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U.S. DEPARTMENT OF ENERGY

Forum for the Implementation of Reliability Standards for Transmission (i2X FIRST) | 12/17/24

An initiative spearheaded by the Solar Energy Technologies Office and the Wind Energy Technologies Office

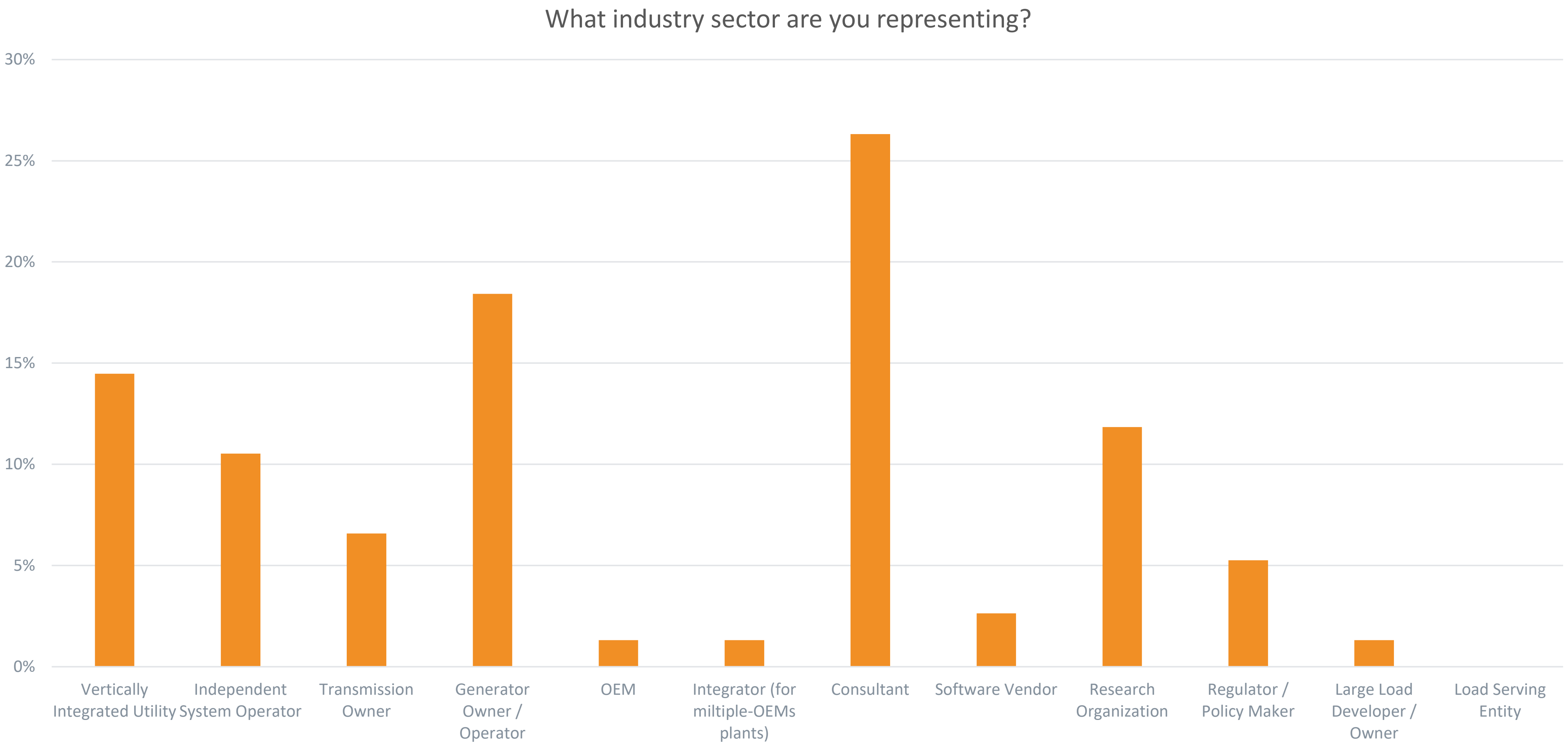
BERKELEY LAB
EPRI
ESIG

The first half of this meeting call is being recorded and may be posted on DOE's website or used internally. If you do not wish to have your voice recorded, please do not speak during the call. If you do not wish to have your image recorded, please turn off your camera or participate by phone. If you speak during the call or use a video connection, you are presumed consent to recording and use of your voice or image.

Polling Question

What industry sector are you representing?

[Go to **slido.com** and enter event code **FIRST8**, then go to **Polls** tab]

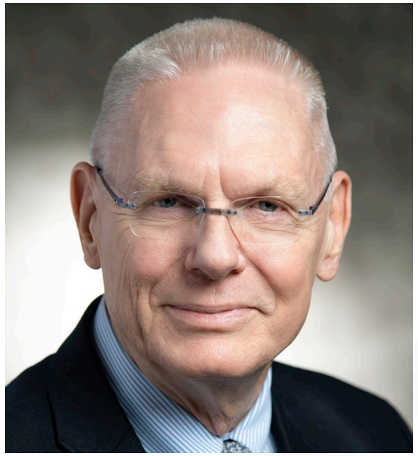

What industry sector are you representing?
30%
25%
20%
15%
10%
5%
0%
Vertically Integrated Utility
Independent System Operator
Transmission Owner
Generator Owner / Operator
OEM
Integrator (for miltiple-OEMs plants)
Consultant
Software Vendor
Research Organization
Regulator / Policy Maker
Large Load Developer / Owner
Load Serving Entity

Key Goals and Outcomes from i2X FIRST

- To facilitate understanding and adoption of new and recently updated standards relevant for existing and newly interconnecting wind, solar and battery storage plants
- The Forum will convene the industry stakeholders to enable practical and more harmonized implementation of these interconnection standards.
- The presentation portion of the meeting will be recorded and posted, and presentation slides will be shared.
- Additionally, the leadership team will produce **a summary of each meeting** capturing:
  - Recommended best practices
  - Challenges
  - Gaps that require future work

Leadership Team

Cynthia Bothwell, Boston Government Services, contractor to DOE's Wind Energy Technologies Office



Robert Reedy, Lindahl Reed, contractor to DOE's Solar Energy Technologies Office

Will Gorman, Lawrence Berkley National Laboratory

Jens Boemer, Electric Power Research Institute

Julia Matevosyan, Energy Systems Integration Group

Ryan Quint, Elevate Energy Consulting

Summary of the last meeting – Active Power—Frequency Response Requirements

- IEEE 2800-2022 Clause 6 *Active Power – Frequency Response Requirements* – Mahesh Morjaria, Terabase Energy
- Wind Generation Frequency Response Capabilities – Miguel Duarte Campos, Vestas
- ISO Experience with Frequency Response Performance – Nitika Mago, ERCOT
- Q&A and Structured Discussion – led by Julia Matevosyan, ESIG
  - IEEE 2800-2022, Clause 6 vs FERC Order 842
  - Fast Frequency Response Capability Requirement

Meeting summary, recording & presentations are posted here (click on Past Events at the bottom of the page)

Key Themes from the Last Meeting

- IBR active power-frequency response controls are not a new technology and have been relatively mature for many years.
- There are technological advancements and developments in this area that continue to improve the performance of IBR PFR controls, particularly for wind.
- IEEE 2800-2022 has standardized and codified the capability and performance requirements for IBRs clearly and effectively.
- IBR FFR is a relatively newer field and continues to evolve. Non-rotating technologies like solar and BESS can provide effective FFR in response to grid events; wind technology has limitations yet can also provide FFR in some cases with a different type of profile. IEEE 2800-2022 defines these differences well.
- IEEE 2800-2022 defines the capabilities of PFR and FFR; generator interconnection agreements, tariffs, and ancillary services markets define the utilization of the capability.
- FERC Order No. 842 required all generators to have PFR capability with defined characteristics and that the capability be enabled operational but did not specify a requirements on headroom (or legroom) for these resources.

Upcoming i2X FIRST Meetings

1. May 28th, 2024, 11 a.m.- 1 p.m. ET: Introduction of Evolving Standards Landscape
2. June 25th, 2024, 11 a.m.- 1 p.m. ET: IEEE 2800 Ride Through Requirements
3. July 30th, 2024, 11 a.m.- 1 p.m. ET: IEEE 2800 Ride Through Requirements, OEM Readiness
4. August 20th, 2024, 11 a.m.- 1 p.m. ET: IEEE 2800 Ride Through Requirements, OEM Readiness, cont.
5. September 24th, 2024, 11 a.m.- 1 p.m. ET: Measurements for Performance Monitoring and Model Validation
6. October 24th, 2024 hybrid, full day, during ESIG Fall Workshop, Providence, RI: Conformity Assessment
7. November 26th, 2024, 11 a.m.- 1 p.m. ET: IEEE 2800 Active Power—Frequency Response Requirements
8. December 17th, 2024, 11 a.m.- 1 p.m. ET: IEEE 2800 Reactive Power – Voltage Control Requirements
9. January 28th 2025, 11 a.m.- 1 p.m. ET: Power Quality and Protection Requirements
10. February 25th 2025
11. March 20th, 2025 hybrid event during ESIG Spring Workshop, Austin, Texas: Conformity Post Commissioning

Sign up for all future i2X FIRST Meetings here: https://www.zoomgov.com/meeting/register/vJltceuorTsiErIC-HInpPbWuTUtrYQAuoM#/registration

Follow DOE i2X FIRST website: https://www.energy.gov/eere/i2x/i2x-forum-implementation-reliability-standards-transmission-first for meeting materials & recordings and for future meeting details & agendas

Reactive Power – Voltage Control Requirements– Agenda

- i2X FIRST Intro (10 mins) – Julia Matevosyan, ESIG
- IEEE 2800-2022 Clause 5 *Reactive Power – Voltage Control Requirements* (20 mins) – Jens Boemer, EPRI
- MISO Phase 2 IEEE 2800-2022 Adoption Efforts (20 mins) – Patrick Dalton, MISO
- Bonneville Power Administration Voltage Control Strategies (20 mins) – Dmitry Kosterev, Eric Heredia, BPA
- Q&A and Structured Discussion (50 mins) – led by Julia Matevosyan, ESIG
    - IEEE 2800-2022, Clause 5 vs FERC Order 827
    - Reactive Power – Voltage Control Requirement Implementation

Virtual Meetings Code of Conduct

1. *Assume good faith and respect differences*
2. *Listen actively and respectfully*
3. *Use "Yes and" to build on others' ideas*
4. *Please self-edit and encourage others to speak up*
5. *Seek to learn from others*

Mutual Respect . Collaboration . Openness

Stakeholder Presentations

Virtual Meetings Code of Conduct

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4. *Please self-edit and encourage others to speak up*
5. *Seek to learn from others*

Mutual Respect . Collaboration . Openness

Q & A Session

Interactive Group Discussion Topics

Topic #1: IEEE 2800-2022, Clause 5 vs FERC Order 827

- Please go to slido to make comments and add questions of your own: **slido.com** and enter event code **FIRST8**
- For verbal commentary, please use the raise hand feature and we will call on you
- Additional related / associated questions:
  - What is your perspective on how IEEE 2800-2022 Clause 5 can be implemented compared with the directives of FERC Order 827?
  - Is capability required by FERC Order 827 currently being assessed during interconnection process, commissioning testing, enabled and assessed during post-commissioning operation?
  - Are there any important decision points that should be discussed between the TS owner/operator and IBR owner/developer to ensure conformity with reactive power/voltage control requirements under range of operating conditions?

Topic #2: Reactive Power – Voltage Control Requirement Implementation

- Please go to slido to make comments and add questions of your own: **slido.com** and enter event code **FIRST8**
- For verbal commentary, please use the raise hand feature and we will call on you
- Additional related / associated questions:
  - What reactive power control mode do you select and why?
  - What voltage droop do you use by default? If you use 0 droop by default, how do you avoid voltage control issues when multiple IBRs connect at the same POI?
  - If you use a droop value, how do you select it?
  - Do you run studies to select the droop? Is it case-by-case study? What types of studies?
  - When in the interconnection study process are these decisions made and how are they articulated to the interconnection customer?
  - What response time do you shoot for and why?

Slido Poll on Topics for Future Discussions

IEEE 2800-2022 Clause 5

Reactive Power-Voltage Control Requirements within the Continuous Operation Region

Jens Boemer, Manish Patel, Alberto Del Rosso
EPRI Transmission and Operations Planning Group

i2X Forum for the Implementation of Reliability Standards for Transmission (i2X FIRST)
December 17, 2024 (virtual)

Classification: public

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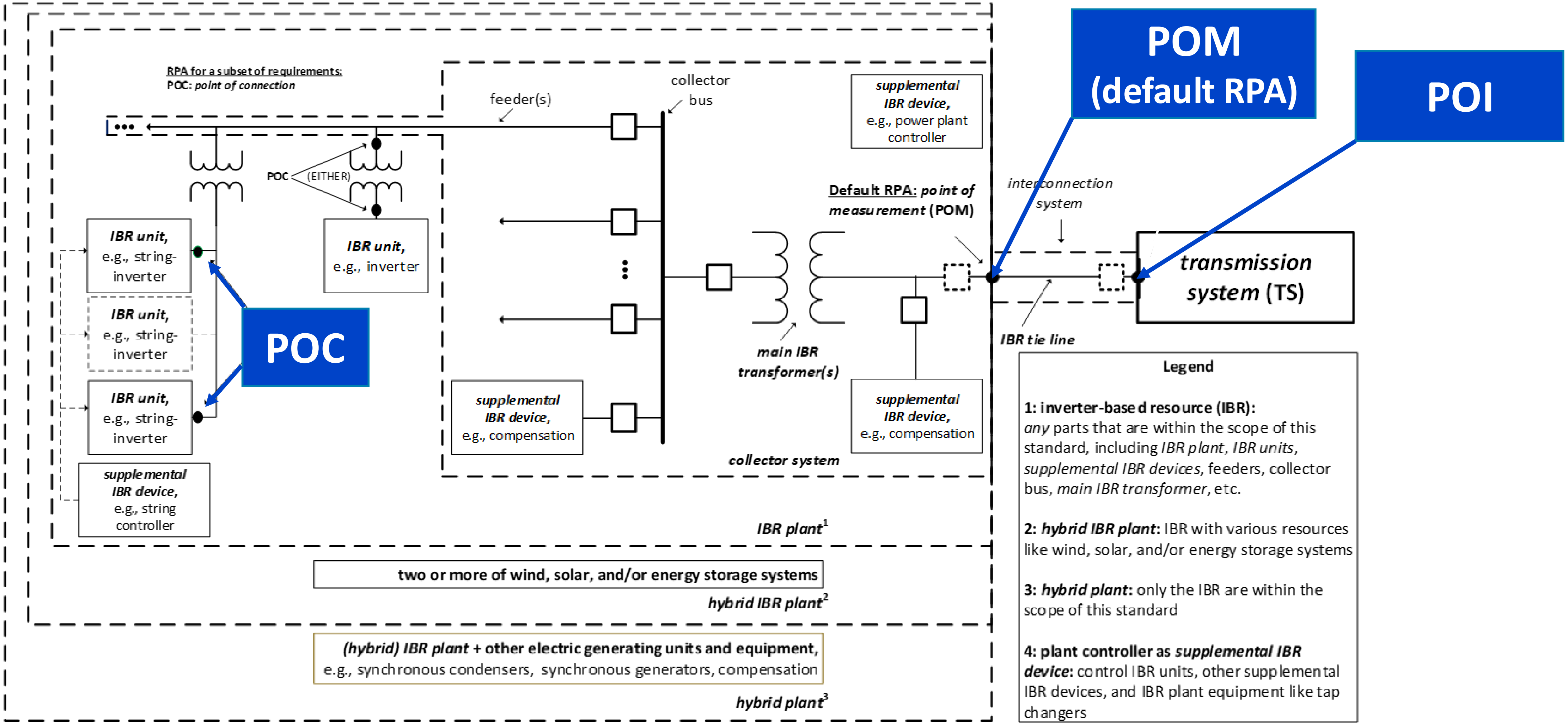
Reference Point of Applicability

Capability Requirements—Not Inferring Utilization!



Legend

1: inverter-based resource (IBR): *any* parts that are within the scope of this standard, including *IBR plant*, *IBR units*, *supplemental IBR devices*, feeders, collector bus, *main IBR transformer*, etc.

