

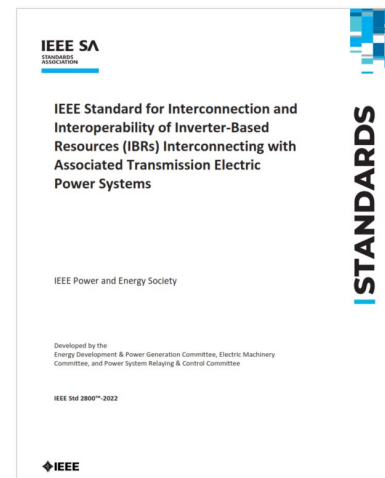
Introduction to IEEE 2800 – Interconnection Standard for Transmission-connected Inverter-based Resources

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National Renewable Energy Laboratory



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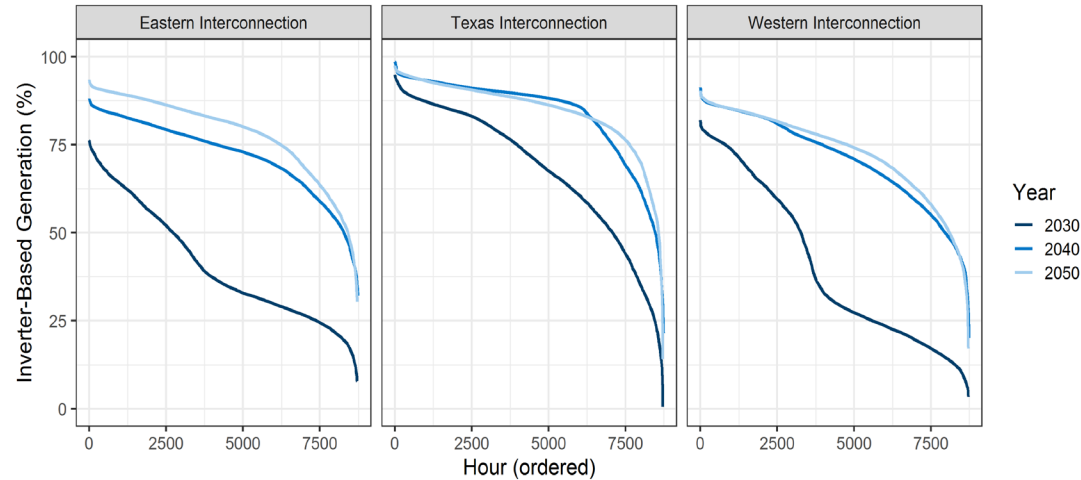
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Pace of IBR Interconnections

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.



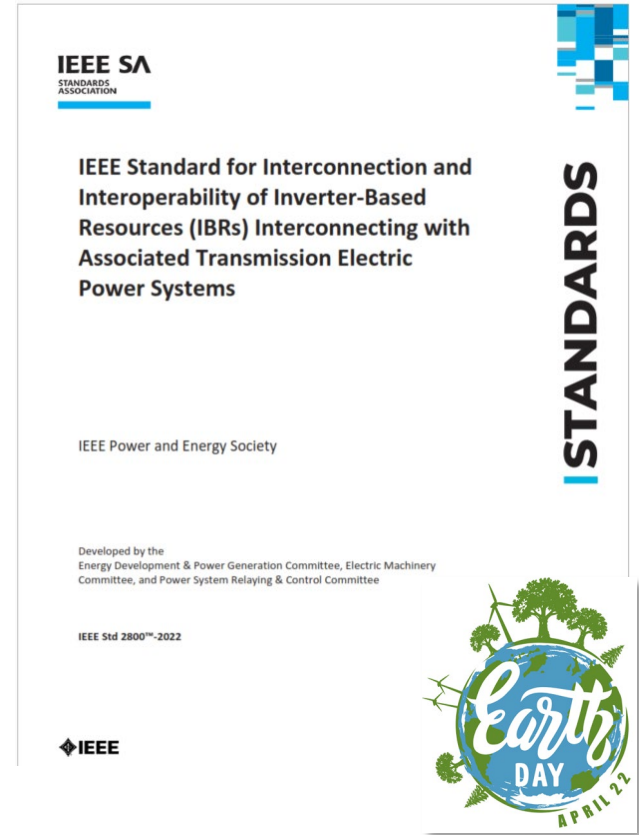
Data from 2021 DOE/NREL Solar Futures Study: <https://www.nrel.gov/analysis/solar-futures.html>

