INTERCONNECTION INNOVATION e-XCHANGE
U.S. DEPARTMENT OF ENERGY

i2X Forum for the Implementation of Reliability Standards for Transmission (FIRST) Season 1 Full Summary Notes

Interconnection Innovation e-Xchange (i2X)

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Disclaimers

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Executive Summary

The DOE i2X Forum for the Implementation of Reliability Standards for Transmission (FIRST) established an open industry forum to facilitate discussion, brainstorming, and information sharing regarding the supports the adoption of new standards and test procedures for inverter-based resources (IBRs)[1] connecting to the transmission and subtransmission electric system. Building on the 2024 *Transmission Interconnection Roadmap*, i2X FIRST convenes industry stakeholders to share practices on standard implementation of IEEE 2800-2022 and the upcoming IEEE P2800.2 recommended practices through webinars and workshops. Topics include IBR ride-through, modeling, monitoring, frequency and voltage support, and evolving technologies like grid forming inverters. Discussions also align with FERC directive and ongoing NERC standards revisions.

Season 1 of the i2X FIRST initiative provided a foundational exploration of IEEE 2800-2022, its core requirements, and early industry experiences with implementation. It also addressed ongoing efforts under IEEE P2800.2 to develop robust test and verification procedures to support IBR performance conformity assessments. The forum included broad participation from ***over 1,225*** unique participants across a diverse set of stakeholders including IBR developers, utilities, system operators, original equipment manufacturers (OEMs), and consultants (see Figure 1).

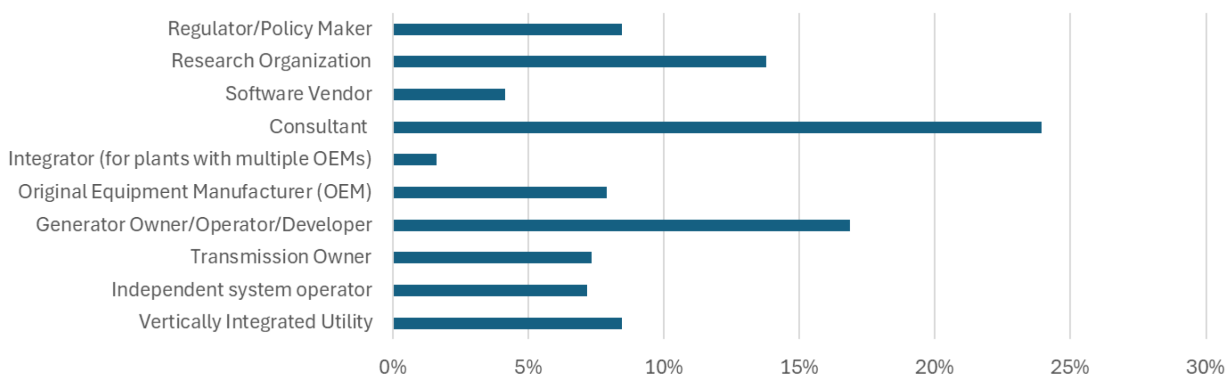


Figure 1. Breakdown of Attendee Type at All Season 1 i2X FIRST Meetings

Recap of Season 1 Meetings

All meetings were recorded and can be accessed on the ESIG i2x website. Key topics from each meeting include:

- **May 2024 – Kickoff (*recording*, *slides*):** Introduced the DOE i2X FIRST initiative, IEEE 2800-2022 requirements, IEEE P2800.2 test and verification recommended practices, and related NERC and EPRI efforts.

[1] Such as solar photovoltaic (PV), wind, and battery energy storage systems (BESS), and hybrid plants comprised of these technologies.