2: *hybrid IBR plant*: IBR with various resources like wind, solar, and/or energy storage systems

3: *hybrid plant*: only the IBR are within the scope of this standard

4: plant controller as *supplemental IBR device*: control IBR units, other supplemental IBR devices, and IBR plant equipment like tap changers

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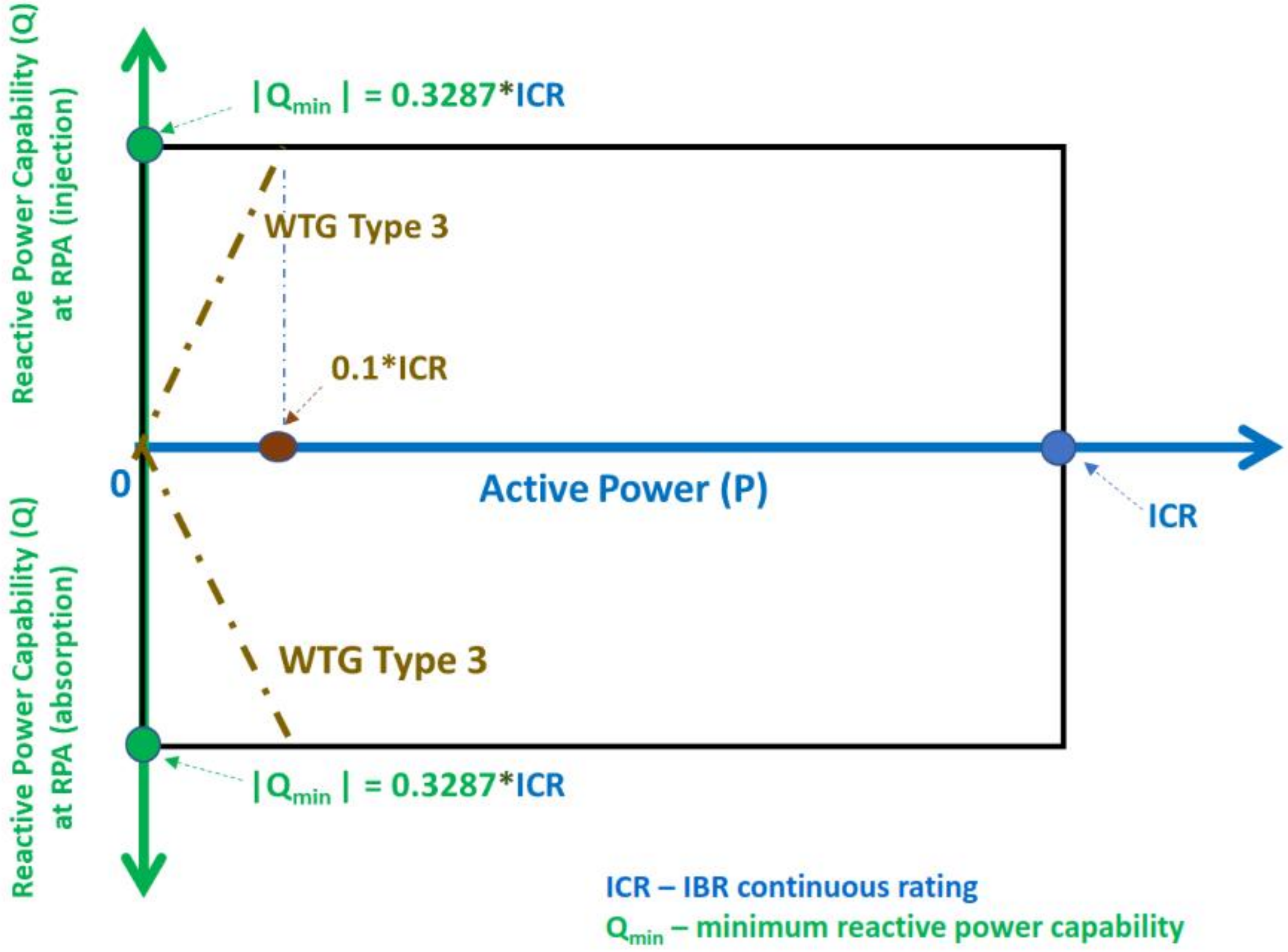
Reactive Power & Voltage Control Requirements

Q_{min} Capability vs P (Injection)



- Default RPA is **POM**
- Minimum reactive power capability of 0.95 power factor at active power of ICR
- Shall be met for all active power output levels (including zero). Exceptions for:
  - Type III wind (dashed brown line)
  - AC-connected offshore IBR plants (should language)

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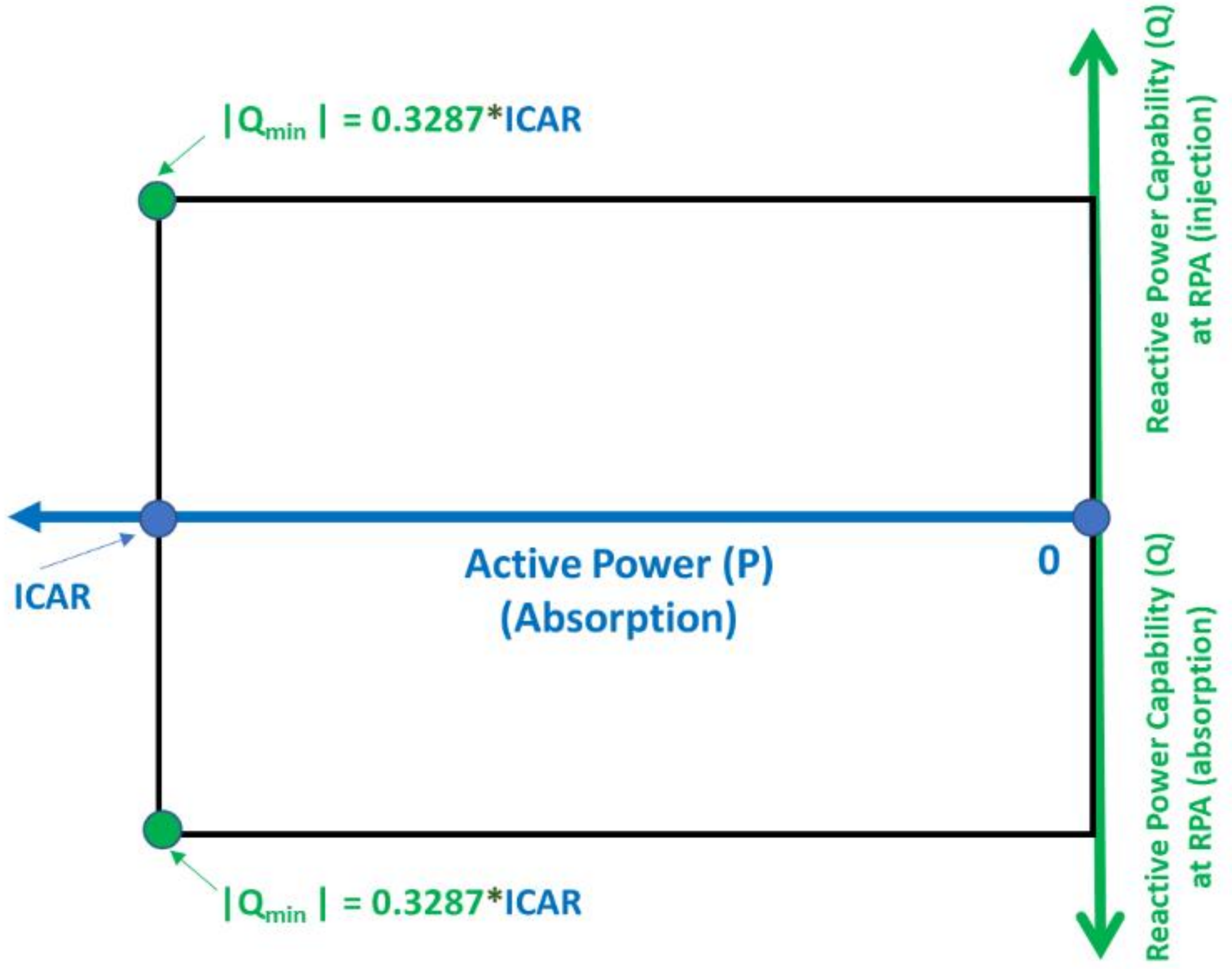
Q_{min} Capability vs P (Absorption)

Default RPA is **POM**



ICAR – IBR continuous absorption rating

Q_{min} – minimum reactive power capability

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Q_{min} Capability vs Voltage

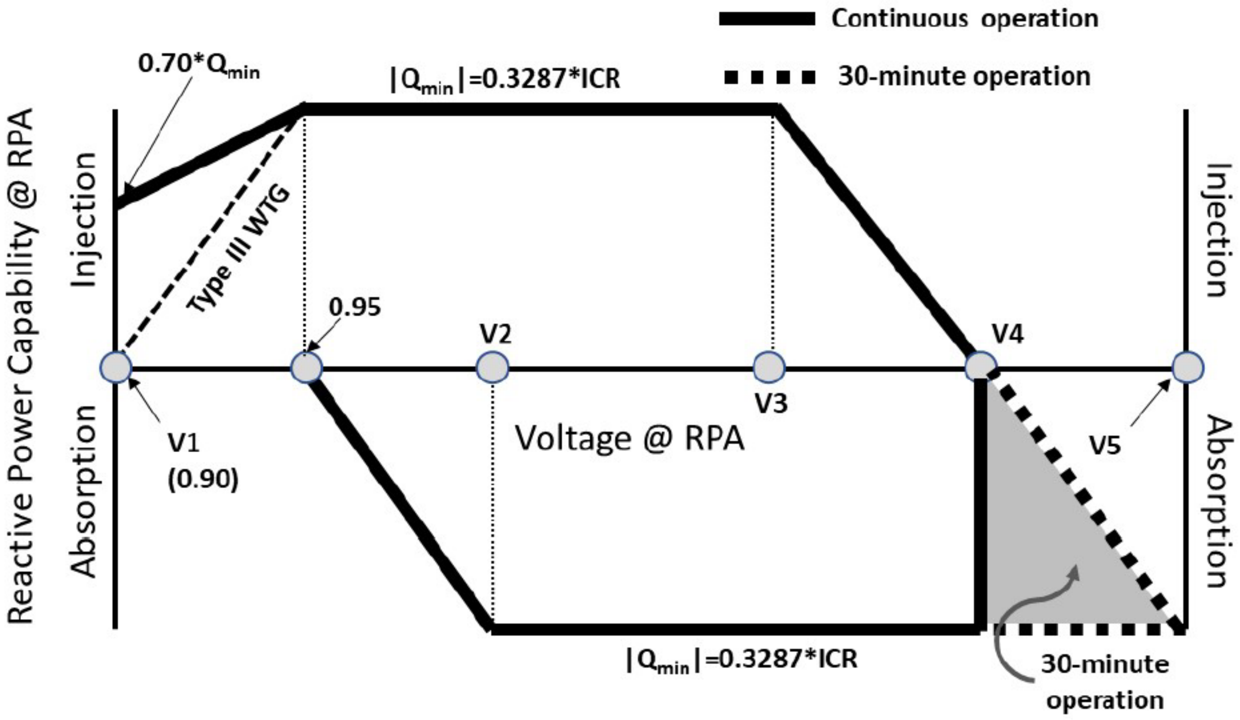

Table 4—RPA voltage range[a]

TS nominal voltage at the 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[b]	0.90	1.02	1.06	1.088	1.10

Note a: TS operator may require different values

Note b: The ANSI C84.1 does not include 735kV as a standard nominal voltage. Voltage ranges are based on an assumption that equipment rated for 800 kV is applied.

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Q_{min} Capability Details

- ***IBR units*** shall have the capability to provide reactive power support when the *primary energy source* is available and not available, and during the transition between these two resource availability states.
- ***IBR units*** shall have the capability to remain ***in service*** while not exporting or importing active power, except for importation of active power to cover losses.
  - The **type III WTGs** may have a reduced reactive power capability when the *primary energy source* is not available due to the size of the line-side converter.
- The **utilization** of this capability shall be under mutual agreement between the IBR owner and the TS owner.
  - If the *IBR owner* and the *TS operator* have agreed that an *IBR plant* is allowed to **cease operation below a specified *minimum active power capability* (Pmin) that is greater than zero**, the *IBR plant* will not produce reactive power when the *IBR plant* has ceased operation.

Q_{min} Capability Details

- Reactive power/current limiters shall only be used to protect equipment and/or personnel.
- Q_{min} shall be dynamic as defined by the time response specifications in Table 5.
  - IBR plant's response time shall be inclusive of any transformer tap changing (if used) that is necessary to keep the IBR units within their required voltage range.
- Reactive power from mechanically-switched reactive power compensation devices (e.g., shunt capacitors and shunt reactors) shall not be considered dynamic.
  - Can be used to offset reactive power losses between the IBR units and the RPA
  - If used to compensate for reactive power losses, they shall be automatically controlled such that the IBR plant maintains the minimum required dynamic reactive capability.
  - Table 5 specifies these devices shall respond within 60s to restore dynamic reactive capability.

Voltage and Reactive Power Control Modes

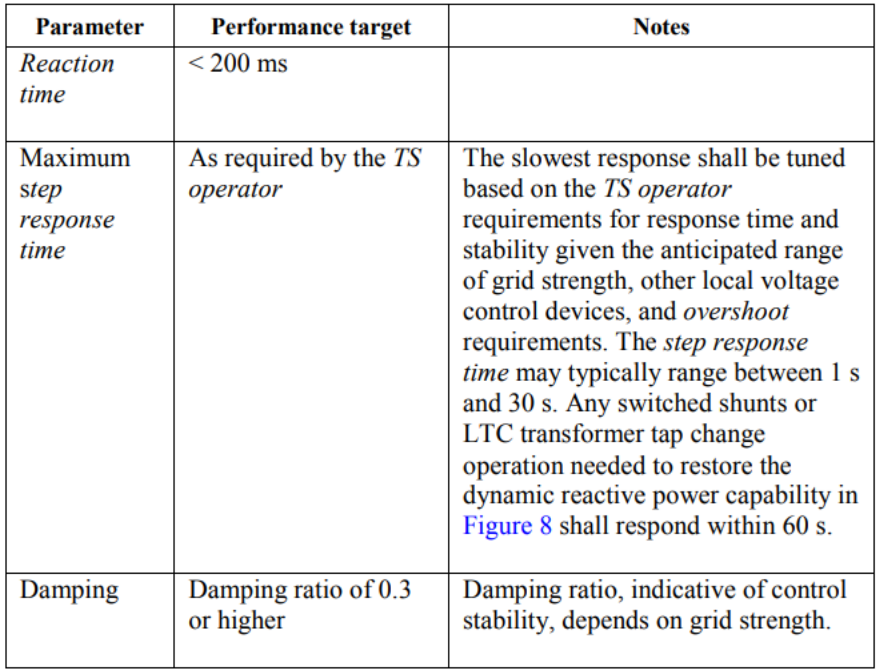
The IBR Plant shall provide following mutually exclusive modes of reactive power control functions:

- RPA Voltage control mode
- RPA Power Factor control mode
- RPA Reactive Power set point control mode

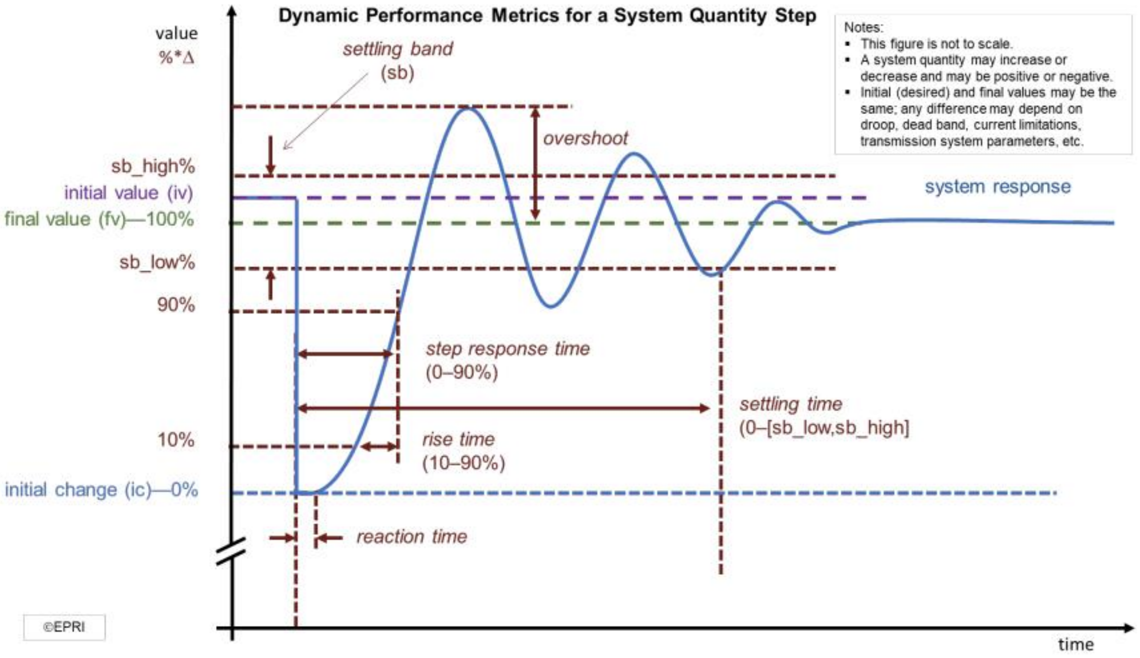
RPA Voltage control mode

Performance target range

Table 5—Performance target range

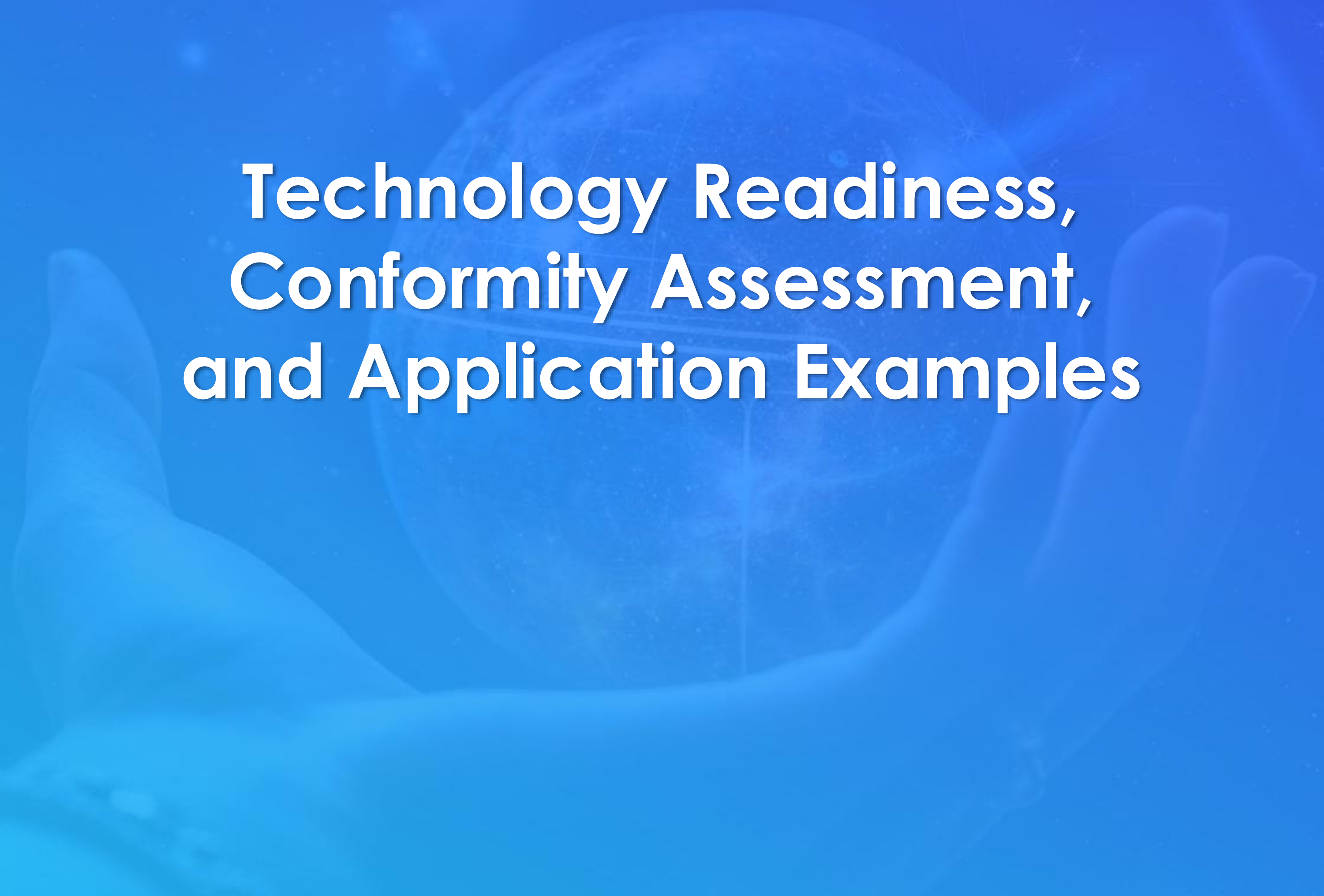


Parameter	Performance target	Notes
Reaction time	< 200 ms	
Maximum *step response time*	As required by the *TS operator*	The slowest response shall be tuned based on the *TS operator* requirements for response time and stability given the anticipated range of grid strength, other local voltage control devices, and *overshoot* requirements. The *step response time* may typically range between 1 s and 30 s. Any switched shunts or LTC transformer tap change operation needed to restore the dynamic reactive power capability in Figure 8 shall respond within 60 s.
Damping	Damping ratio of 0.3 or higher	Damping ratio, indicative of control stability, depends on grid strength.