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

Summary of IEEE 2800

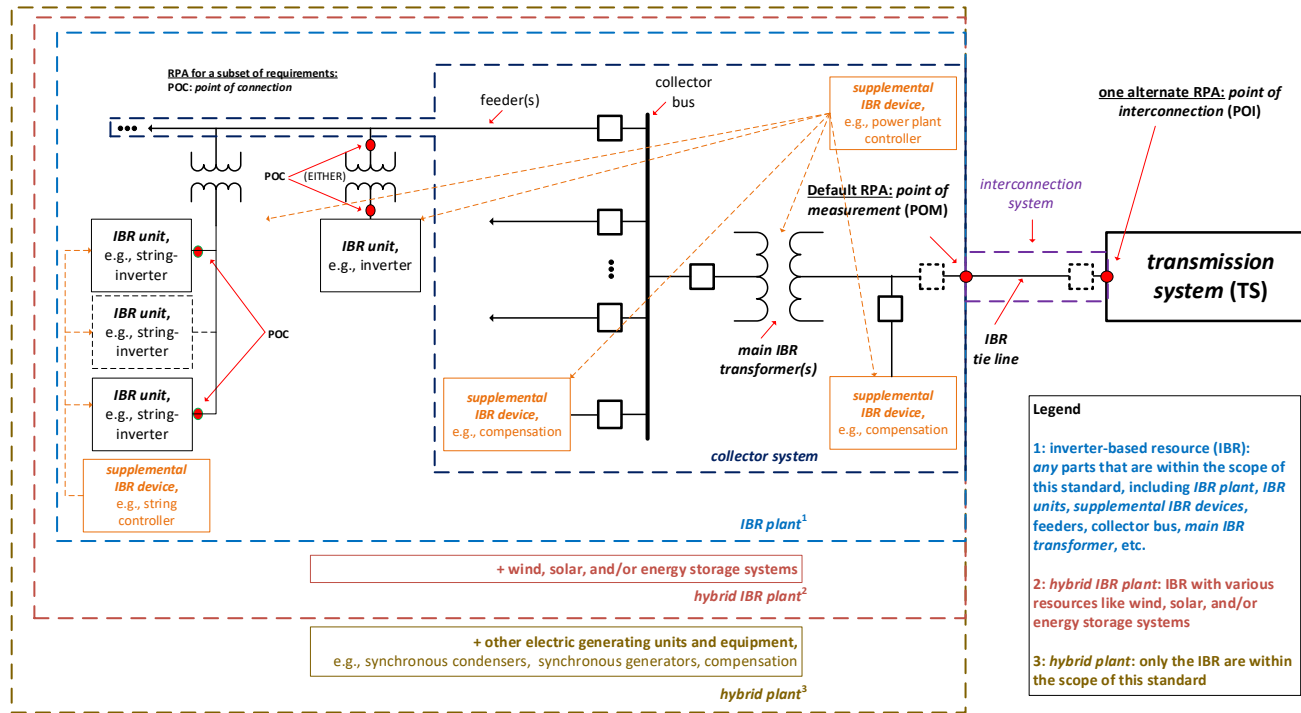
- ❑ **Harmonizes** interconnection requirements for large solar, wind and storage plants (including IBR connected via VSC-HVDC)
- ❑ It is a **consensus-based** standard developed by over ~175 Working Group participants from utilities, system operators, transmission planners, & OEMs over 2 years
- ❑ Passed the IEEE SA ballot among 466 balloters (**>94% approval**, >90% response rate)
- ❑ Published on April 22, 2022 (Earth Day)

More Info at <https://sagroups.ieee.org/2800/>



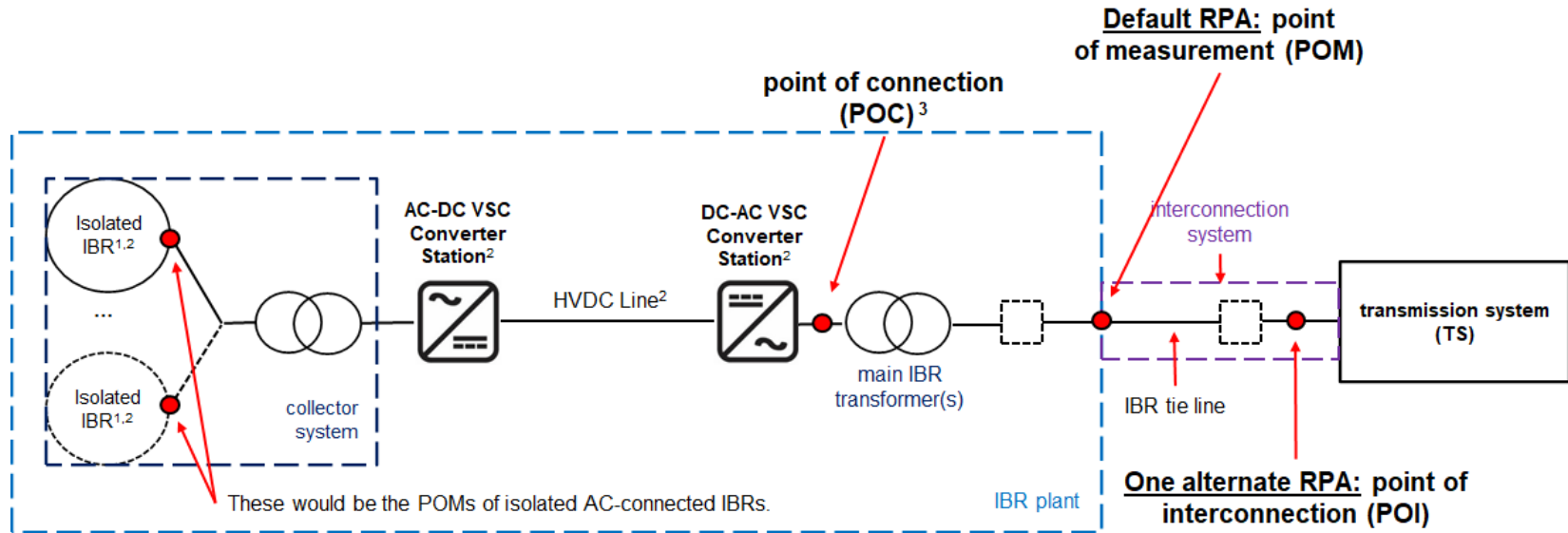
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Reference Point of Applicability – AC Interconnection



