 2022.

   –The [Nodal] Protocols outline the procedures and processes used by ERCOT and Market Participants for the orderly functioning of the ERCOT system and nodal market.

2. Nodal Operating Guides (NOGs) – applicable Sections available at https://www.ercot.com/mktrules/guides/noperating/current and published on or prior to March 1, 2022

   –The Nodal Operating Guides, which supplement the Protocols, describe the working relationship between ERCOT and the entities within the ERCOT Region that interact with ERCOT on a minute-to-minute basis to ensure the reliability and security of the ERCOT System.

3. Planning Guide (PG) – applicable Sections available at https://www.ercot.com/mktrules/guides/planning/current and published on or prior to `January 1, 2022

   –The Planning Guide, which supplements the ERCOT protocols, provides ERCOT stakeholders and market participants with information and documentation concerning the ERCOT transmission planning process.

4. Model Quality Guide (MQG) – applicable Sections available at https://www.ercot.com/services/rq/integration and published on or prior to April 20, 2021

   –Assists REs/IEs submit stability models per Planning Guide Section 6.2, including the new Model Quality Testing requirements. Also includes the UDM Model Guideline and PSCAD Model Guideline.

IEEE 2800-2022

IEEE 2800-2022 (April 2022)

Remarks on ERCOT documents:

- Both NPs and NOGs are mandatory.
- NPs are broad in scope and tend to high level.
- NOGs tend to be narrower in scope and provide guidance on more practical/ operational aspects.
- The language in NPs and NOGs should not be in conflict; if it is in conflict, it should be pointed out as a finding.
- Some requirements only apply to resources providing ancillary services (AS); this would be explicitly stated, or it is obvious from the Section of the NPs.
  - For example, where an entire section is on Responsive Reserve (RRS) qualification or performance.

Thirteen (13) high-level gaps in ERCOT relate to 2800 mandatory requirements

Adoption by ERCOT Inverter-Based Resources Task Force (IBRTF)

Preliminary High-Level Gap Assessment of ERCOT Nodal Protocols

Legend: X Prohibited, √ Allowed by Mutual Agreement, ‡ Capability Required, NR Not Required
(‡) Procedural Step Required as specified, Δ Test and Verification Defined, !!! Important Gap

Acknowledgements for contributions and peer-review: Julia Matevosyan (ESIG)

Function Set	Advanced Functions Capability	ERCOT Nodal Protocols	IEEE 2800-2022
General	Definitions	?	?
	Reference Point of Applicability	POI	POM
	Adjustability in Ranges of Available Settings	NR (!!!)	‡
	Prioritization of Functions	‡	‡
Monitoring, Control, and Scheduling	Ramp Rate Control		
	Communication Interface	‡	‡
	Disable Permit Service (Remote Shut-Off, Remote Disconnect/Reconnect)	‡	‡
	Limit Active Power	‡	‡
	Monitor Key Data	‡	‡
	Remote Configurability		√
	Set Active Power	‡	√
	Scheduling Power Values	‡	√
Reactive Power & (Dynamic) Voltage Support	Constant Power Factor	‡	‡
	Voltage-Reactive Power (Volt-Var)	‡	‡
	Autonomously Adjustable Voltage Reference	?	
	Capability at zero active power ("VArs at night")	NR (!!!)	‡
	Active Power-Reactive Power (Watt-Var)		
	Constant Reactive Power	NR (!!!)	‡
	Voltage-Active Power (Volt-Watt)	NR	NR
	Dynamic Voltage Support / Current Injection during VRT — Balanced	‡	‡
	Dynamic Voltage Support / Current Injection during VRT — Unbalanced	NR (!!!)	‡

Function Set	Advanced Functions Capability	ERCOT Nodal Protoc.	IEEE 2800-2022
Bulk System Reliability & Frequency Support	Frequency Ride-Through (FRT)	‡	‡
	Rate-of-Change-of-Frequency (ROCOF) Ride-Through	NR (!!!)	‡
	Voltage Ride-Through (VRT)	‡	‡
	Transient Overvoltage Ride-Through	√ (!!!)	‡
	Consecutive Voltage Dip Ride-Through	NR (!!!)	‡
	Restore Output After Voltage Ride-Through	NR (!!!)	‡
	Voltage Phase Angle Jump Ride-Through	NR (!!!)	‡
	Frequency Droop / Frequency-Watt	‡	‡
	Fast Frequency Response / Inertial Response — Underfrequency FFR	√ (!!!)	‡
	Fast Frequency Response / Inertial Response — Overfrequency FFR	NR	√
	Return to Service (Enter Service)	?	‡
	Black Start	NR	√
Protection Functions and Coordination	Abnormal Frequency Trip	NR	√
	Rate of Change of Frequency (ROCOF) Protection	?	√
	Abnormal Voltage Trip	NR	√
	AC Overcurrent Protection	?	√
	Unintentional Islanding Detection and Trip	NR	√
	Interconnection System Protection	?	√
Power Quality	Limitation of DC Current Injection		
	Limitation of Voltage Fluctuations	NR (!!!)	‡
	Limitation of Current Distortion	NR (!!!)	‡
	Limitation of Voltage Distortion	NR	√
	Limitation of (Transient) Overvoltage	NR (!!!)	‡

Source: EPRI, 2022

Thirteen (13) high-level gaps in ERCOT relate to 2800 mandatory requirements

Future Joint Webinars

Today:

Joint IEEE–ESIG–PSERC–CURENT Webinar for Subject Matter Experts & Academia

Tomorrow:

Joint NERC–NATF–NAGF–EPRI Webinar for Transmission Planners

May 3, 2022 @ 12:00pm-1:30pm ET | 9:00am-10:30pm PT | 6:00pm-7:30pm CET); no registration required, join the webinar here

TBD:

Joint SEIA–ACP (formerly AWEA) Webinar for OEMs & Developers

QUICK HOUSEKEEPING ITEMS

1. **Upon entering the webinar, all attendee lines are automatically MUTED. Today's presentation is a one-way broadcast.**

2. **If you are experiencing technical issues (audio or visual), use the CHAT feature and message the host, for help troubleshooting.**

3. **To ask QUESTIONS throughout the webinar, use the Q&A feature.**