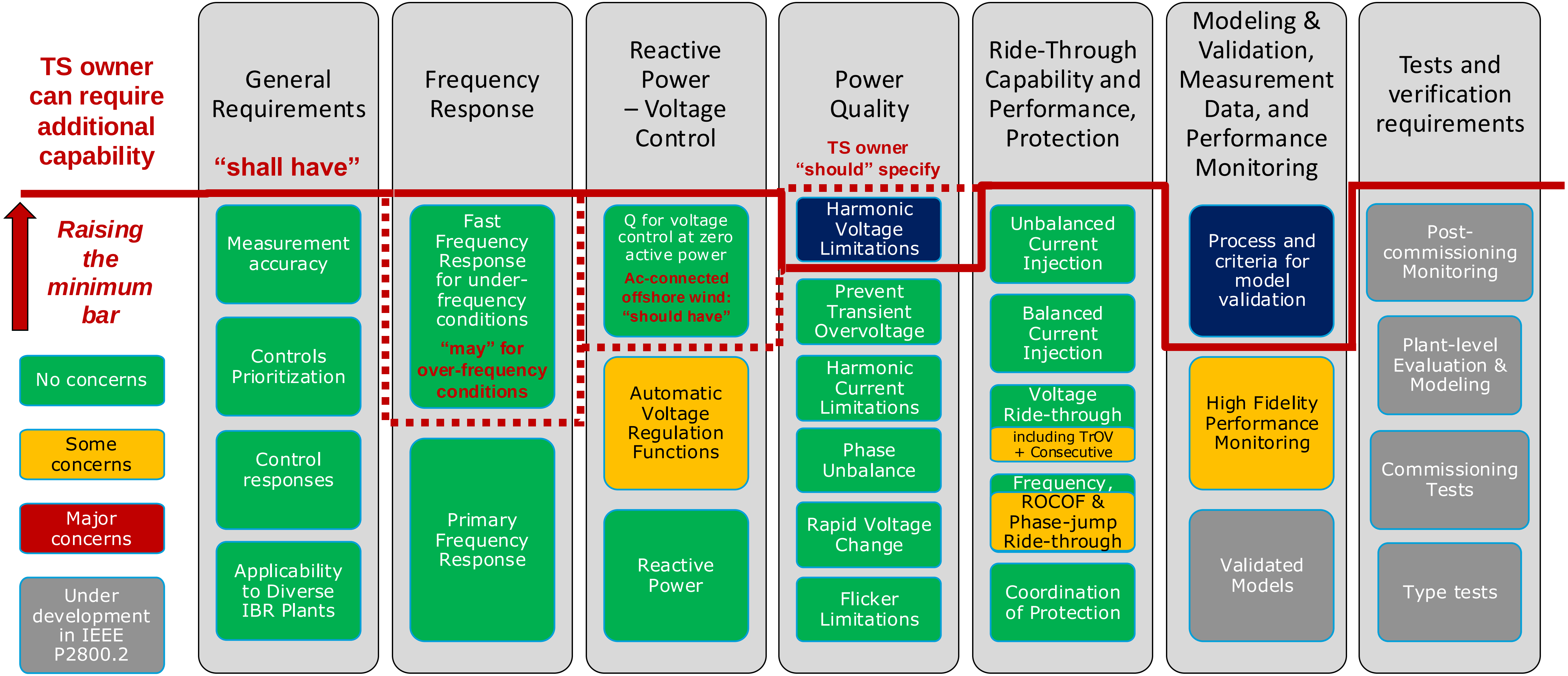
Notes:
- This figure is not to scale.
- A system quantity may increase or decrease and may be positive or negative.
- Initial (desired) and final values may be the same; any difference may depend on droop, dead band, current limitations, transmission system parameters, etc.

- Note the <u>maximum</u> step response time is specified
- Step response time depends on the grid impedance: “Dynamic performance requirements shall be based on, and only applicable to, a defined range of TS equivalent impedance at the POM, specified by the TS operator.”



Technology Readiness, Conformity Assessment, and Application Examples

Technology Readiness / Compatibility of New IBR Units with IEEE 2800



TS owner can require additional capability

Raising the minimum bar

- 🟩 No concerns
- 🟨 Some concerns
- 🟥 Major concerns
- ⬜ Under development in IEEE P2800.2

General Requirements

“shall have”

- Measurement accuracy
- Controls Prioritization
- Control responses
- Applicability to Diverse IBR Plants

Frequency Response

- Fast Frequency Response for under-frequency conditions “may” for over-frequency conditions
- Primary Frequency Response

Reactive Power – Voltage Control

- Q for voltage control at zero active power Ac-connected offshore wind: “should have”
- Automatic Voltage Regulation Functions
- Reactive Power

Power Quality

TS owner “should” specify

- Harmonic Voltage Limitations
- Prevent Transient Overvoltage
- Harmonic Current Limitations
- Phase Unbalance
- Rapid Voltage Change
- Flicker Limitations

Ride-Through Capability and Performance, Protection

- Unbalanced Current Injection
- Balanced Current Injection
- Voltage Ride-through including TrOV + Consecutive
- Frequency, ROCOF & Phase-jump Ride-through
- Coordination of Protection

Modeling & Validation, Measurement Data, and Performance Monitoring

- Process and criteria for model validation
- High Fidelity Performance Monitoring
- Validated Models

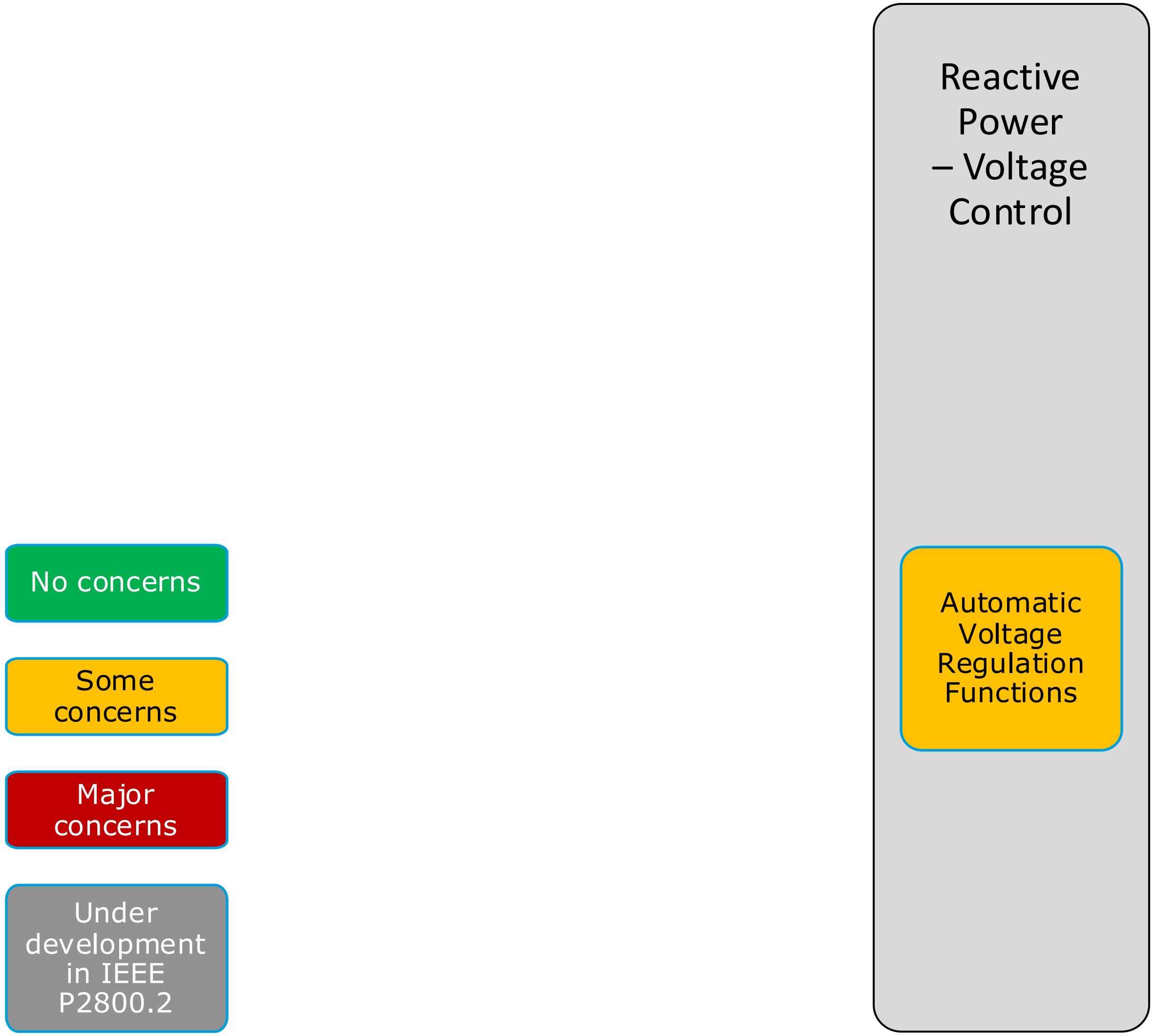
Tests and verification requirements

- Post-commissioning Monitoring
- Plant-level Evaluation & Modeling
- Commissioning Tests
- Type tests

Inverter OEMs have flagged concerns about certain requirements.

Examples taken from: ERCOT OEM assessment as presented on the Dec 8, 2023, IBRWG meeting; note that assessment depends on specific requirements language.

Technology Readiness / Compatibility of New IBR Units with IEEE 2800



Reactive Power – Voltage Control

Automatic Voltage Regulation Functions

No concerns

Some concerns

Major concerns

Under development in IEEE P2800.2

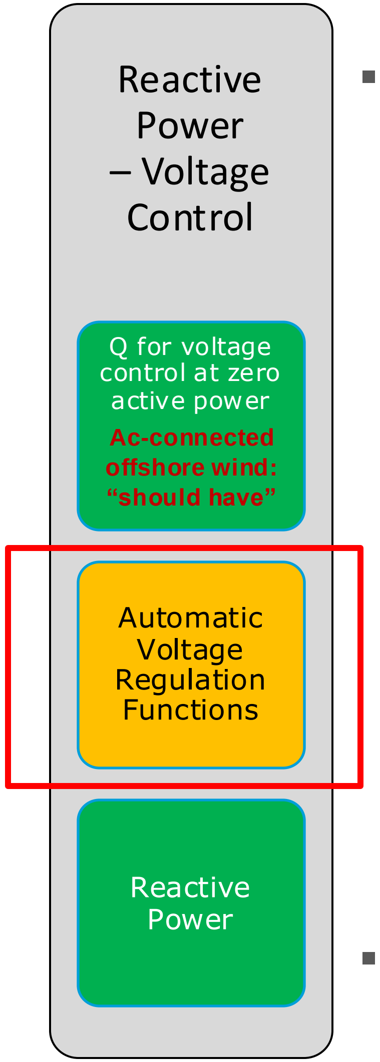
Review of Voltage Control Reaction Time as One Specific Example

Examples taken from: ERCOT OEM assessment as presented on the Dec 8, 2023, IBRWG meeting; note that assessment depends on specific requirements language.

Clause 5.2.2 Voltage Control Reaction Time

(New and Legacy IBRs)

Default RPA: POM



Reactive Power – Voltage Control

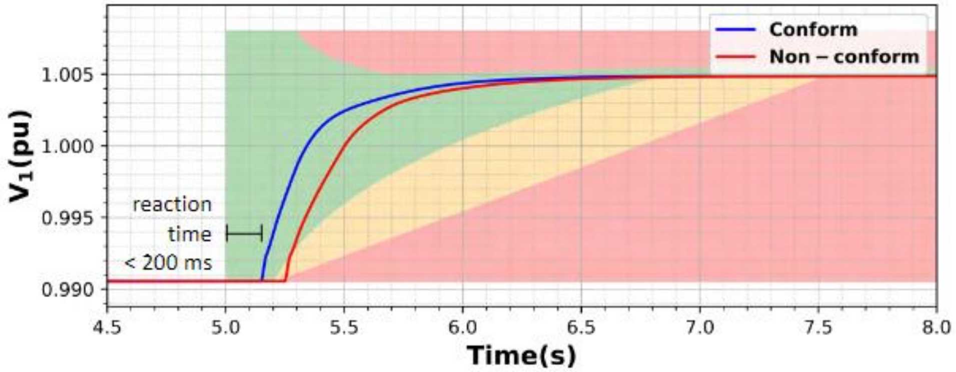
Q for voltage control at zero active power

Ac-connected offshore wind: "should have"

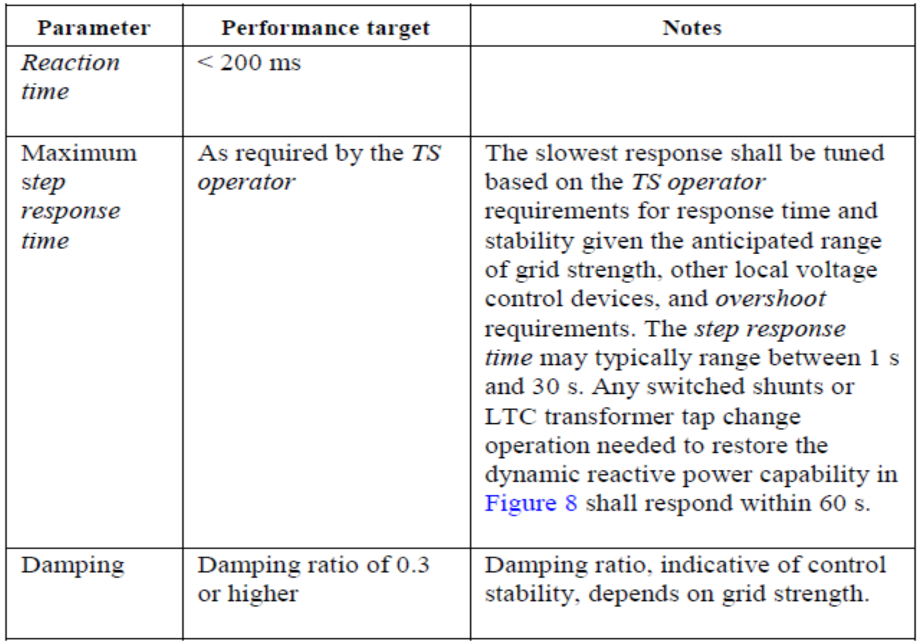
Automatic Voltage Regulation Functions

Reactive Power

- <u>Reaction time of 200 ms may be challenging to achieve</u> due to
  - Time needed to **measure** voltage at POM
  - **Communication latency** between meter and PPC
  - **Power plant controller** recognizing change and issuing new commands to IBR units
  - **Communication latency** between PPC and IBR units
  - **IBR unit** control's cycling time
- GFM IBR may require slower performance than specified in Table 5 of IEEE 2800-2022.



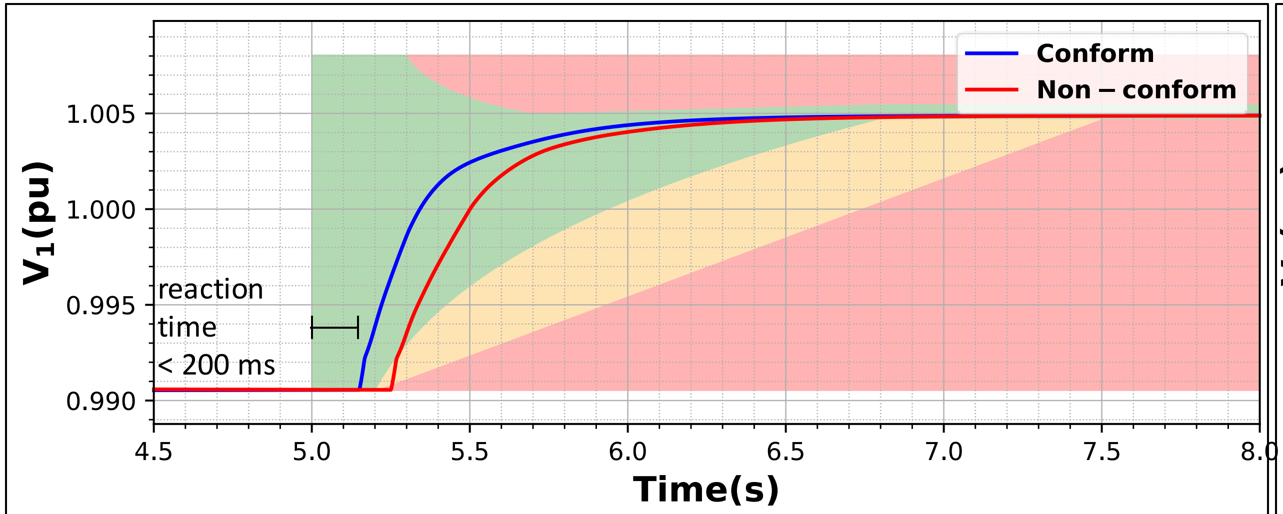
Clause 5.2.2 Voltage Control (Table 5)



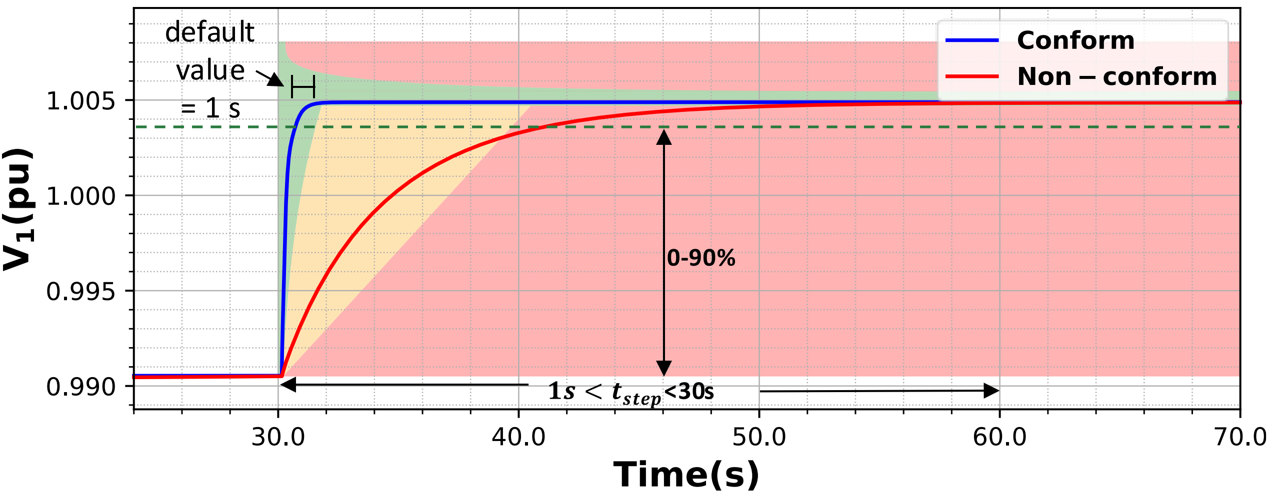
Parameter	Performance target	Notes
Reaction time	< 200 ms	
Maximum *step response time*	As required by the *TS operator*	The slowest response shall be tuned based on the *TS operator* requirements for response time and stability given the anticipated range of grid strength, other local voltage control devices, and *overshoot* requirements. The *step response time* may typically range between 1 s and 30 s. Any switched shunts or LTC transformer tap change operation needed to restore the dynamic reactive power capability in Figure 8 shall respond within 60 s.
Damping	Damping ratio of 0.3 or higher	Damping ratio, indicative of control stability, depends on grid strength.