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Reference Point of Applicability – DC Interconnection



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

TS owner
can require
additional
capability

Raising
the
minimum
bar

Capability
Required in 2800

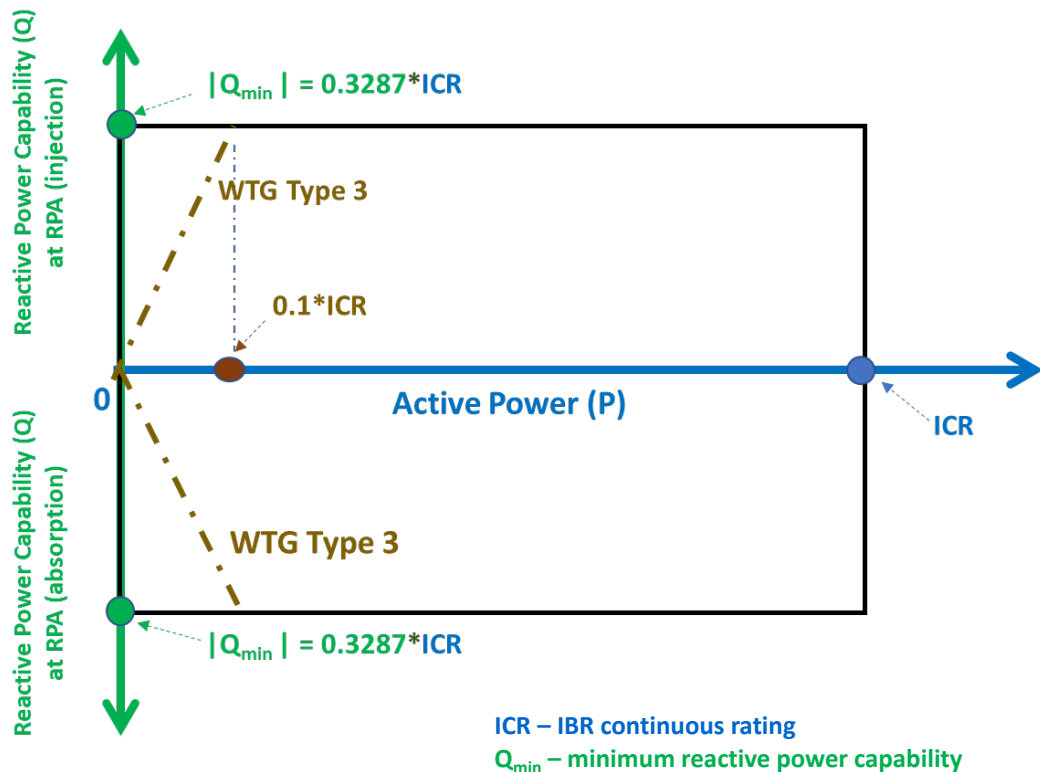
General Requirements "shall have"	Frequency Response	Reactive Power – Voltage Control	Power Quality TS owner "should" specify	Ride-Through Capability and Performance, Protection	Modeling & Validation, Measurement Data, and Performance Monitoring	Tests and verification requirements
Measurement accuracy	Fast Frequency Response for under-frequency conditions	Q for voltage control at zero active power AC-connected offshore wind: "should have"	Harmonic Voltage Limitations	Unbalanced Current Injection	Process and criteria for model validation	Post-commissioning Monitoring
Controls Prioritization	"may" for over-frequency conditions	Automatic Voltage Regulation Functions	Prevent Transient Overvoltage	Balanced Current Injection	High Fidelity Performance Monitoring	Plant-level Evaluation & Modeling
Control responses	Primary Frequency Response	Reactive Power	Harmonic Current Limitations	Voltage Ride-through including TrOV + Consecutive	Validated Models	Commissioning Tests
Applicability to Diverse IBR Plants			Phase Unbalance	Frequency & Phase-jump Ride-through		Type tests
			Rapid Voltage Change	Coordination of Protection		
			Flicker Limitations			

Utilization of these capabilities is outside the purview of 2800

MINIMUM REACTIVE POWER CAPABILITY REQUIREMENTS

Min. Reactive Power Capability vs Active Power Injection

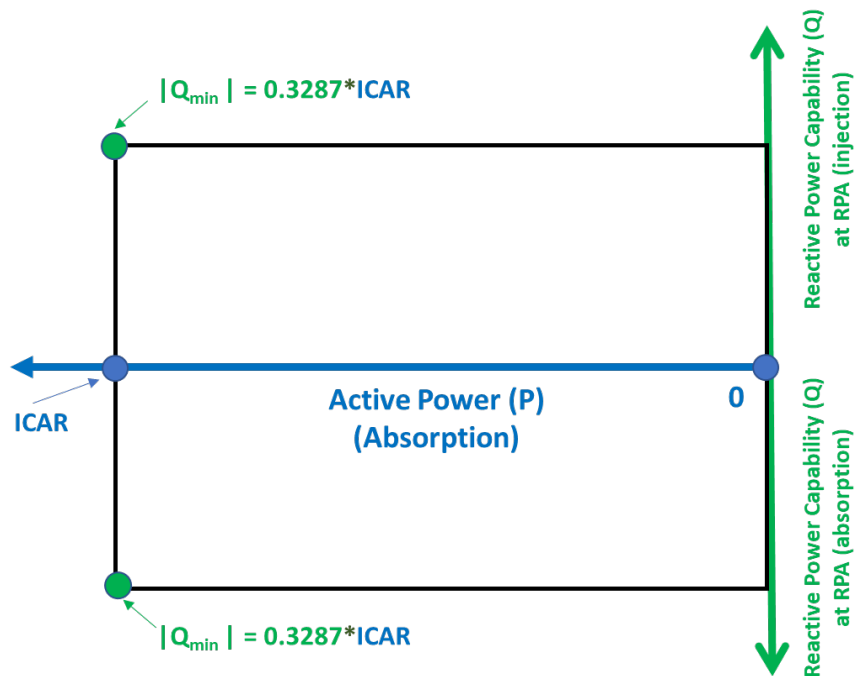
Default RPA: Point of Measurement



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

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Min. Reactive Power Capability vs Active Power Absorption