- **June 2024 – IBR Ride-Through Capability and Performance (*recording*, *slides*):** Reviewed IEEE 2800-2022 Clause 7 ride-through capability and performance requirements, NERC PRC-029 developments, and MISO implementation.
- **July 2024 – IBR Ride-Through Requirements and OEM Readiness – Part I (*recording*, *slides*):** Covered OEM readiness to meet IEEE 2800-2022, model validation needs, and potential challenges with meeting certain voltage ride-through characteristics.
- **August 2024 – IBR Ride-Through Requirements and OEM Readiness – Part II (*recording*, *slides*):** Continued OEM readiness discussions, highlighted need for requirements harmonization, and reviewed PRC-029 and ERCOT ride-through approaches.
- **September 2024 – Measurement Data for Performance Monitoring and Model Validation (*recording*, *slides*):** Focused on IEEE 2800-2022 Clause 11 data requirements, alignment with PRC-028, and use of high-resolution monitoring data.
- **October 2024 – IEEE P2800.2 IBR Plant Conformity Assessment (*event page*, *slides*):** Addressed IEEE P2800.2 conformity assessments including modeling, commissioning, and as-built evaluations.
- **November 2024 – Active Power–Frequency Response Requirements (*recording*, *slides*):** Reviewed IEEE 2800-2022 frequency response requirements, PFR and FFR capabilities, and operational considerations for technologies such as wind.
- **December 2024 – Reactive Power–Voltage Control Requirements (*recording*, *slides*):** Covered IEEE 2800-2022 Clause 5 requirements, MISO interconnection improvements, and BPA operational experience.
- **February 2025 – Protection and Power Quality Requirements (*recording*, *slides*):** Focused on IEEE 2800-2022 Clause 8 requirements and practical approaches for monitoring and mitigation.
- **March 2025 – IEEE P2800.2 Post-Commissioning (*Session 1 recording and slides, Session 2 recording and slides*):** Addressed post-commissioning validation, monitoring, testing, and automation tools to assess model and plant performance.
- **April 2025 – Reactive Power-Voltage Control Requirements (Continued) (*recording*, *slides*):** Focused on reactive power and voltage support at zero active power output, including testing results, reporting requirements, and design considerations.

Sign up for Season 2 i2X FIRST meetings here.

Season 1 Key Themes and Recurring Messages

In the Season 1 meetings, some key themes and recurring messages emerged:

- **Harmonizing IBR Requirements:** Harmonizing interconnection standards and requirements, particularly leveraging IEEE 2800-2022 and the forthcoming IEEE P2800.2, and enhancing IBR plant conformity assessments are vital for streamlining the interconnection process while supporting a reliable and resilient grid. Harmonization at the highest possible level results in greater consistency across entities, effectively raising the technical minimum bar for IBR capabilities and performance equitably. NERC or FERC adoption of IEEE 2800-2022 could lead to uniformity and consistency across entities and regions.

- **IEEE 2800-2022 Adoption and Implementation:** Adopting and uniformly implementing IEEE 2800-2022 help codify important design, capability, and operational performance characteristics for newly connecting IBRs. Uniform adoption helps renewables developers have a clear understanding of expectations and obligations rather than disparate and disjointed requirements. Lack of uniformity can lead to confusion, lack of technical details, reliability risks, and slowdown of the interconnection process.

- **Coordination with Regulatory Requirements:** Ensuring that any implementation is coordinated with changes occurring at the FERC and NERC levels is critical to avoid overlaps, redundancy, and most importantly conflicting requirements. Industry participation in NERC standards development efforts is essential to align new NERC Reliability Standards with IEEE 2800-2022 and vice versa, and to avoid duplication of effort.

- **Cross-Sector Collaboration:** OEMs are advancing IBR ride-through capabilities and preparing for IEEE 2800-2022 implementation. Guidance is needed from transmission providers on configuration and setting parameters. Increased education, engagement, and collaboration across the electricity ecosystem is needed by OEMs, service providers, systems integrators, IBR plant developers and owners, and transmission entities to enable a streamlined process.

- **Modeling and Performance Conformity Assessments:** Accurate IBR unit and IBR plant modeling is a foundational aspect of IEEE 2800-2022 performance conformity assessments. This includes IBR unit model validation based on type testing, IBR plant modeling including electromagnetic transient (EMT) modeling, verification of model structures and parameter values, model benchmarking (comparison of model performance between different simulation tools or modeling domains), IBR plant design and as-built/as-left evaluations, commissioning tests, post-commissioning plant-level model validation, and other aspects.

- **Industry Education, Outreach, and Engagement:** Continued education, outreach, and industry engagement are critical to ensuring all stakeholders are informed, educated, and ready to take appropriate actions to improve interconnection requirements for IBRs, including adopting IEEE 2800-2022, and streamline the interconnection process and post-commissioning monitoring.
- **Avoiding Retroactivity; The Need for Action:** Applying advanced standards and requirements to the existing fleet retroactively has proven to be difficult, costly, and burdensome on industry overall. Some aspects of improved capability and performance can be achieved with software-based updates to maximize IBR performance with minimal cost, and these are encouraged to be pursued. However, mandatory hardware-based upgrades have notable risks for existing assets that should be carefully considered. Thus, adopting and enhancing standards on a regular basis to keep pace with technological advancements, paired with proactive requirements for emerging capabilities prior to their actual utilization (as long as these are considered cost-effective by industry stakeholders) could help minimize the need for potential future retroactivity of requirements.
- **Continuous Improvement and Evolving Requirements**: Similarly, the IBR standards are likely to evolve over time as technology advances and as industry experience with adoption grows. However, this should not curb or preclude industry from implementing these new requirements to ready and fully utilize modern IBR technological capabilities, and to provide essential reliability services such as disturbance ride-through, voltage control, frequency response, and to benefit grid stability.