Fast reaction time is achievable but perhaps need some relaxation to 200 ms requirement

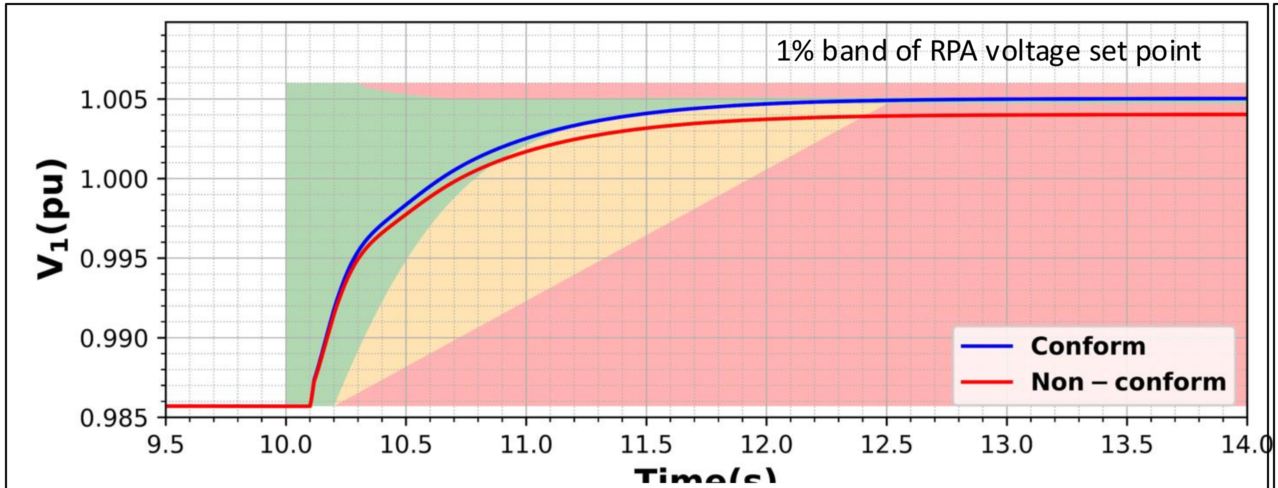
Conformity Assessment Examples



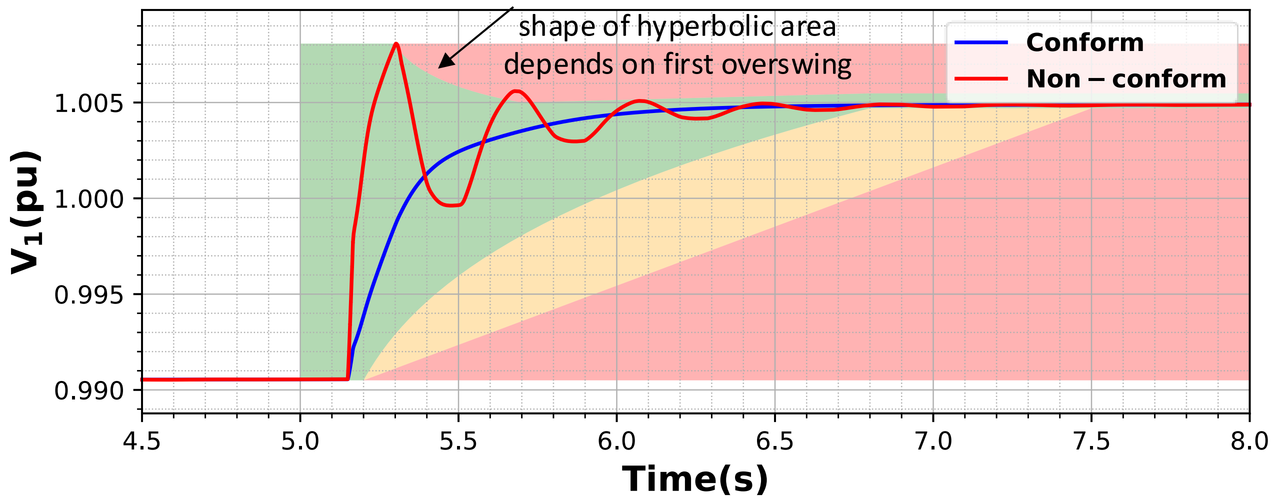
reaction time to be less than 200 ms,



maximum response time between 1 s and 30 s

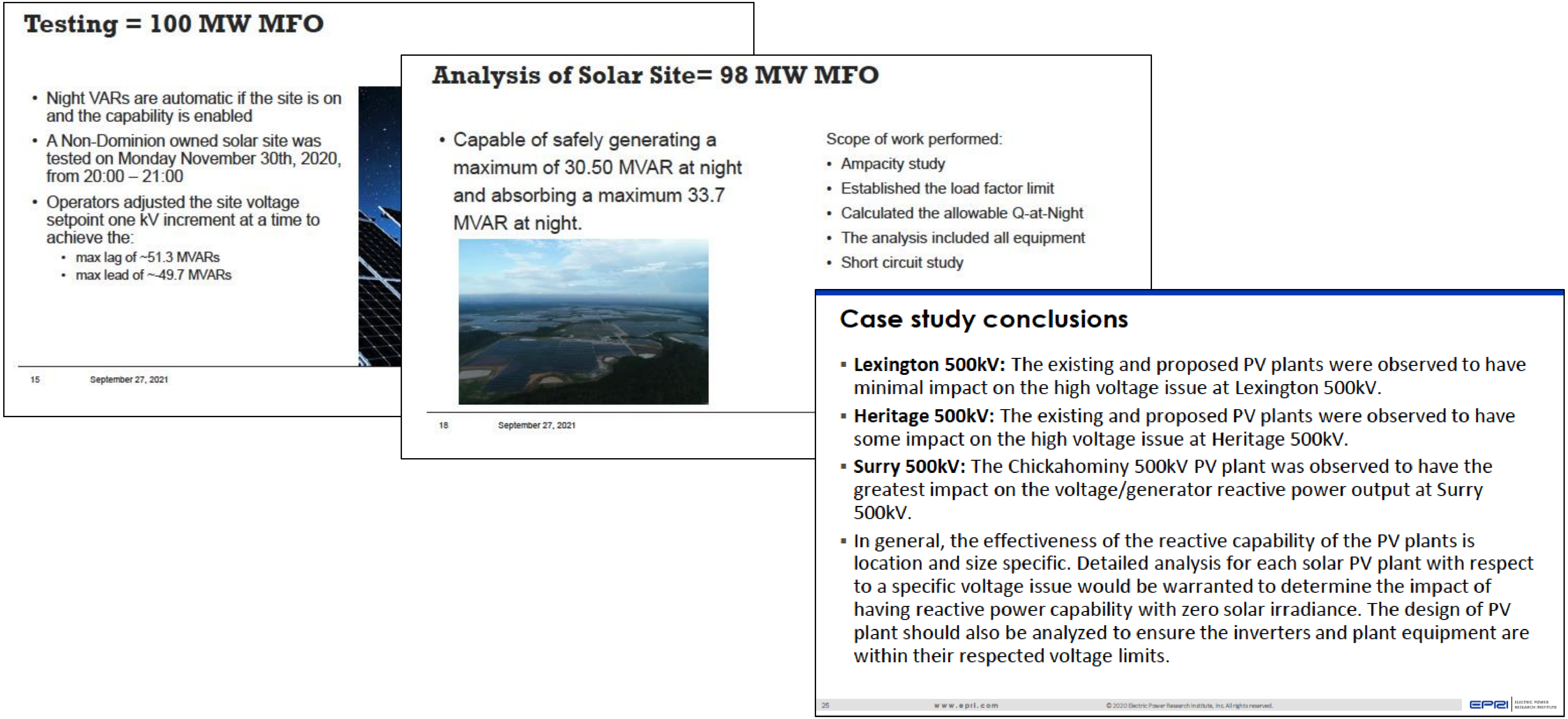


regulate the steady-state voltage at the RPA to the reference value, as adjusted by the droop function, **to within 1% of the RPA voltage set point**



damping ratio of 0.3 or higher

Application Examples



Testing = 100 MW MFO

- Night VARs are automatic if the site is on and the capability is enabled
- A Non-Dominion owned solar site was tested on Monday November 30th, 2020, from 20:00 – 21:00
- Operators adjusted the site voltage setpoint one kV increment at a time to achieve the:
  - max lag of ~51.3 MVARs
  - max lead of ~-49.7 MVARs

Analysis of Solar Site= 98 MW MFO

- Capable of safely generating a maximum of 30.50 MVAR at night and absorbing a maximum 33.7 MVAR at night.

Scope of work performed:

- Ampacity study
- Established the load factor limit
- Calculated the allowable Q-at-Night
- The analysis included all equipment
- Short circuit study

Case study conclusions

- **Lexington 500kV:** The existing and proposed PV plants were observed to have minimal impact on the high voltage issue at Lexington 500kV.
- **Heritage 500kV:** The existing and proposed PV plants were observed to have some impact on the high voltage issue at Heritage 500kV.
- **Surry 500kV:** The Chickahominy 500kV PV plant was observed to have the greatest impact on the voltage/generator reactive power output at Surry 500kV.
- In general, the effectiveness of the reactive capability of the PV plants is location and size specific. Detailed analysis for each solar PV plant with respect to a specific voltage issue would be warranted to determine the impact of having reactive power capability with zero solar irradiance. The design of PV plant should also be analyzed to ensure the inverters and plant equipment are within their respected voltage limits.

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BPA Voltage Control

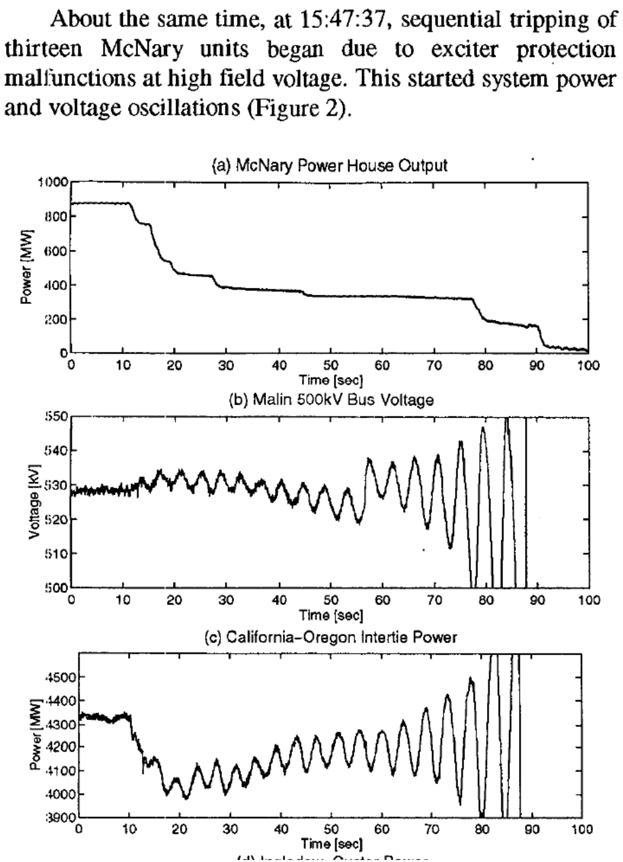
DOE i2X Meeting

December 17, 2024

A History of Voltages Control

- BPA's decades of operating the Northwest Bulk Transmission System has provided experience in understanding the importance of voltage control, E.g.
  - Loss of important reactive resources contributed to August 1996 instability
  - We experienced a large integration of wind in mid 2000s
  - At that time wind was exempt from voltage control.
  - Initial operation of wind plants resulted in local voltage instability
- BPA supported FERC Order 827 requiring non-synchronous generators provide voltage control
- BPA supported NERC working groups and adoption of the NERC IBR Guidelines
- BPA is in the process of adopting Std 2800-2022

A History of Voltages Control

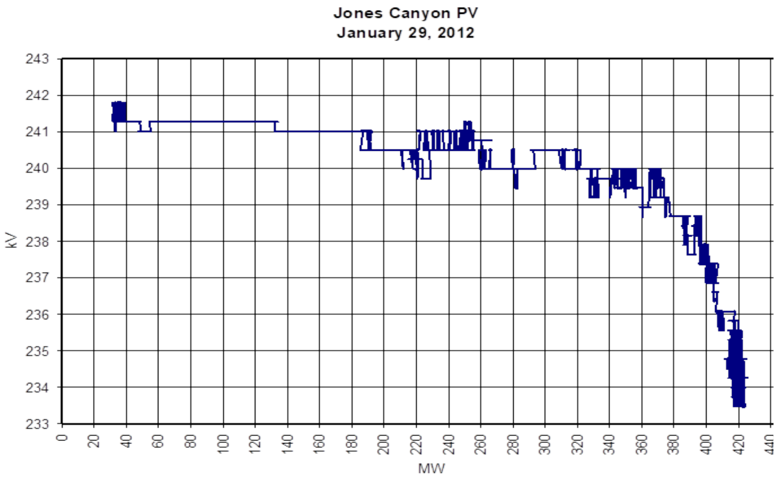


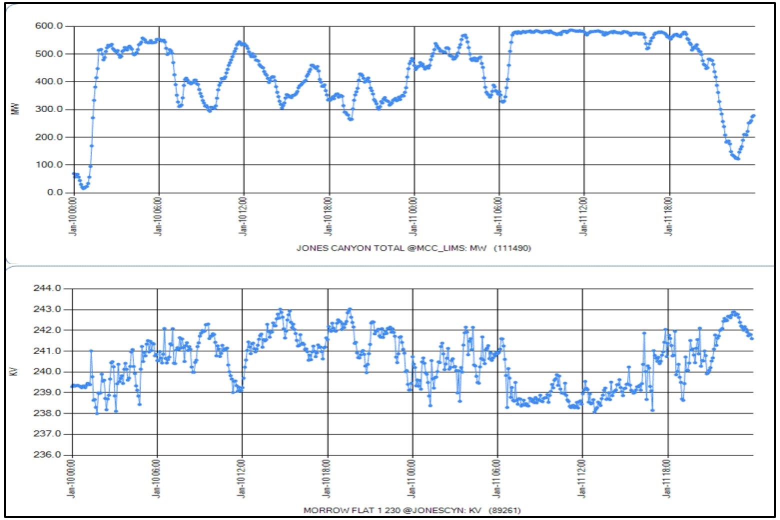
About the same time, at 15:47:37, sequential tripping of thirteen McNary units began due to exciter protection malfunctions at high field voltage. This started system power and voltage oscillations (Figure 2).

- Loss of important voltage control resources can contribute to system instability.
  - Lessons from the past have shown the importance of maintaining system strength through highly capable reactive power delivery, voltage control, and event ride through capability
  - BPA has a strong working relationship with the US Army CE and Bureau of Reclamation regarding testing, improving, and modeling hydro plant resources.