Default RPA: Point of Measurement

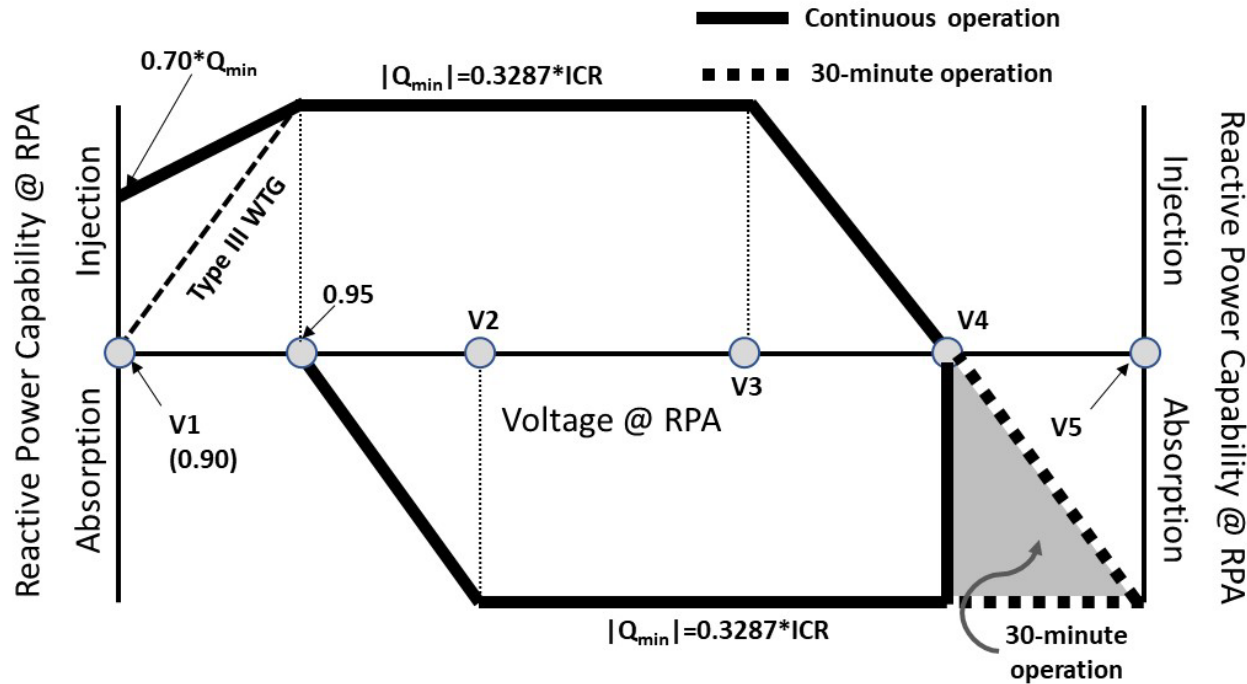
ICAR – IBR continuous absorption rating

Q_{min} – minimum reactive power capability

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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
<i>Reaction time</i>	< 200 ms	
<i>Max. step response time</i>	As required by the <i>TS operator</i>	Typical <i>step response time</i> 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.

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FREQUENCY DISTURBANCE RIDE-THROUGH CAPABILITY AND PERFORMANCE REQUIREMENTS

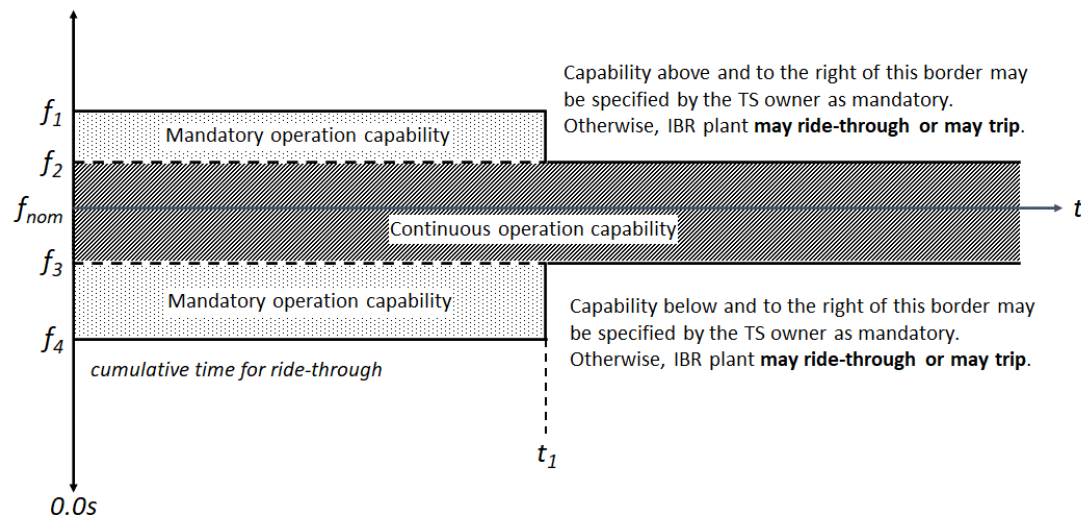
Frequency Disturbance Ride-Through Capability Requirements