Stakeholder Perspectives

The i2x FIRST initiative identified areas of both strong alignment and some divergence among stakeholder groups involved in IBR integration. Alignment was strongest around high-level objectives such as grid reliability and the need for interconnection process efficiencies. However, stakeholder perspectives diverged in several areas including data access and sharing, cost burdens, enforceability and compliance obligations, and concerns related to intellectual property. Table ES1 summarizes these perspectives across several central issues discussed during the meetings.

Table ES1. Summary of Perspectives across Stakeholders at the i2X FIRST Meetings

Issue Area	Transmission Providers, System Operators, & Utilities	Developers and Independent Power Producers	OEMs and Vendors	Regulators and Policymakers
Capability vs. Utilization	Hesitant to require capabilities proactively; lack understanding of how these could mitigate potential reliability risks	Tend to focus on lowest cost but also understand that readying plants with capabilities can mitigate risks of retrofits later on	Build equipment for the global market, with broad range of functional capabilities	Tend to limit requirements for capability to functions that are immediately utilized at commercial operation date
Cost/Benefit Tradeoffs[2]	Value reliability over speed; seek cost recovery for tool upgrades	Want lowest cost interconnection path; concern over study delays	Value IP and flexibility in requirements	Balance system reliability with cost-effectiveness for ratepayers and projects
Data Transparency and Coordination	Want structured data from developers and clear OEM model guidance	Desire standardized processes and predictability across regions	Prefer to limit data exposure while meeting minimum compliance	Interested in fairness and enforceability of transparency during interconnection
Compliance Burden vs. Technical Need	Desire clear guidance on when advanced studies (e.g., EMT) are required	Prefer light-touch compliance and risk-based study thresholds	Need clarity on compliance obligations without sacrificing IP	Encourage risk-based standards,[3] but require stakeholder consensus
Modeling Aspects	Want consistent, validated EMT and RMS models; emphasize reliability	Seek clearer expectations; wary of redundant or overly complex requirements	Concerned about protecting proprietary model data and slowdown	Support standardization for transparency and fairness
Model Ownership and Sharing	Need model transparency to perform studies	Prefer streamlined data provision; wary of delays	Resist full model sharing due to IP concerns	May require policy support to enable sharing of key information across stakeholders
Tool/Study Process Improvements	Need better, more automated study tools and more skilled workforce	Want faster queue movement and more efficient studies	Open to tool collaboration if standards are respected	Interested in reforms that reduce delays and enable clean energy goals

[2] Costs were not always discussed explicitly; however, several tradeoffs were apparent in stakeholder positions.
[3] Rather than address all known risk to grid reliability, regulators are often focused on a "risk-based" or "risk-prioritized" set of standards that mitigate the greatest known risks to the grid. Thus, costs are managed while high risk areas are mitigated with mandatory standards.

Table 1 illustrates notable alignment in the following areas:

- The importance and criticality of ensuring reliable operation of the bulk power system, eliminating the risk of potential latent risks to the grid.
- The importance of accurate and effective data sharing and data transparency and the challenges and risks posed by inconsistent or incomplete data provided to stakeholders.
- The need for more accurate and usable models throughout the interconnection and into commercial operation for IBR plants, and the need for clear and effective standards around the use of these models.
- The need for further interconnection process reform, particularly regarding establishing minimum technical IBR plant capability and performance requirements and the process by which interconnecting IBR plants are tested against those established requirements.