Kosterev, D., Taylor, C., Mittlestadt, W. (1999). Model Validation for the August 10, 1996 WSCC System Outage. *IEEE Transactions on Power Systems*, Vol. 14, No. 3

A History of Voltages Control





- Planning of reactive deliverability and voltage control improves grid performance and provides optimal transmission capacity.
- Initial operation of wind plants
  - did not provide coordinated voltage control and reactive power support (power factor control).
  - resulted in voltage instability at lower generation levels (just over 400 MW)
- Improved voltage control maintains stability for up to 600 MW of power injection.
  - Required reactive droop to provided coordinated reactive power sharing amongst 6 independently developed projects

Voltage Control and Reactive Requirements

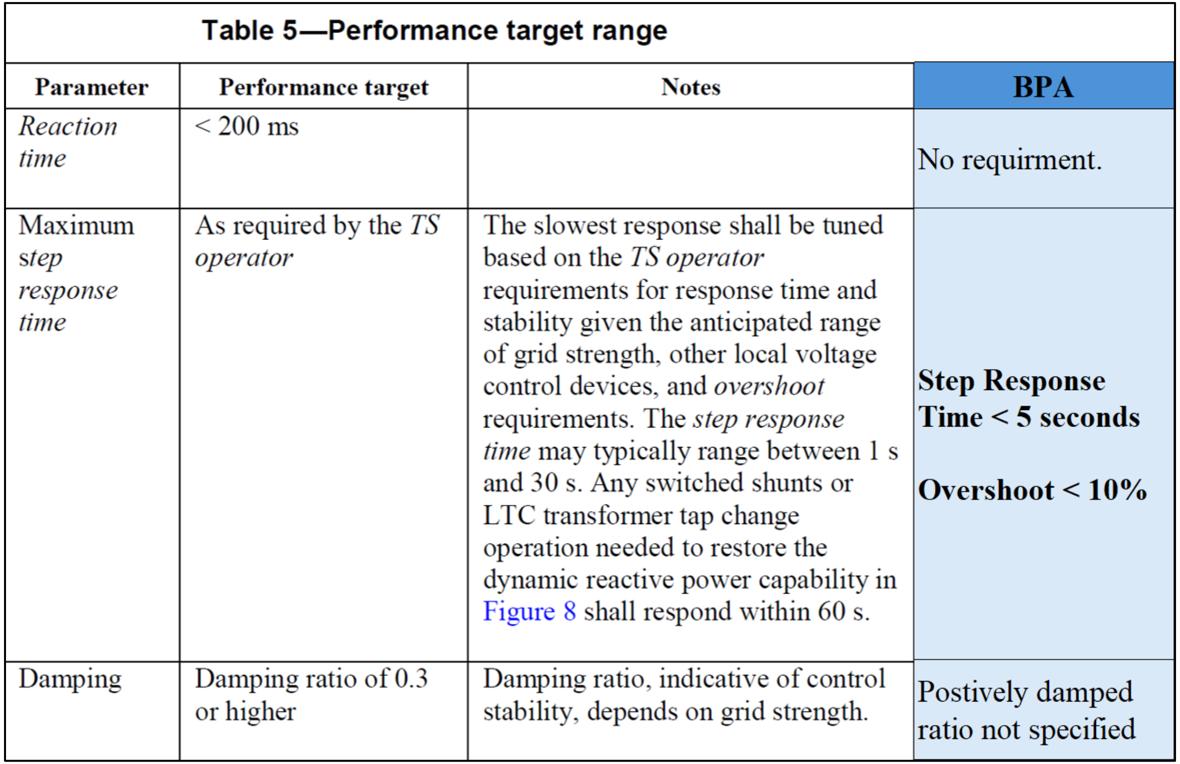
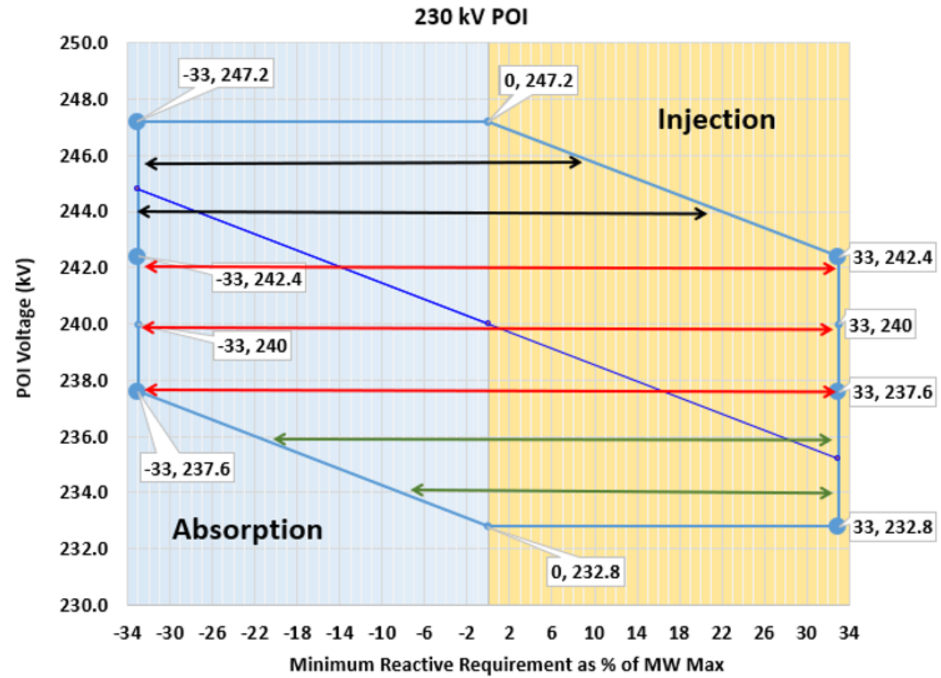


Table 5—Performance target range

Parameter	**Performance target**	**Notes**	**BPA**
Reaction time	< 200 ms		No requirment.
Maximum *step response time*	As required by the *TS operator*	The slowest response shall be tuned based on the *TS operator* requirements for response time and stability given the anticipated range of grid strength, other local voltage control devices, and *overshoot* requirements. The *step response time* may typically range between 1 s and 30 s. Any switched shunts or LTC transformer tap change operation needed to restore the dynamic reactive power capability in Figure 8 shall respond within 60 s.	**Step Response Time < 5 seconds** **Overshoot < 10%**
Damping	Damping ratio of 0.3 or higher	Damping ratio, indicative of control stability, depends on grid strength.	Postively damped ratio not specified

- POI voltage must be controlled with a 2% reactive droop.
- Voltage normalized to typical voltage schedule targets
- Reactive normalized to maximum reactive capability required (33% of MW maximum).
- The 2% reactive droop is defined at the POI, such that a +/- 2% change in POI voltage from the voltage schedule will result in a full reactive response from the generating facility, or reactive injection/absorption at the POI equal to 33% of the plant's nameplate MW.

Voltage Control and Reactive Requirements



Example Minimum Reactive Requirement Adjusted for the POI Voltage.

Scheduled Voltages:

540 kV (500 kV POI), 240 kV (230 kV POI), 118 kV (115 kV POI)

Reactive Required at the Scheduled Voltage:

The minimum reactive required (Q) at the scheduled voltage is represented as a percentage of the projects maximum real power capability (P).

Qrequired = +/- (0.33) * (Pmax)

Voltage Band around Scheduled Voltage (default 1%):

The reactive required at the scheduled voltage is required for all voltages defined by the voltage band. **Voltage Band = Scheduled Voltage +/- 1%.**

Voltage Adjusted Minimum Reactive Requirement:

Minimum reactive required for boosting voltage (injection) is reduced as the POI voltage rises outside the voltage band. Minimum reactive required for bucking voltage (absorption) is reduced as the POI voltage drops below the voltage band.

Minimum Reactive Required for the voltage band ⟷

Minimum Reactive Required for voltage above the voltage band ⟷

Minimum Reactive Required for voltage below the voltage band ⟷

Example 2% droop with zero reactive injected at the voltage schedule ●—●

This is BPA’s approach to voltage adjusted reactive minimum deliverability (IEEE Std 2800-2022, 5.1 Reactive power capability, page 54, Figure 8., on the next slide for quick reference)

Voltage Control and Reactive Requirements

- BPA would like reactive resources to be as responsive to change in voltage as possible without causing control instability.
  - Experience has demonstrated that 2% droop on the maximum reactive base (6% on the MVA base) is a good level of response
  - This shows to be a good compromise between responsiveness and control stability.
  - Typical step-up transformers are 10-12% of the plant MVA base. This droop moves the voltage control point about half-way into the step-up transformer.
- BPA would like reactive resources to respond as fast as possible without causing control instability.
  - Fast response has shown to improve fault recovery and dampening of swings.
  - Experience has shown a step response (0-90%) in less than 5 seconds is a good compromise of speed and control stability (overshoot, well damped).
- Maintain System Strength
  - POIs to have a short-circuit ration of 3 or higher. When determined appropriate a Weighted SCR can be applied for multiple POIs in an area.
- These are default performance requirements.
  - Modifications can be considered when case by case studies identify a need.

Performance Commissioning Tests

- Plant voltage control test
  - Reactive power **droop** at the POI between 1.5% to 2%
  - Reactive power **step response time** (0-90%) is less than 5 seconds
  - POI voltage **overshoot** less than 10%
- Plant reactive capability test
  - The plant must be able to able to absorb/inject reactive power greater than or equal to 33% of the maximum active power capability, including transitions from low primary energy to zero primary energy.
- Plant frequency control test
  - Real power **droop** at the POI between 3% to 5%
  - The frequency **dead-band** is less than or equal to +/- 0.06% (of 60 Hz, 36 mHz)
  - Active power **step response time** (0-90%) is less than 5 seconds for IBRs

Disturbance Monitoring

- BPA required dynamic disturbance recorders (DDR) at all new power plants
  - Positive sequence data is streamed continuously to the BPA control center
  - Point on wave disturbance data is recorded locally
  - The data is used for model validation and performance assessment

IEEE Std 2800-2022 Adoption

- BPA views the IEEE Std 2800-2022 to be a very helpful industry standard and is directly apply it in our interconnection standard.

- The following clauses in the IEEE Std 2800-2022 requirements shall apply to IBR facilities, including the IBR portions of hybrid facilities. These shall be in addition to the requirements in BPA's "Technical Requirements for Interconnection to the BPA Transmission Grid" (STD-N-000001) such that the interconnecting facility meet the requirements of IEEE Std 2800-2022 specified clauses below and BPA's STD-N-000001.

The IEEE Std 2800-2022 clauses applicable to IBRs are:

✓ 4. General interconnection technical specifications and performance requirements
✓ 5. Reactive power-voltage control requirements within the continuous operating region
✓ 6. Active-power—frequency response requirements
✓ 7. Response to TS abnormal conditions
✓ 10 Modeling data
✓ Annex G, Recommendation for modeling data, shall apply to inverter based resources

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

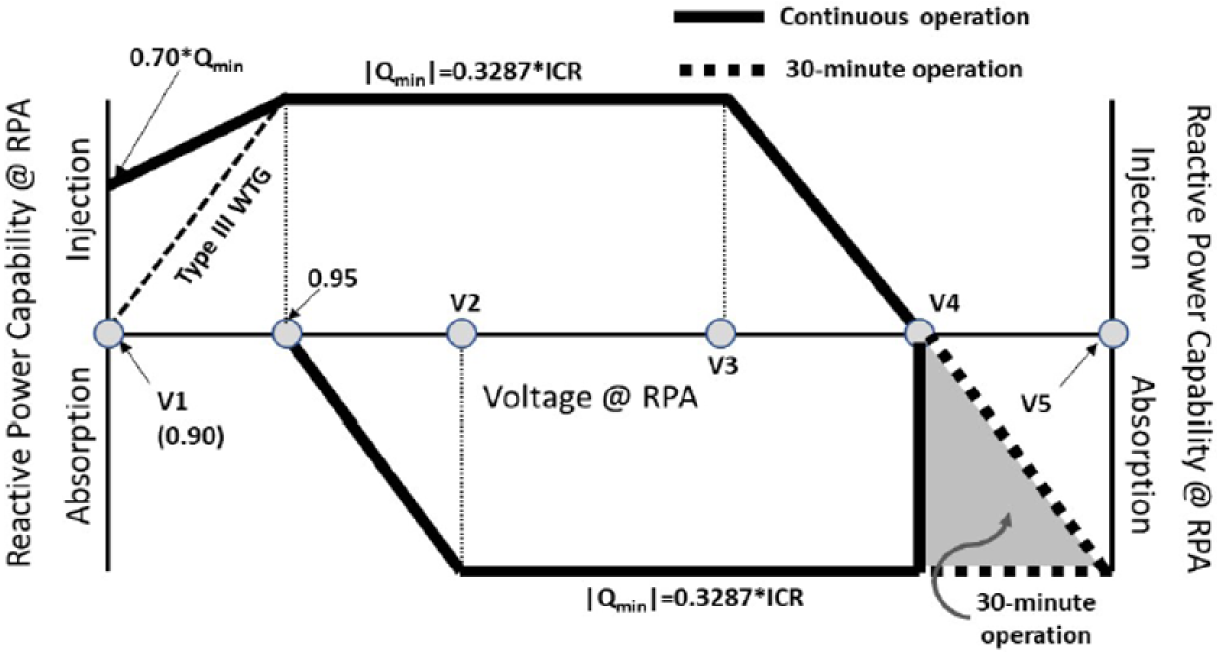


Figure 8—Minimum reactive power capability—Q versus V (generator sign convention)

i2X Forum on Implementation of Reliability Standards -

MISO Reactive Power and Voltage Control Requirements

December 17, 2024

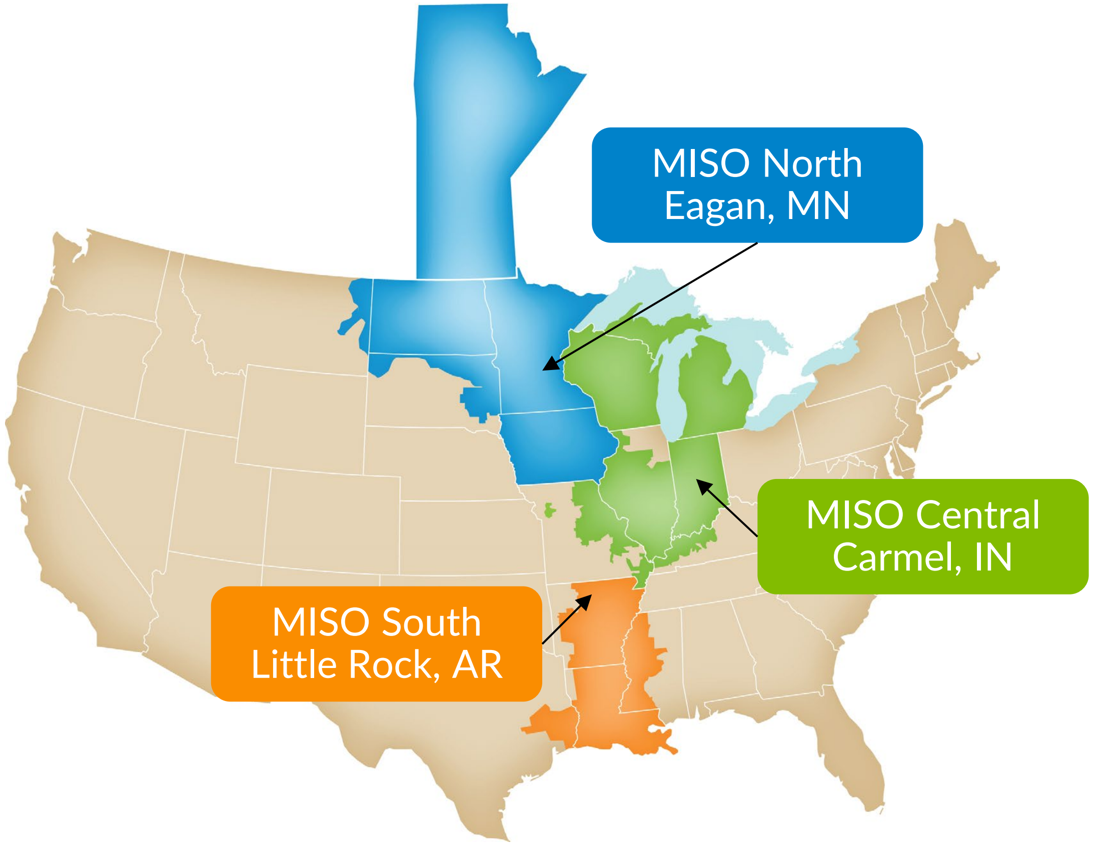
Purpose & Key Takeaways

Purpose: Share MISO's experience adopting Inverter-Based Resource (IBR) performance requirements related to reactive power and voltage control

Key Takeaways:

- MISO's proposed adoption of IEEE 2800-2022 Clause 5 will bring greater performance specificity to existing voltage control requirements
- Stakeholders requested MISO select certain voltage control performance parameters, in part driven by existing plant design and weak grid concerns
- Existing federal regulations pose challenges to full implementation of standard reactive power capabilities

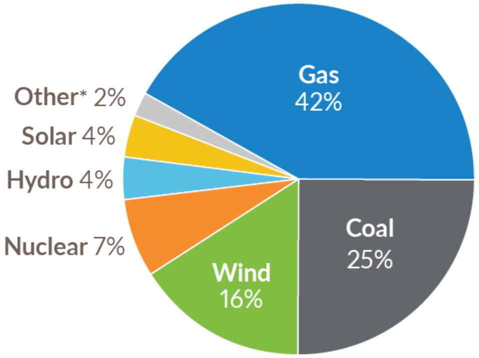
MISO is an independent system operator and regional transmission organization, centrally located in the U.S.



MISO's reliability footprint and regional control center locations

INSTALLED CAPACITY

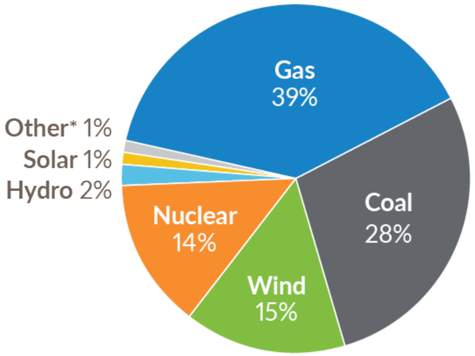
December 2023



191 GW

ENERGY PRODUCTION

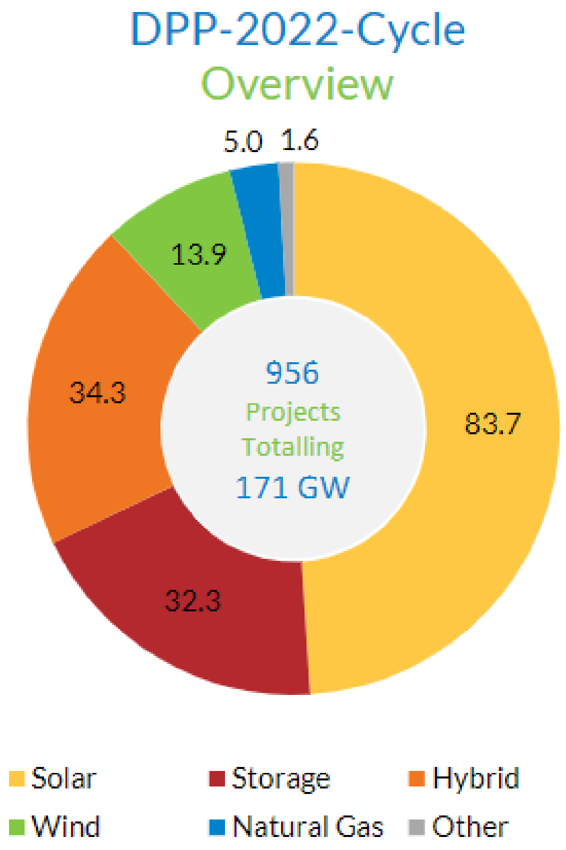
January-December 2023



614 Million MWh

*Other: Diesel, Biomass, Storage, Demand Response Resources

MISO's 2022 generator interconnection queue submissions set new records, with IBR making up the vast majority of proposed resources



Fuel	# of Requests	GW
Solar	469	83.7
Storage	231	32.3
Hybrid	163	34.3
Wind	66	13.9
Natural Gas	21	5.0
Other	6	1.6
Grand Total	**956**	**170.8**

Around 96% of capacity is likely inverter-based

MISO, 2022 Generator Interconnection Queue Submissions. Available at: https://cdn.misoenergy.org/2022%20GIQ%20Submission%20Statistics626443.pdf