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

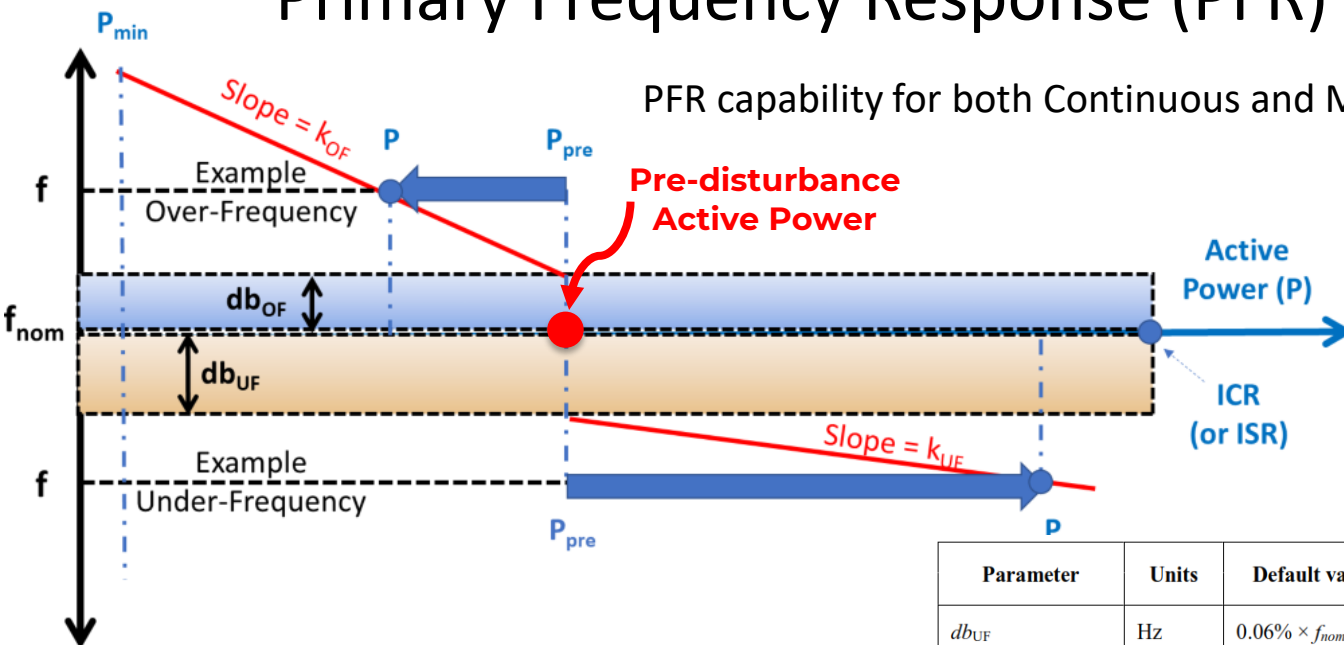
- Within **V/Hz capability** of IBR units, transformers & supplemental IBR devices.



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	$0.06\% \times f_{nom}$	$0.025\% \times f_{nom}$	$1.6\% \times f_{nom}$
db_{OF}	Hz	$0.06\% \times f_{nom}$	$0.025\% \times f_{nom}$	$1.6\% \times f_{nom}$
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	<i>Ranges of available settings</i>	
			Minimum	Maximum
<i>Reaction time</i>	Seconds	0.50	0.20 (0.5 for WTG)	1
<i>Rise time</i>	Seconds	4.0	2.0 (4.0 for WTG)	20
<i>Settling time</i>	Seconds	10.0	10	30
Damping ratio	Unitless	0.3	0.2	1.0
<i>Settling band</i>	% 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

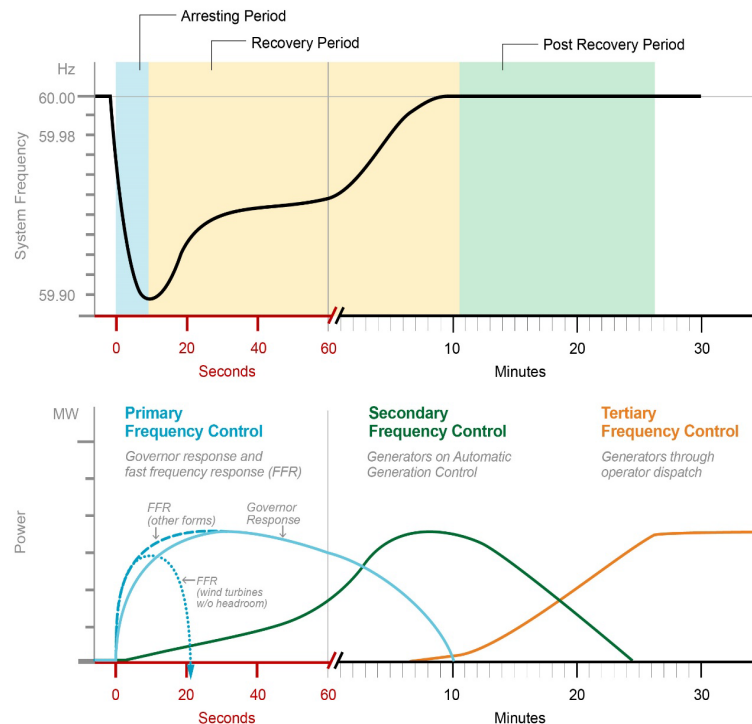
Inertial response is also known as FFR in North America