However, as was discussed throughout the year, some areas of misalignment emerged:

- System operators and utilities stressed the need for accurate, detailed modeling (especially EMT models) for IBR performance conformity tests, asserting compliance should fall on the interconnection customer. OEMs and developers pointed to inconsistent requirements and lack of standardized practices as key challenges.
- Developers and OEMs raised concerns about the rising complexity and cost of meeting modeling and testing expectations. Utilities and regulators argued that poor modeling poses serious reliability risks, justifying stricter requirements.
- Stakeholders differed on how to conduct performance verification; some favored flexible, region-specific approaches, while others supported uniform national standards for clarity and consistency.
- Differing perspectives emerged over roles in model validation. Utilities want assurance that models reflect actual plant behavior, while OEMs noted limited control over site-specific conditions post-deployment. Generator owners, operators, and developers acknowledge their emerging role in bridging these tensions by increasing technical capabilities in IBR plant design and evaluation.
- Some stakeholders questioned who should bear the cost of advanced modeling, testing, and compliance. Developers felt costs should be allocated differently, while utilities emphasized their necessity for reliable interconnection.
- Views on automation diverged, with some seeing it as key to reducing manual burden and standardizing practices, while others warned against overreliance without human oversight given current variability in system designs and model quality.

These areas of alignment and misalignment illustrate that stakeholders agree on the "what" yet diverge on the "how" and "who" in terms of implementing IEEE 2800-2022 requirements and IEEE P2800.2 practices.

Areas of IEEE 2800-2022 Perceived as Least and Most Challenging to Implement

Overall, stakeholders identified areas that are relatively straightforward regarding IEEE 2800-2022 adoption. For example:

- Many of the IEEE 2800-2022 clauses can be effectively implemented with a hybrid integration approach wherein the authority governing interconnection requirements (AGIR) incorporates the standard's requirements by detailed reference to specific clauses and sub-clauses and may specify additional clarifying details that are specific for their jurisdiction. (Refer to an ESIG brief published on this topic in October 2024.) Utilities have begun using this approach effectively. Examples include specifying nominal voltage, voltage schedule, control reaction and rise times, etc.
- Building the IEEE 2800-2022 requirements into existing interconnection and modeling requirements, interconnection processes, market manuals or operating guides, contract language, etc.
- Continued attention and information sharing across stakeholders will help improve alignment and streamline processes without adding too much compliance burden; stakeholder education and continuous improvement are important factors in this area.

Some of the more challenging areas of IEEE 2800-2022 adoption appear to include:

- Some requirements in IEEE 2800-2022 for IBR performance during abnormal voltage conditions, particularly those for transient overvoltage ride-through and consecutive voltage ride-through, were either considered unclear or very difficult to meet or verify for some stakeholders.
- Some of the more specific requirements in IEEE 2800-2022 like response time performance for voltage control and for reactive current injection during faults may be difficult for OEMs to meet across *all* operating conditions, raising concerns and a need to focus on addressing these issues in IEEE P2800.2 practices.
- Handling the more sophisticated and thorough set of requirements and testing and verification procedures used to demonstrate compliance with the rules, particularly with respect to existing resources, tools, and timelines.

- Aligning modeling requirements and the existing interconnection process with these new IBR requirements and test and verification procedures.
- Improving industry understanding and expertise with detailed IBR dynamic models such as EMT models which are critical for IEEE 2800-2022 performance conformity assessments.
- Regulatory fragmentation and handling of legacy IBRs and any risks posed by performance deficiencies with those resources.

Suggestions for Future Standards Development Efforts

Future standards development and improvement are needed to continue enabling a more efficient interconnection process while supporting reliable operation of the interconnected bulk power system. A few common themes emerged:

- There are some areas of IEEE 2800-2022 technical requirements that may be difficult to comply with under all operating conditions. These are captured in the meeting synopses and demonstrate the depth of industry's expertise in this area. Future editions of IEEE 2800 should strive to address these concerns.
- Incorporating GFM capabilities and performance characteristics in the standard or potential future sub-standards, and clarifying how the standard's existing IBR requirements should be adapted or exempted to GFM resources when their characteristics differ yet improve and support grid reliability.
- Standardized, accurate, and user-friendly modeling of IBRs that can streamline interconnection processing and studies; improved IBR performance conformity assessment practices that align with IEEE 2800-2022 yet can be incorporated into the existing interconnection process mandated by FERC Order No. 2023; IBR unit and plant model verification and validation (qualitative and quantitative), and model benchmarking pass/fail criteria.
- Handling system-specific differences while seeking harmonization to the greatest extent possible.

These suggestions reflect a desire for predictability, transparency, and consistency across jurisdictions while handling any unique characteristics of specific systems. They also emphasize the need for continuous improvements to keep pace with technological advancements.