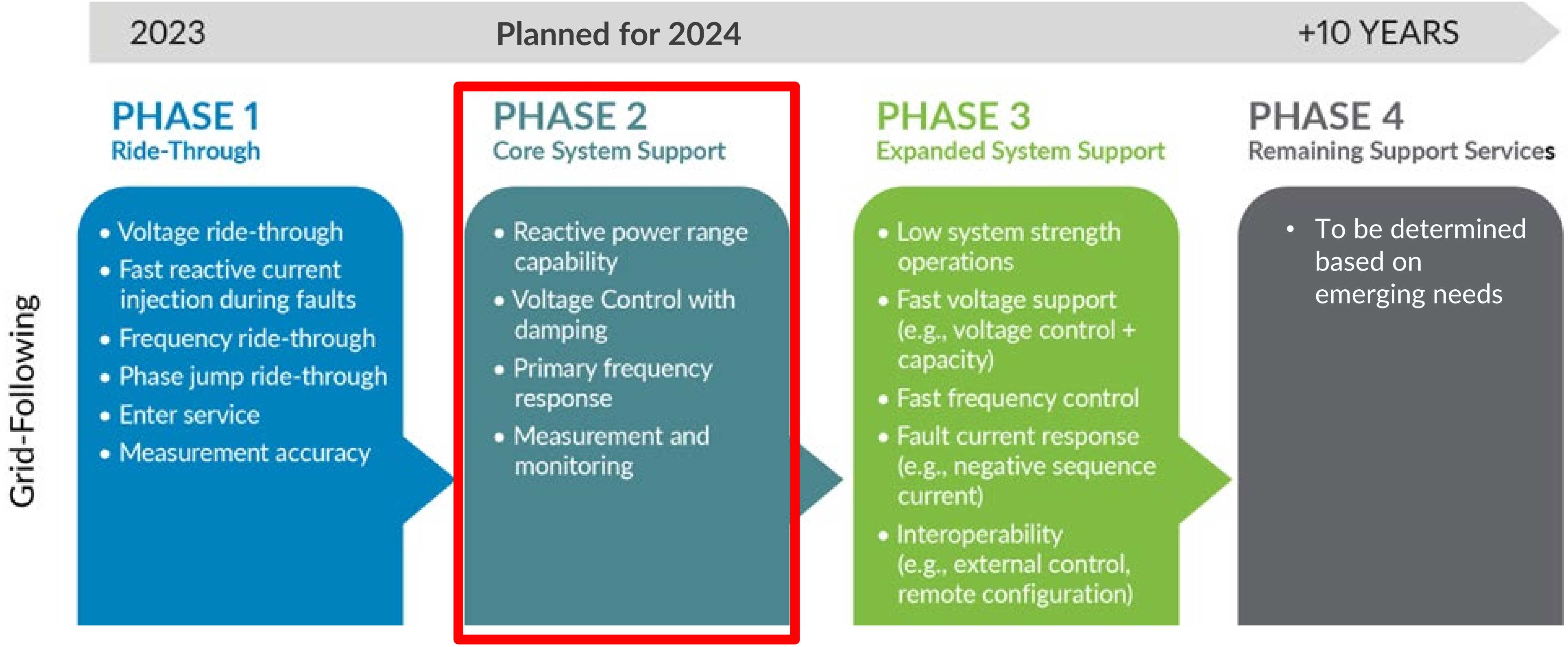
In 2022, MISO performed a risk assessment of IBR performance, with different aspects of voltage and frequency ride-through performance emerged as priority focus areas

Category	*Performance Capability*	*Priority*
General	**Measurement accuracy**	**Highest**
	Range of Available Settings	**Lower**
	Prioritization of Functions	
	Ramping for control parameter change	
Monitoring, Control, and Scheduling	**Responding to external control inputs**	**Lower**
	Remote Configurability	
Voltage Support	**Reactive capability at Zero Active Power**	**Medium**
	Constant Reactive Power	
	Current injection during voltage ridethrough	
Dynamic Responses and Reliability Services	**Frequency Ride-Through**	**Highest**
	ROCOF Ride-Through	
	Voltage Ride-Through	
	Transient Overvoltage Ride-Through	
	Return-to-Service (Enter Service)	
	Restore Output After Voltage Ride-Through	
	Voltage Phase Angle Jump Ride-Through	
	Consecutive Voltage Deviation Ride-Through	**Medium**
	Underfrequency Fast Frequency Response	
	Overfrequency Fast Frequency Response	
	Primary Frequency Response	

- Using NERC Disturbance reports as the primary input, MISO acknowledges a bias towards historical events and tripping related issues
- The performance and capabilities needs were broken up into phases based on priority

Note: the areas listed above turned up as gaps or opportunities to improve specificity in MISO’s assessment of current IBR performance requirements in relation to IEEE 2800-2022

IBR performance requirements were identified as a key solution to ensuring system stability, and four main phases were proposed in the Attributes roadmap



PHASE 1
Ride-Through

- Voltage ride-through
- Fast reactive current injection during faults
- Frequency ride-through
- Phase jump ride-through
- Enter service
- Measurement accuracy

PHASE 2
Core System Support

- Reactive power range capability
- Voltage Control with damping
- Primary frequency response
- Measurement and monitoring

PHASE 3
Expanded System Support

- Low system strength operations
- Fast voltage support (e.g., voltage control + capacity)
- Fast frequency control
- Fault current response (e.g., negative sequence current)
- Interoperability (e.g., external control, remote configuration)

PHASE 4
Remaining Support Services

- To be determined based on emerging needs

- Original Equipment Manufacturer (OEM) equipment capabilities are a key input into MISO's proposed adoption of IBR performance, along with an assessment of potential risks from requirement gaps.

- The proposed requirements apply to IBR interconnection requests that are in early phases of MISO's interconnection process to minimize potential plant design implications and interconnection process impacts.

Attributes Roadmap Publication: https://cdn.misoenergy.org/2023%20Attributes%20Roadmap631174.pdf

Most of IEEE 2800-2022 requirements for Phase 2 adoption are refinements of existing requirements, adding more specificity and clarity

Summary of MISO requirements proposed for adoption

Category	***Performance Capability[1]***	***IEEE 2800 Clause[2]***	***Refinement[1]***	***New Requirement***
Voltage Support	Minimum Reactive Power Capabilities	5.1	**X**	
	Reactive Power Capability at Zero Active Power	5.1		**X**
	Voltage and Reactive Power Control Modes - General	5.2.1	**X**	
	Voltage Control	5.2.2	**X**	
	Constant Power Factor	5.2.3	**X**	
	Constant Reactive Power	5.2.4		**X**
Frequency Response	Primary Frequency Response (PFR)	6.1	**X**	
Dynamic Responses/Reliability Services	Consecutive Voltage Deviation Ride-Through	7.2.2.4		**X**

[1] items are performance areas that are currently included in MISO's tariff (Generator Interconnection Agreement). See Appendix (Slide 21) for details on existing MISO requirements in each area

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

Adopting IEEE 2800 Clause 5 required making decisions on approaches and default settings

- Reactive power capability
- Reactive power performance
- Voltage control dynamic performance
  - Reaction time
  - Step response time
- Power factor control mode applicability with respect to active power conditions

A brief note on terminology: IEEE 2800-2022 addresses both *Capabilities* and *Performance* requirements, but not *Utilization*

Term	MISO Usage, Aligned with IEEE 2800	IEEE 2800 Example
Capability	Plant or unit behavior (i.e., operating characteristics) when executing a function, or when responding to a change in system conditions	Frequency ride-through
Performance	Plant's ability to meet specified performance	Fast frequency response
Utilization	Delivery of specified performance	Enabling fast frequency response

Bicycle is designed and built to be **capable** of being powered by a human at a range of speeds from 0 mph to 40 mph

Human decides to **utilize** bicycle for speed; mounting bicycle and pedaling with a given force

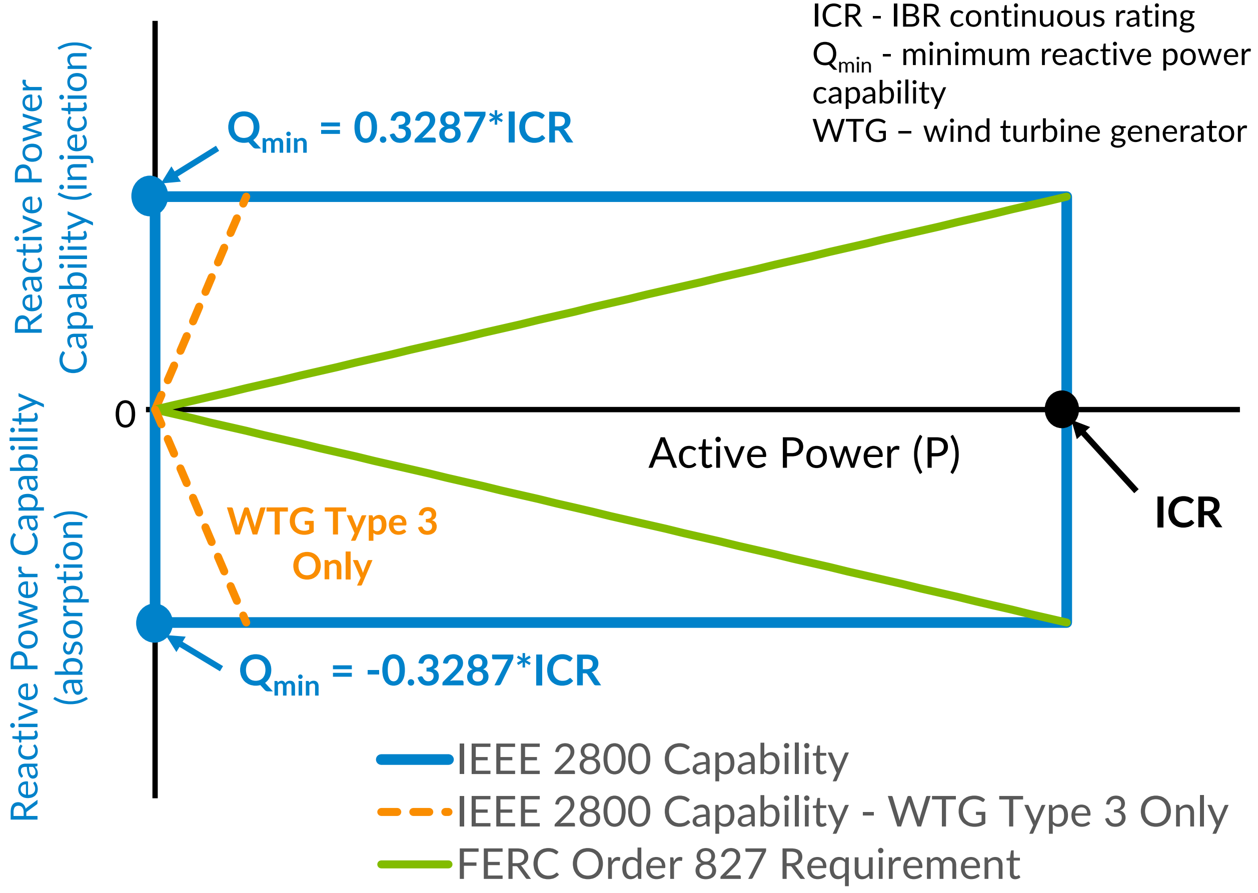
Measured speed of 25 mph is the **performance** based on the bicycle's response to human pedaling

MISO's proposed tariff changes drive utilization of reliability supporting performance within an IBR's capabilities.

MISO’s adoption of IEEE 2800 reactive power requirements is currently constrained by FERC Order 827

- MISO proposes to adopt IEEE 2800 requirements for reactive power **capabilities**, including at zero active power
- MISO will not require **utilization** of the reactive power capability from IEEE 2800 beyond what is required by FERC Order 827 (0.95 leading to 0.95 lagging across the active power range) at this time

Minimum Range for Reactive Power (Q) Capability at RPA



ICR - IBR continuous rating
Q_{min} - minimum reactive power capability
WTG – wind turbine generator

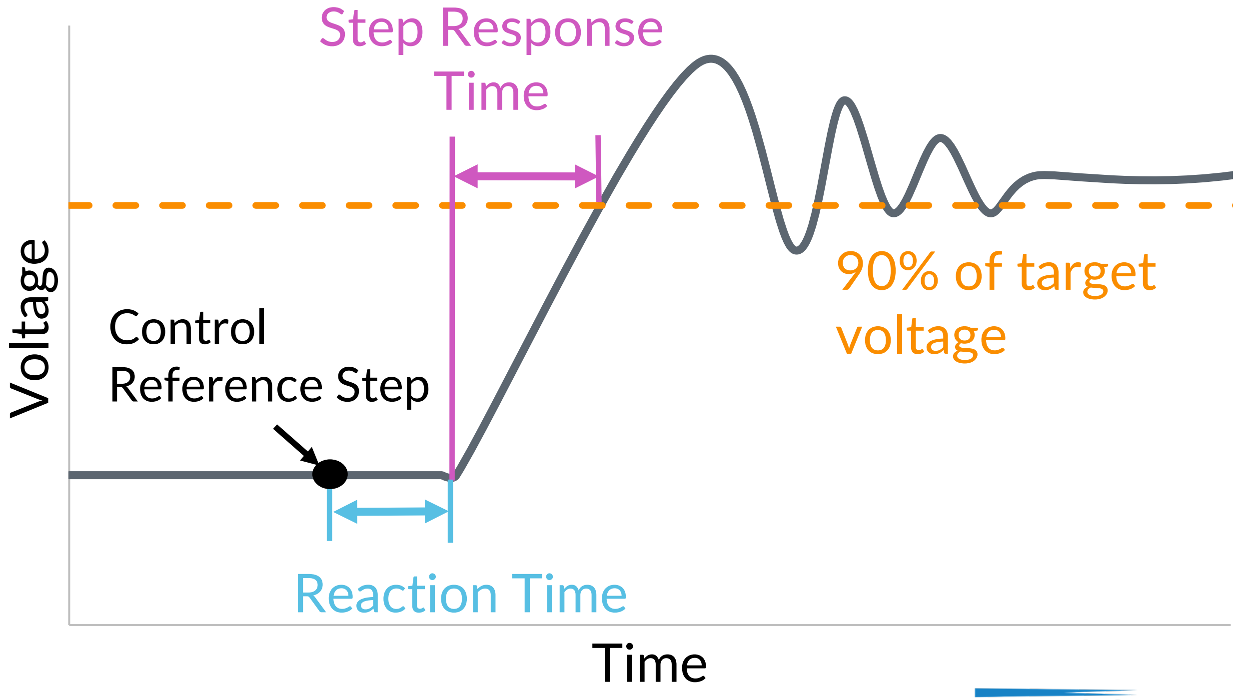
Reference Point of Applicability (RPA) shall be the Point of Measurement (POM)

MISO's proposed voltage control dynamic performance requirements

- IEEE 2800 provides dynamic performance requirements that apply to the **voltage control mode**
- **Maximum *step response time*** is not defined in the standard, MISO has proposed a default value of 30 seconds, subject to modification by the Transmission Owner based on local system needs.
- Stakeholders have shared concerns about the ability of DC-coupled battery systems to achieve the IEEE 2800 ***reaction time*** of 200 ms
  - MISO is proposing to extend the ***reaction time*** requirement to 250 ms

Parameter	**Performance Target**
Reaction time	< 250 ms
Maximum *step response time*[1]	30 s
Damping ratio	0.3 or higher

Requirements in this table shall only be applicable to a defined range of TS equivalent impedance at the POM, specified by the *TS operator.*



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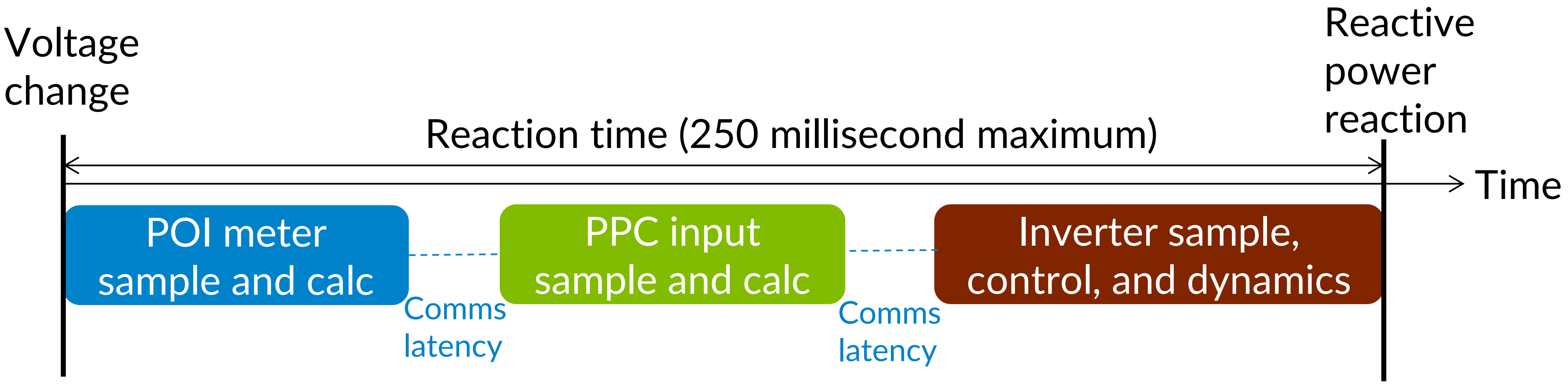
[1] The standard states that the slowest response shall be tuned based on the *TS operator* requirements for response time and stability given grid strength, local voltage control devices, and overshoot requirements

MISO lengthened the reaction time based on stakeholder feedback from resource developers and generator owners

- Communication latency in a plant with different wind turbine manufactures was a concern for a utility.
- For solar, the same utility stated that some equipment used for bulk system plants is certified to IEEE 1547 which does not have the same IEEE 2800 reaction time.
- A developer of battery energy storage systems indicated that an additional local controller for managing battery charging is present in DC coupled systems which introduces additional latency.
- Open questions remain on challenges and necessity of achieving 200 ms reaction time, but MISO adapted a 250 ms reaction time to move the requirements forward.



Voltage change

Reaction time (250 millisecond maximum)

Reactive power reaction

Time

POI meter sample and calc

Comms latency

PPC input sample and calc

Comms latency

Inverter sample, control, and dynamics

Image adapted from information shared by EPRI

MISO’s proposed tariff language defines applicability of the power factor control mode operations

- IEEE 2800-2022, Clause 5.2.3 (power factor control mode) states that the controls “shall appropriately operate at all active power levels down to a certain minimum IBR power level…” as specified by the transmission system operator.
- MISO’s proposed tariff language states: :Subclause 5.2.3: The power factor control mode shall appropriately operate at all active power levels from the ICR continuous rating down to, but not including, zero.”