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



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FFR Performance Requirements

FFR1: FFR proportional to frequency deviation

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

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

- FFR capability shall be an autonomous function
- The FFR response time, 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
- FFR and PFR may actuate independently from each other or may complement each other

In many cases, FFR is just “a faster PFR”

FFR Performance Requirements – WTG-Based IBR Plant

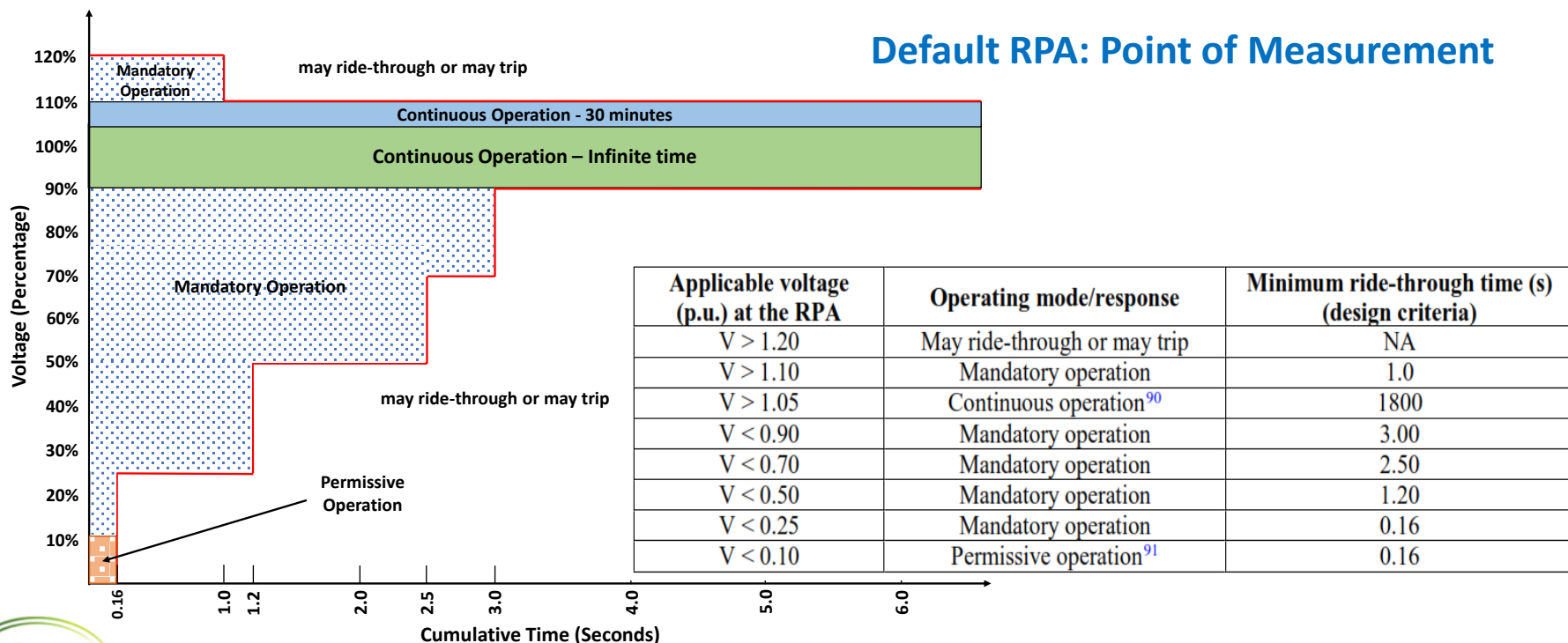
- **adjustable** frequency threshold **dead band** from -0.1 Hz to -1.0 Hz
- temporary increase of active power output, **provided wind resource is available**:
 - equal to at least 5% of rated power of each WTG in service when operating at or above 25% of rated power
 - for the duration from 5 s to 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**

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VOLTAGE DISTURBANCE RIDE-THROUGH CAPABILITY AND PERFORMANCE REQUIREMENTS

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

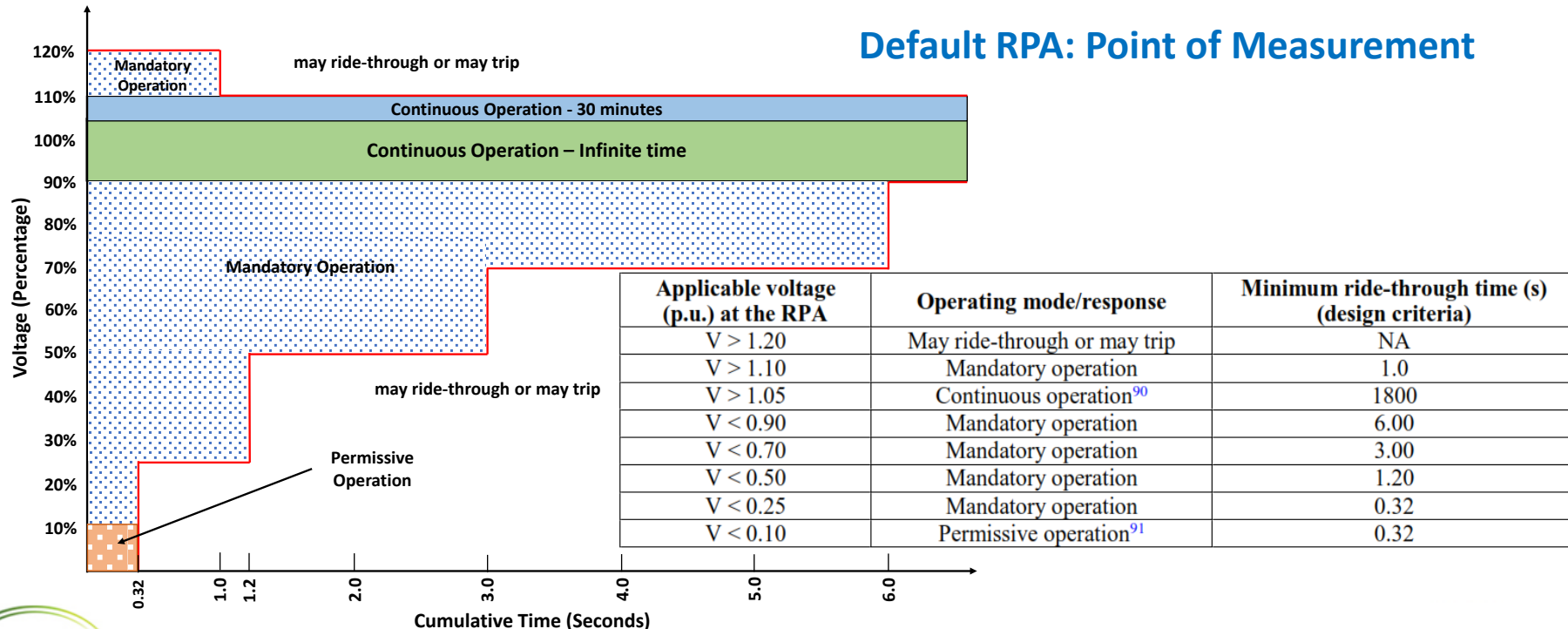
Default RPA: Point of Measurement



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Voltage Ride-Through Capability – Plants without Aux. Load Limitations, e.g., Solar Plant

Default RPA: Point of Measurement



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Exceptions from Voltage Ride-Through Capability Reqs

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 Requirements

When in ride-through mode (including fault conditions):

- Type & magnitude of current injection shall be **dependent** on voltage at inverter (IBR unit) terminals. 
- 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 that of the terminal voltage with following exceptions:
 - Close-in faults (PLL fails to track system frequency, type III WTG if control of rotor current is lost)
 - Transients, transformer inrushes, etc....

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Transient overvoltage ride-through requirements

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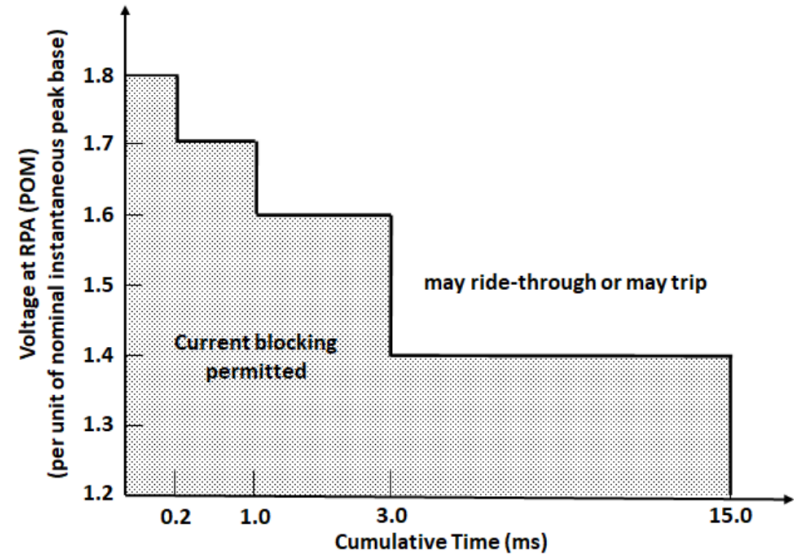
Voltage ^c (p.u.) at the RPA	Minimum ride-through time (ms) ^d (design criteria) ^b
$V > 1.80$	See footnote ^a
$V > 1.70$	0.2
$V > 1.60$	1.0
$V > 1.40$	3.0
$V > 1.20$	15.0

^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.