MISO presented at five Interconnection Process Working Group meetings, requesting feedback on three occasions in developing MISO's proposal

	Date	Objective in support of IEEE 2800 adoption Phase 2
IPWG	Jan 30	Present planned IBR performance requirements to be addressed in 2024
	Mar 12	Propose IEEE 2800 clauses for adoption **[Feedback]**
	May 2	Review feedback and propose implementation plan and tariff redlines **[Feedback]**
	June 4	Review feedback and share edits to tariff redlines
	July 23	Share details on measurement data and implementation plan and edits to tariff redlines **[Feedback]**
	September 3	Review feedback and share edits to tariff redlines
PAC	October 16	Present draft tariff redlines and implementation plan **[Feedback]**
	November 13	Share feedback responses and modifications. **Tariff language final**

MISO plans to file the proposed tariff language with FERC

Several themes emerged in 2024 stakeholder feedback and MISO made significant changes to the proposal

Topic	Stakeholder feedback theme	MISO response
Reactive power	Remove requirement to utilized capability for reactive power at zero active power (a.k.a. “VArs at night”)	MISO removed proposed requirement for utilization
Operational monitoring	Wait for PRC-028 to be complete before considering IEEE 2800 Clause 11 on operational monitoring	MISO proposed minor additions to existing tariff monitoring requirements to clarify and to add PMU data which will be required by PRC-028
Voltage control	Modify voltage control performance requirements based on certain plant designs	MISO lengthened proposed reaction time for voltage control based on Interconnection Customer feedback and adopted Transmission Owner feedback for default step response time

Questions?

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pdalton@misoenergy.org

Appendix

Links to previous 2024 MISO presentations:

- 20240130 IPWG Item 04 IBR Performance Requirements
- 20240312 IPWG Item 04c IBR Performance Requirements IEEE 2800 (PAC-2024-2)
- 20240502 IPWG Item 04a IBR Performance Requirements IEEE 2800 (PAC-2024-2)
- 20240604 IPWG Item 04a IBR Performance Requirements IEEE 2800 (PAC-2024-2)
- 20240723 IPWG Item 04a IBR Performance Requirements IEEE 2800 (PAC-2024-2).pdf
- 20240903 IPWG Item 03c IBR Performance Requirements (IEEE 2800) (PAC-2024-2).pdf

FERC approved MISO’s tariff updates to implement the first phase of IEEE 2800-2022 requirements for IBRs

IEEE 2800 requirements were added into MISO’s Generator Interconnection Agreement (GIA) by detailed reference

Clause 4
General

- Reference Point of Applicability
- Applicable Voltages and Frequency
- Measurement Accuracy
- Return-to-Service (Enter Service)

Clause 7.2
Voltage Ride-Through

- Voltage Ride-Through (VRT)
- Current Injection During VRT
- Transient Overvoltage Ride-Through
- Restore Output after VRT

Clause 7.3
Frequency Ride-Through

- Frequency Ride-Through
- Rate-of-Change-of-Frequency (ROCOF) Ride-Through
- Voltage Phase Angle Jump Ride-Through

- FERC issued an Order accepting the tariff revisions, subject to conditions, in early June
- In response, MISO proposed a small revision to the Applicability section of Appendix G to clarify that the Phase I IEEE 2800 requirements are applicable to the DPP-2022-Cycle and beyond (not to any IBR plants in prior queue cycles)

Link to parent slide

MISO posted draft redlines to the Generator Interconnection Agreement and is requesting feedback

- MISO proposes redlines in the October 16th PAC materials for the follow sections of MISO’s Tariff Attachment X - Appendix 6[1]:
  - Appendix G - Interconnection Requirements for Inverter-Based Resource Plants
  - 9.6.1 – Power Factor Design Criteria
  - 9.6.4 – Primary Frequency Response
- Redlines references IEEE 2800 clauses for adoption, with additional language to clarify decision points left open in the standard[2]
- MISO proposes applying these IEEE 2800 requirements to the DPP-2023-Cycle, with exceptions allowed for GIAs signed before Jan 1, 2026[3]

[1] MISO, Tariff, Attachment X-Appendix 6. 4/2/24. Available at: https://misodocs.azureedge.net/miso12-legalcontent/Attachment_X-Appendix_6_-_Generator_Interconnection_Agreement_%28GIA%29.pdf

[2] See Appendix slides for summary of decision points

[3] Exceptions will also be granted for Generator Replacements and Surplus Interconnection GIAs signed before Jan 1, 2026

MISO recommends moving forward with the following performance requirements from IEEE 2800-2022 to refine existing requirements in MISO's GIA

Category	***Performance Capability[1]***	***IEEE 2800 Clause[2]***	***Summary of Performance Improvement Opportunity***
Voltage Support	**Minimum Reactive Power Capabilities**	**5.1**	**Define more specific reactive power requirements for IBRs, with additional details for Battery Energy Storage Systems (BESS) and Type III wind turbines**
	Reactive Power Capability at Zero Active Power	5.1	Require the capability to provide reactive power support when the primary energy source is not available
	Voltage and Reactive Power Control Modes - General	**5.2.1**	**List three required operating modes and specify voltage control as the default**
	Voltage Control	**5.2.2**	**Clearly define the voltage control mode, require a damping ratio of 0.3 or higher and other dynamic performance requirements**
	Constant Power Factor	**5.2.3**	**Clearly define the constant power factor control mode, require a damping ratio of 0.3 or higher**
	Constant Reactive Power	5.2.4	Clearly define the constant reactive power control mode, require a damping ratio of 0.3 or higher
Frequency Response	**Primary Frequency Response (PFR)**	**6.1**	**Add ranges of available settings for PFR droop and deadband values. Define dynamic performance parameters for PFR.**
Dynamic Responses/Reliability Services	Consecutive Voltage Deviation Ride-Through	7.2.2.4	Define consecutive voltage deviation ride-through to increase general ridethrough robustness
Measurement	**Measurement Data for Monitoring and Validation**	**11**	**Clear requirements for data types, format, sampling/recording, and retention**

[1] **Bolded** items are performance areas that are currently included in MISO's tariff (Generator Interconnection Agreement). See Appendix (Slide 21) for details on existing MISO requirements in each area

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

Link to parent slide

There are decision points associated with MISO’s recommended performance requirements that will be detailed in the tariff language

Category	Performance Capability	*IEEE 2800 Clause*	*Decision Points*
Voltage Support	Minimum Reactive Power Capabilities	5.1	None (adopt by reference)
	Reactive Power Capability at Zero Active Power	5.1	None (adopt by reference)
	Voltage and Reactive Power Control Modes - General	5.2.1	None (adopt by reference)
	Voltage Control	5.2.2	Dynamic performance requirements decisions: max *step response time* and range of conditions for requirement applicability
	Constant Power Factor	5.2.3	Determine minimum active power level for power factor control mode
	Constant Reactive Power	5.2.4	None (adopt by reference)
Frequency Response	Primary Frequency Response (PFR)	6.1	Specify utilization of PFR capability
Dynamic Responses/Reliability Services	Consecutive Voltage Deviation Ride-Through	7.2.2.4	None (adopt by reference)
Measurement	Measurement Data for Monitoring and Validation	11	Specify exact data categories, data points, recording rates, retention and duration times

Link to parent slide

Consecutive voltage deviation is the only remaining requirement needed to complete adoption of all ride-through capabilities in the standard

- Requires the IBR plant to ride through multiple voltage excursions outside of the continuous operation region
  - Exceptions provided in tables[1]
- This clause was not included in Phase I of 2800 requirement adoption due to concerns about original equipment manufacturer (OEM) readiness
- MISO is requesting feedback about technology readiness for this clause, now that there has been more time to evaluate the impacts of 2800 requirements on different inverter models

Time Period	May Trip for this number of Voltage Deviations
10s	5+
120s	7+
30min (1,800s)	11+

Time Period	May Trip for this number of Voltage Deviations Below 50% of Nominal Voltage
10s	3+
120s	4+

[1] Additional exceptions are listed in the Appendix (Slide 33)

MISO proposes to require PMUs to meet DDR requirements

- Dynamic Disturbance Recording (DDR) data requirements in the June draft of PRC-028-1 (at the high-side of main power transformer, or POM):

Measured Electrical Quantities

- Phase-to-neutral or positive sequence voltage
- Phase or positive sequence current
- Three-phase real and reactive power
- Frequency

Input Sampling Rate

- At least 960 samples per second

Output Recording Rate

- At least 60 times per second

- MISO is proposing to require that the DDR requirements be met using phasor measurement units (PMUs)[1]
  - PMU data should be locally stored per retention requirements in the tariff redlines (60 days)
  - Streaming requirements for PMU data will be addressed through a separate topic at IPWG later this year

[1] A PMU can be a stand-alone physical unit or can be a functional unit within another physical unit (such as a protective relay)

Existing MISO transient data recording requirements from Appendix G of the GIA

Requirement	Existing Tariff Language

Plant-Level Data	• Plant three-phase voltage, current and power factor
	• Status of:
	  • Ancillary reactive devices
	  • Plant circuit breakers
	  • Plant controller
	  • Main plant transformer no load taps
	  • Main plant transformer tap changer
	• Plant control set points
	• Protective relay trips

Inverter-Level Data	• Frequency, current, and voltage during frequency ride-through events
	• Voltage and current during:
	  • Momentary cessation for transient high-voltage events (when used)
	  • Reactive current injection for transient low or high-voltage events
	• Inverter alarm and fault codes
	• DC current and voltage

Additional requirements:

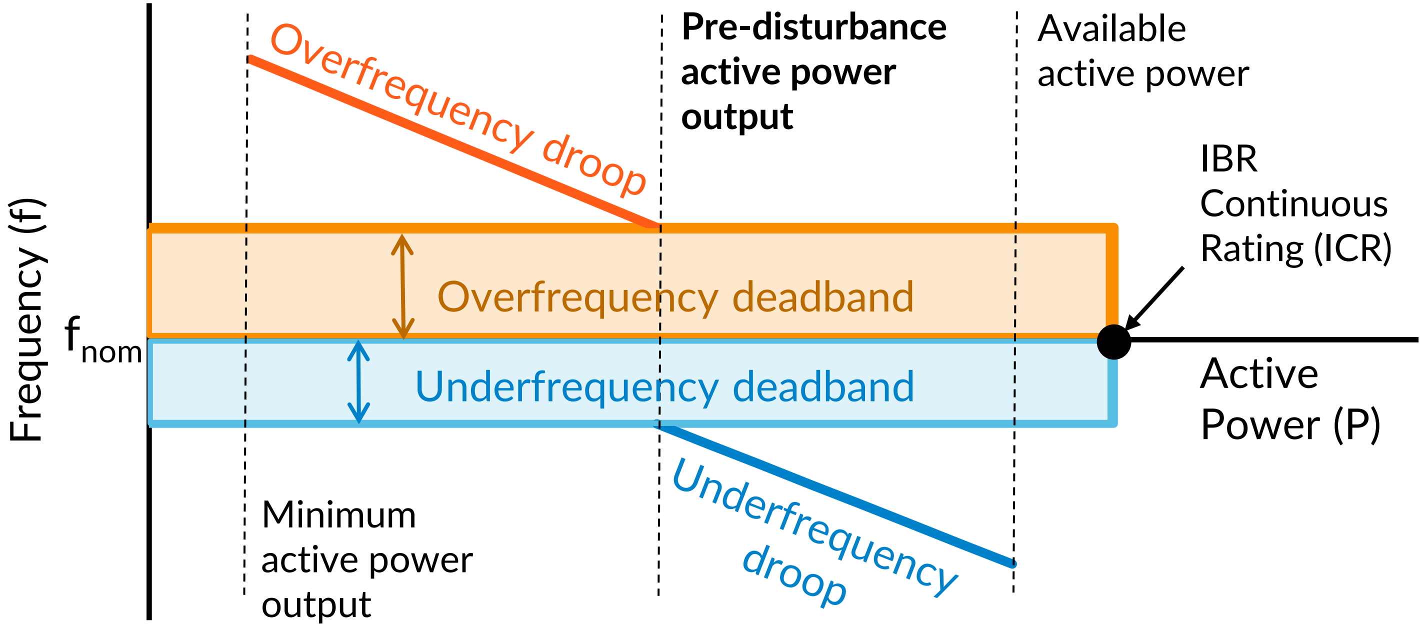
- Data must be time synchronized to 1 ms of resolution
- Data must be sampled at least every 10 ms
- Data storage for a minimum of 60 calendar days
- Data shall be made available within 10 calendar days of request

Category	Performance Capability	*IEEE 2800 Clause*	*Current MISO Tariff Requirement*	*Summary of Performance Improvement Opportunity*
Voltage Support	Minimum Reactive Power Capabilities	5.1	Attachment X Appendix 6 Section 9.6.1.2: Plant shall be "capable of maintaining a composite power delivery at continuous rated power output at the high-side of the generator substation at all power factors over 0.95 leading to 0.95 lagging". Attachment X Appendix 6, Appendix G, Section A.ii. : Plant "shall maintain a factor within the range of 0.95 leading to 0.95 lagging … measured at the high side of the generator substation."	Define more specific reactive power requirements for IBRs, with additional details for BESS and Type III WTGs
	Reactive Power Capability at Zero Active Power	5.1	Not required	Require the capability to provide reactive power support when the primary energy source is not available
	Voltage and Reactive Power Control Modes - General	5.2.1	Attachment X Appendix 6 Section 9.6.2: "Interconnection Customer shall operate the Generating Facility to maintain the specified output voltage or power factor"	List three required operating modes and specify voltage control as the default
	Voltage Control	5.2.2	Attachment X Appendix 6 Section 9.6.2.1: "Interconnection Customer shall operate the Generating Facility with its speed governors and voltage regulators in automatic operation."	Clearly define the voltage control mode, require a damping ratio of 0.3 or higher and other dynamic performance requirements
	Constant Power Factor	5.2.3	Attachment X Appendix 6 Section 9.6.2: "Interconnection Customer shall operate the Generating Facility to maintain the specified output voltage or power factor"	Clearly define the constant power factor control mode, require a damping ratio of 0.3 or higher
	Constant Reactive Power	5.2.4	Not required	Clearly define the constant reactive power control mode, require a damping ratio of 0.3 or higher
Frequency Response	Primary Frequency Response (PFR)	6.1	Attachment X Appendix 6 Section 9.6.4: IC "is required to install a governor or equivalent controls with the capability of operating with a maximum 5 percent droop and +-0.036 Hz deadband...". Attachment X Appendix 6 Section 9.6.4.2: IC shall ensure that the plant's real power response is automatic, immediate, and sustained until the frequency returns to a value within the deadband. See additional language in sections 9.6.4, 9.6.4.1, 9.6.4.2. 9.6.4.3, and 9.6.4.4	Add ranges of available settings for PFR droop and deadband values. Define dynamic performance parameters for PFR.
Dynamic Responses/Reliability Services	Consecutive Voltage Deviation Ride-Through	7.2.2.4	Not required	Define consecutive voltage deviation ride-through to increase general ridethrough robustness
Measurement	Measurement Data for Monitoring and Validation	11	Attachment X Appendix 6, Appendix G, Section A.iv. : "Non-synchronous generating facilities with generating capacities of more than 20 MW must monitor and record data for all frequency ride-through events, transient low-voltage disturbances that initiated reactive current injection, reactive current injection or momentary cessation for transient high-voltage disturbances, and inverter trips. See full tariff section for more details.	Clear requirements for data types, format, sampling/recording, and retention

IEEE 2800 primary frequency response (PFR) requirements will enhance existing PFR requirements for IBRs

- Adoption of the PFR section of the standard would add dynamic performance requirements, along with range of available setting guidance for droop and deadband parameters
- IBR plants will **NOT** be required to operate with headroom to address under-frequency disturbances, as is the case today.
- MISO will evaluate language in the standard to ensure there are no conflicts with the requirements from FERC Order 842[1] in MISO's tariff, especially for battery energy storage systems (BESS)

Primary Frequency Response Characteristics



[1] Federal Energy Regulatory Commission, Docket No. RM16-6-000; Order No. 842. Essential Reliability Services and the Evolving Bulk-Power System—Primary Frequency Response. Issued February 15, 2018.

MISO proposes to add only DDR and PMU requirements, and will address the remaining data recording items in the future

- The draft NERC standard PRC-028 was undergoing rapid and substantial revisions during MISO’s Phase 2 IBR requirements[1]
- MISO proposed waiting until PRC-028 is completed to substantially alter the existing data recording language in MISO’s GIA
  - MISO will evaluate Clause 11 of IEEE 2800 at that time as well
- In the meantime, to fill a MISO monitoring need being addressed in PRC-028, MISO proposed new tariff redlines to clarify existing requirements applied to dynamic disturbance recording (DDR) and MISO is requiring phasor measurement unit (PMU) data to meet DDR requirements

[1] PRC-028 is being developed under Project 2021-04 Modifications to PRC-002 - Phase II: https://www.nerc.com/pa/Stand/Pages/Project-2021-04-Modifications-to-PRC-002-2.aspx

[2] Slide 17 in the Appendix summarizes the existing data recording requirements in the GIA that will not be altered at this time

Additional information on IEEE 2800-2022 performance requirements

Slides contain MISO’s summary of the standard, see the IEEE 2800-2022 publication for complete details

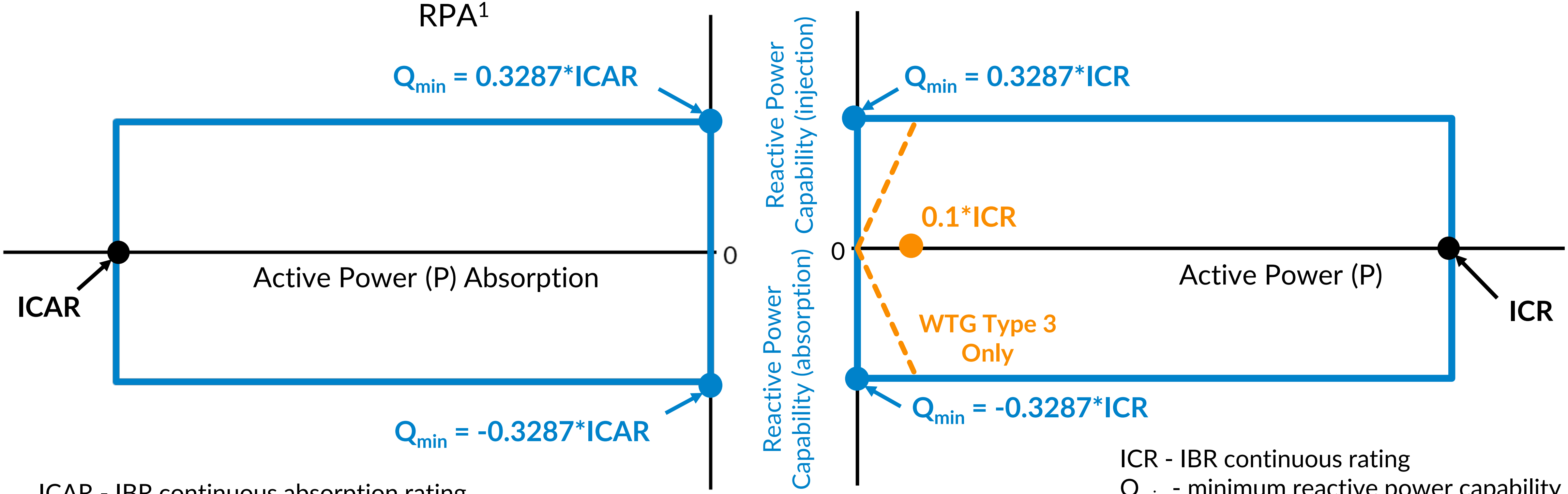
IEEE 2800 defines minimum reactive power capabilities

- IBR minimum reactive power capability to inject or absorb at least 32.87% of IBR continuous rating (ICR) at the point of measurement (POM).
  - Applies only when applicable voltage and frequency are within the *continuous operation region*
  - Applies both when IBR is injecting and absorbing active power[1].
  - Applies at all levels of active power, with several exceptions[2]
    - Type III wind turbine generators have reduced reactive requirement at low active power levels.
  - Equates to +/-0.95 power factor, consistent with FERC Orders 2003[3] and 827[4]
  - Capability requirement applies regardless of primary energy source availability status.[5]
    - Under mutual agreement, the capability may be used to participate in reactive power exchange at zero active power.
    - If IBR is designed to cease operation below a specified minimum active power capability that's greater than zero, the IBR plant will not produce reactive power after operation ceases.