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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 not specified. TS owner should 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 any specific type of protection to be applied within IBR Plant.
- If protection is applied (including on auxiliary load), it shall allow IBR plant to meet 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, dynamic stability, 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

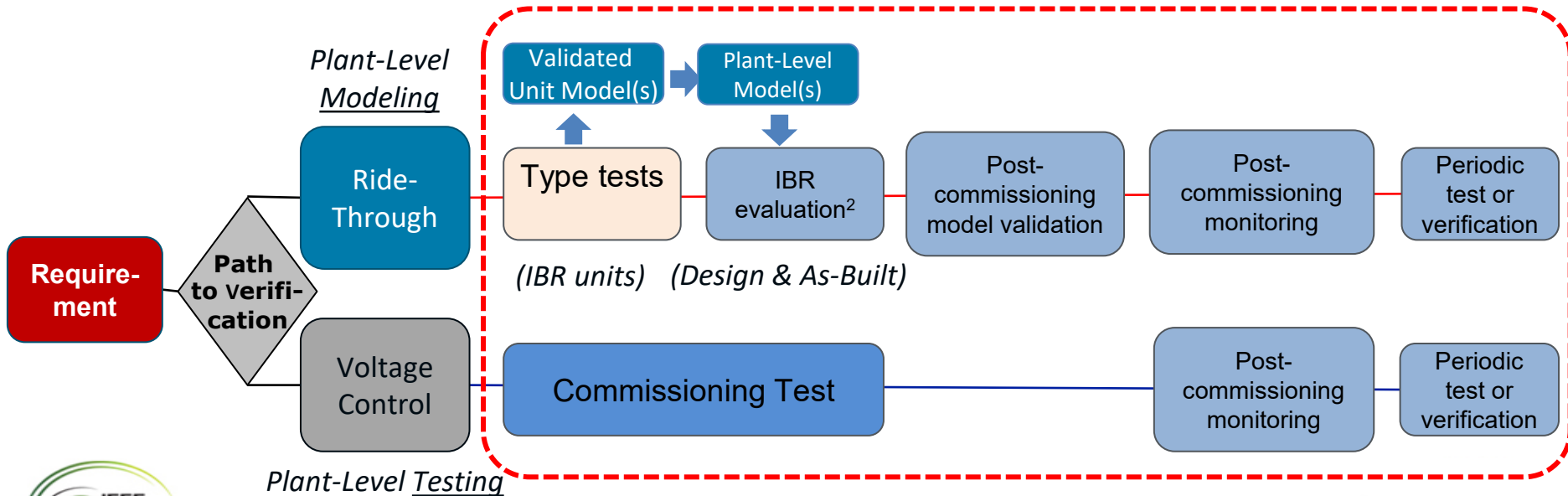
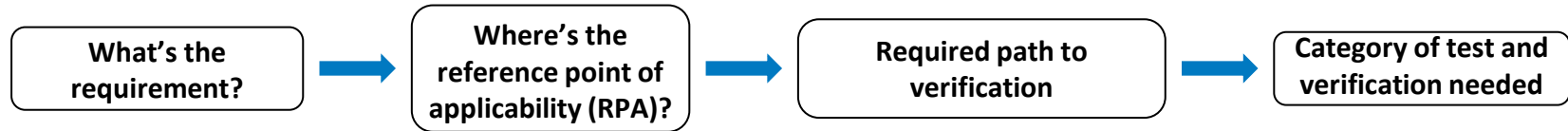
Measurements for Performance Monitoring/Model Validation

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

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Test and Verification Framework



IEEE P2800.2 Motivation

IEEE 2800 contains performance requirements for IBRs, and a table of methods to verify each requirement

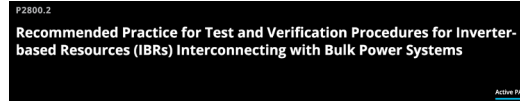
- Details of verification methods not included

IEEE P2800.2 is developing details of conformance verification methods

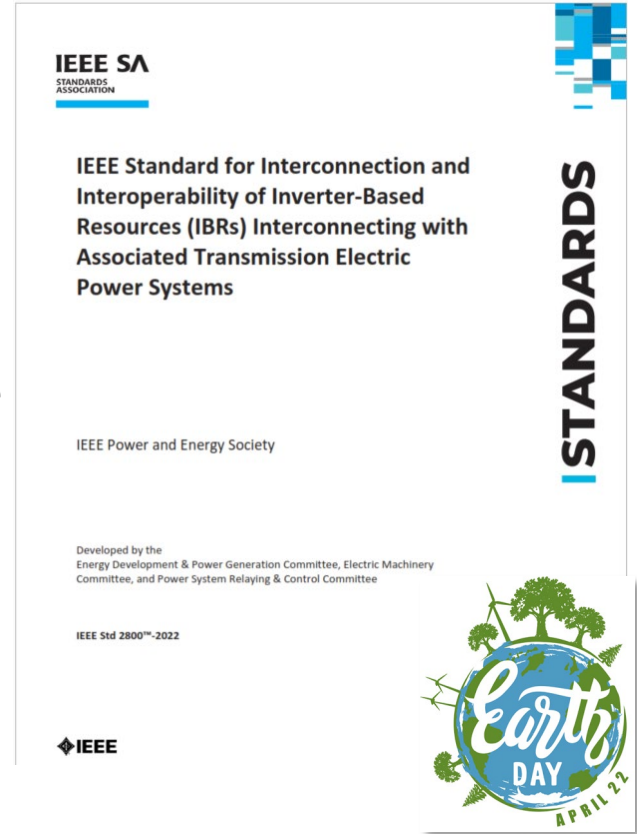
Requirement	RPA at which requirement applies	IBR unit-level tests (at the POC)	IBR plant-level verifications (at the RPA)						
		Type tests ¹⁵⁷	Design evaluation (including modeling)	As-built installation evaluation	Commissioning tests	Post-commissioning model validation	Post-commissioning monitoring	Periodic tests	Periodic Verification
		Responsible Entity							
		IBR Manufacturer	Developer /TS owner/TS operator	Developer /TS owner/TS operator	Developer /TS owner/TS operator	Developer /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)							

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:**



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



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