[1] Absorbing active power applies to energy storage. The continuous active power absorption rating is used for determining reactive power during absorption.
[2] An exception related to off-shore wind exists in IEEE 2800-2022 clause 5.1.
[3] Federal Energy Regulatory Commission, Docket No. RM02-1-000; Order No. 2003. Standardization of Generator Interconnection Agreements and Procedures. Issued July 24, 2003.
[4] Federal Energy Regulatory Commission, Docket No. RM16-1-000; Order No. 827. Reactive Power Requirements for Non-Synchronous Generation. Issued June 16, 2016.
[5] Type III WTG may have reduced reactive power capabilities when primary energy source is not available

Minimum reactive power capability requirements apply during both active power injection and active power absorption (if applicable)

Minimum Range for Reactive Power (Q) Capability at RPA[1]



ICAR - IBR continuous absorption rating

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

Reference Point of Applicability (RPA) shall be the Point of Measurement (POM)

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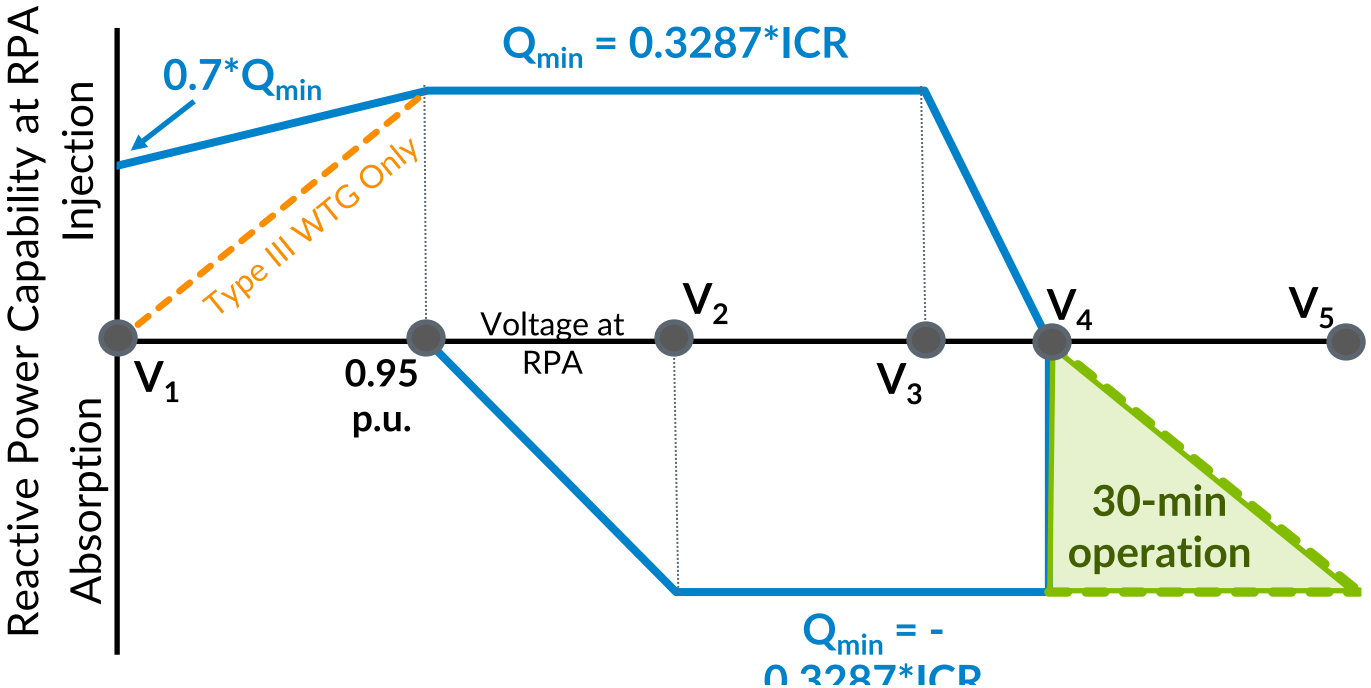
[1] Figures shows minimum reactive power capability, actual reactive power capability can go beyond this

Additional reactive power capability requirements apply for non-nominal voltage conditions

- Minimum reactive power capability requirements differ by nominal RPA voltage, as shown in the table below.[1]
- Different requirements exist for continuous versus 30-minute operation.
- IBR shall maintain voltage schedule provided by transmission operator, within required capability[2]

TS nominal voltage at the RPA[3]	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)	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



Reference Point of Applicability (RPA) shall be the Point of Measurement (POM)

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[1] An exception exists for Type III WTG for voltages less than 0.95 p.u.
[2] Requirement applies to storage across charging or discharging statuses, including the transition between.
[3] *TS operator* can require different values for V1-V5

IEEE 2800 provides requirements and dynamic performance requirements for the default voltage control operating mode

- Automatic voltage control mode droop shall have a range of settings from 0 to 0.3 p.u. voltage change for 1.0 per unit reactive power on the ICR base
- Dynamic reactive power response to a step change in voltage must meet the performance requirements in the table
  - A stable and damped response takes precedence over response time

Voltage Control Mode

Closed-loop automatic voltage control mode to regulate steady-state voltage at RPA to the reference value within 1% of the set point

Parameter	**Performance Target**
Reaction time	< 200 ms
Maximum *step response time*[1]	As required by the *TS operator*[2]
Damping ratio[3]	0.3 or higher

Requirements in this table shall only be applicable to a defined range of TS equivalent impedance at the POM, specified by the *TS operator*.

[1] The standard states that the slowest response shall be tuned based on the *TS operator* requirements for response time and stability given grid strength, local voltage control devices, and overshoot requirements

[2] *Step response time* typically ranges between 1 – 30 seconds

[3] Damping ratio will depend on grid strength

IEEE 2800 requires primary frequency response within the limits of minimum and available active power

- The IBR plant shall have the capability to provide primary frequency response in both the continuous and mandatory operation regions
    - Response to under-frequency conditions is limited by available active power
    - Response to over-frequency conditions is limited by minimum active power capability
- The IBR plant PFR controller shall have the following default values and ranges of possible settings
    - Default values for deadband and droop match what is currently required in the MISO Generator Interconnection Agreement[1]

Parameter	**Units**	**Default Value**	**Ranges of available settings**	
			Minimum	Maximum
Underfrequency deadband (db_{UF})	Hz	0.06% x f_{nom}	0.025% x f_{nom}	1.6% x f_{nom}
Overfrequency deadband (db_{OF})	Hz	0.06% x f_{nom}	0.025% x f_{nom}	1.6% x f_{nom}
Underfrequency droop (k_{UF})		5%	2%	5%
Overfrequency droop (k_{OF})		5%	2%	5%

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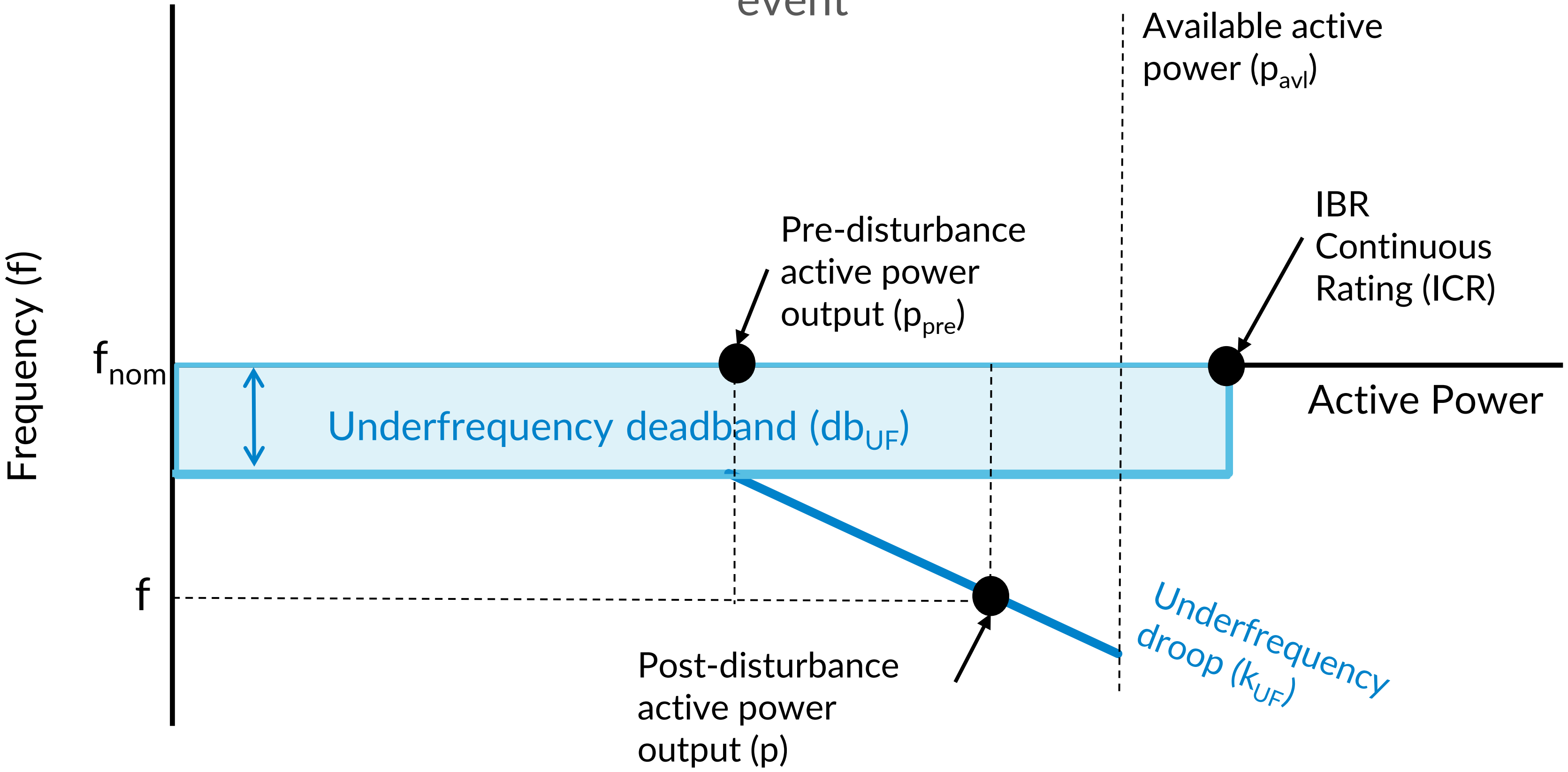
[1] With an f_{nom} value of 60 Hz, the default underfrequency and overfrequency deadbands show in the table are 0.036 Hz

PFR - Underfrequency Event Example

- Calculate the desired active power output with PFR response following the provided equation
- Active power output will be the desired active power output with PFR response, unless available active power is limiting

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

Primary Frequency Response Characteristics - underfrequency event

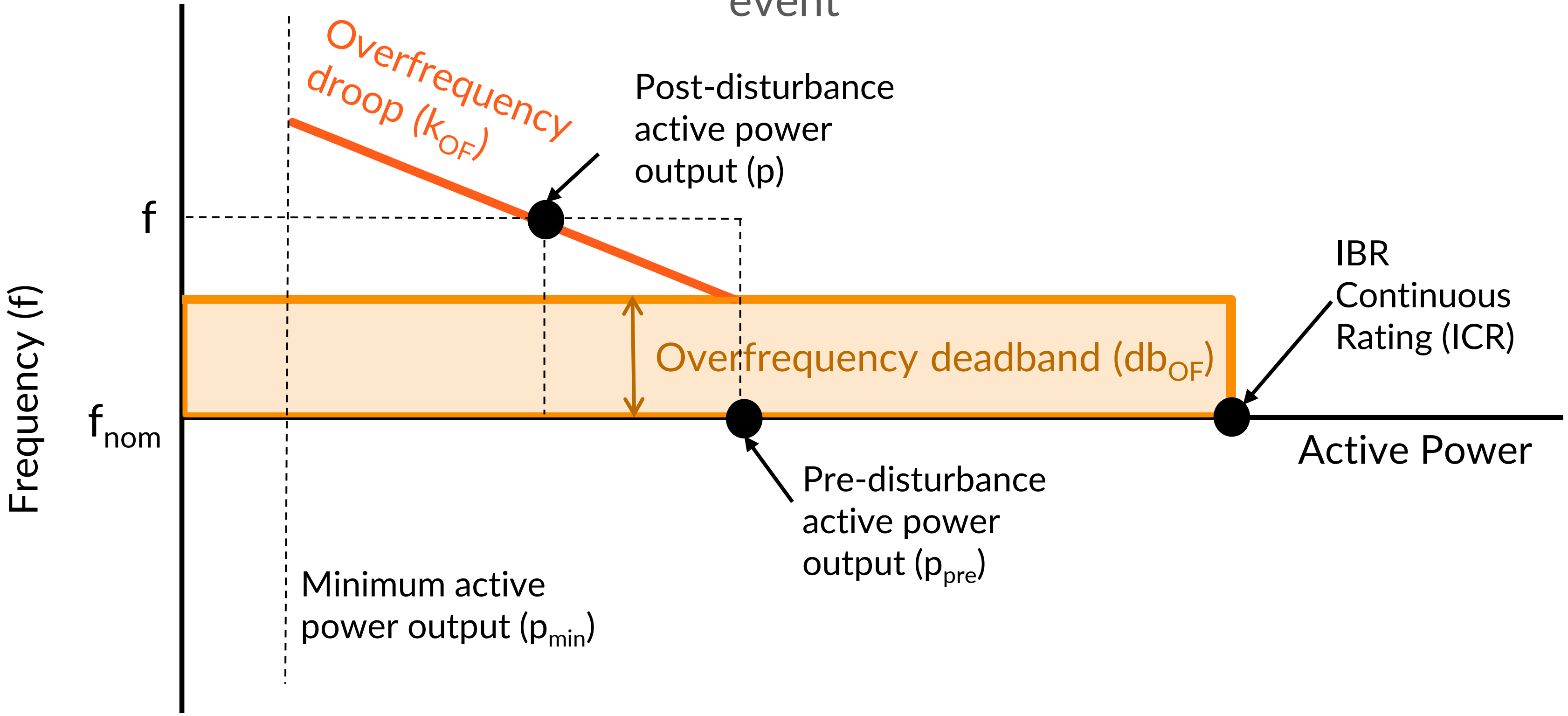


PFR Overfrequency Event Example

- Calculate the desired active power output with PFR response following the provided equation
- Active power output will be the desired active power output with PFR response, unless minimum active power is limiting

$$p = \max\left\{p_{\min}, p_{\text{pre}} + p_{\text{PFR}}\right\} = \max\left\{p_{\min}, p_{\text{pre}} + \min\left(0, \frac{f_{\text{nom}} - f + db_{\text{OF}}}{f_{\text{nom}} \times k_{\text{OF}}}\right)\right\}$$

Primary Frequency Response Characteristics - overfrequency event



Dynamic performance capabilities are defined for primary frequency response

- IBR plant shall sustain PFR for as long as the primary energy source is available
- Dynamic response for a step change in applicable frequency shall adhere to the parameters in the table below
- IBR plant will not be required to change its active power output at a rate greater than its ramping capability
- Response shall be stable and positively damped with a ratio of 0.3 or higher
  - A damped response takes priority over the rise and settling time parameters

Parameter	Units	Default Value	Ranges of available settings	
			Minimum	Maximum
Reaction time[1]	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 of: 2.5% of change or 0.5% of ICR	1	5

[1] Reaction time starts when the applicable frequency deviates outside of the PFR deadband

IEEE 2800 also contains clarifications for the utilization of PFR in operations

- If the IBR plant is in curtailed operation, response to under-frequency disturbances is required up to the IBR plant's available active power
- Total active power output may be allowed to temporarily exceed the ICR of the IBR plant up to its IBR short-term rating (ISR)
- IBR plant shall return to normal operation when the frequency returns within the PFR deadbands, at that point the PFR magnitude will inherently become zero
- For energy storage systems, the dynamic performance during PFR when changing from exporting to importing active power (and vice versa) shall not prevent the IBR plant from meeting the dynamic performance requirements

ICR: IBR continuous rating

Consecutive voltage deviation ride-through is required, but exceptions are provided for high numbers of voltage deviations

- IBR plant shall ride through multiple voltage excursions outside of the continuous operation regions except:
  - May trip for the cases shown in the tables below
  - May trip if the cumulative duration of voltage deviations exceeds the voltage ride-through durations
  - May trip for any voltage deviation outside of continuous operation regions that follows the end of a previous deviation by less than 20 cycles of system fundamental frequency
  - Individual WTG units may trip to self-protect for consecutive voltage deviations that result in mechanical resonances that exceed equipment limits

Voltage Deviation Definition

- Begins when the voltage leaves the continuous operation region
- End when the rms magnitude of the voltage is within the continuous operation region

Time Period	May Trip for this number of Voltage Deviations
10s	5+
120s	7+
30min (1,800s)	11+

Time Period	May Trip for this number of Voltage Deviations Below 50% of Nominal Voltage
10s	3+
120s	4+