Other Emerging Industry Needs

Beyond IEEE 2800-2022 standards adoption, i2X FIRST uncovered several broader industry needs including:

- **Tool Improvement and Workforce Development:** Utility and system operator stakeholders raised concerns about the lack of tools and automations to streamline IEEE 2800-2022 performance conformity assessments during the interconnection process, which could help offload resource needs and streamline the process.
- **Modeling Enhancements across all Domains:** Stakeholders regularly highlighted that IBR modeling is a notable challenge, particularly as user-defined models are becoming increasingly complex yet the standard library models are not keeping pace with technological advancement and may not reflect newer IBR technologies. The diverging capabilities of these models create a dilemma for utilities trying to create new performance and for IBR developers attempting to meet those modeling requirements with available IBR models. Furthermore, IBR project development milestones and times need to align with model accuracy requirements. It is nearly inevitable that projects go through multiple model revisions during the interconnection process as design decisions solidify; however, this likely is not happening effectively today. While standard library models with site-specific configuration of control parameter values may suffice in early stages of the interconnection process, vendor-specific user-defined models configured and tuned to mitigate site-specific grid stability issues could be needed in later stages of the interconnection process.
- **Grid Forming Capabilities:** While grid forming was not a direct focus of the meetings, it was a topic that regularly came up in various discussions related to IBR requirements, the evolving grid service needs, and stabilizing high IBR scenarios. Guidance on use cases, requirements, integration methods, and performance expectations remains a key area of focus.

What's Next

Industry stakeholders are encouraged to apply the practical insights gained through this diverse, collaborative forum to support effective implementation of IEEE 2800-2022 and strengthen IBR testing and verification practices throughout the resource lifecycle. Looking ahead, active industry engagement in the continued development of IEEE 2800 and P2800.2 standards—as well as related NERC and FERC initiatives—is critical to ensuring harmonized, workable approaches to IBR interconnection across jurisdictions. A consistent theme across discussions was the need for clearer, more specific guidance on IBR modeling, verification, and validation, which are all essential for meaningful performance conformity testing. There is strong momentum to establish common frameworks that balance technical rigor with practical feasibility and protection of proprietary information.

To that end, stakeholders should participate in Season 2 of the i2X virtual meeting series, running monthly from May 2025 to March 2026. These sessions will delve into key technical and procedural topics—including NERC standards updates, IBR plant design evaluations, modeling best practices, commissioning guidance, and challenges related to IEEE 2800-2022 implementation. Special focus will also be given to evolving requirements for grid-forming inverters and managing change during the interconnection process. Active participation in these discussions will help stakeholders stay ahead of regulatory and technical developments, influence emerging best practices, and contribute meaningfully to the reliable integration of clean energy technologies.

List of Technical Acronyms

AC	Alternating Current
ACE	Area Control Error
AVR	Automatic Voltage Regulator
BOP	Balance of Plant
BPS	Bulk Power System
DC	Direct Current
DER	Distributed Energy Resource
DFR	Digital Fault Recorder
DFT	Discrete Fourier Transform
EMT	Electromagnetic Transient
FFR	Fast Frequency Response
FRT	Frequency Ride-Through
GFL	Grid Following
GFM	Grid Forming
GIA	Generator Interconnection Agreement
GIP	Generator Interconnection Procedure
GO	Generator Owner
GOP	Generator Operator
HIL	Hardware in the Loop
IBR	Inverter-Based Resource
IFRO	Interconnection Frequency Response Obligation
IRR	Intermittent Renewable Resource
ISO	Independent System Operator
LSL	Low Sustained Limit
OEM	Original Equipment Manufacturer
RMS	Root Mean Square
RPA	Reference Point of Applicability
RTO	Regional Transmission Organization
PFR	Primary Frequency Response
PMU	Phasor Measurement Unit
POC	Point of Connection
POI	Point of Interconnection
POM	Point of Measurement
PPC	Power Plant Controller
RFI	Request for Information
ROCOF	Rate of Change of Frequency
RPA	Reference Power of Applicability
RVC	Rapid Voltage Change
SCADA	Supervisory Control and Data Acquisition
SCR	Short Circuit Ratio
SIL	Software in the Loop
SSR	Subsynchronous Resonance
TS	Transmission System
UFLS	Underfrequency Load Shedding
VRT	Voltage Ride-Through
VSC	Voltage Source Converter
WSCR	Weighted Short Circuit Ratio
WTG	Wind Turbine Generator

* Generally not including names of organizations, institutions, or initiatives.

May 28, 2024 Virtual Meeting

Background of DOE i2X and Kickoff of the DOE i2X FIRST Initiative (~240 simultaneous attendees)

Figure 1 shows the makeup of the meeting attendees by industry sector:

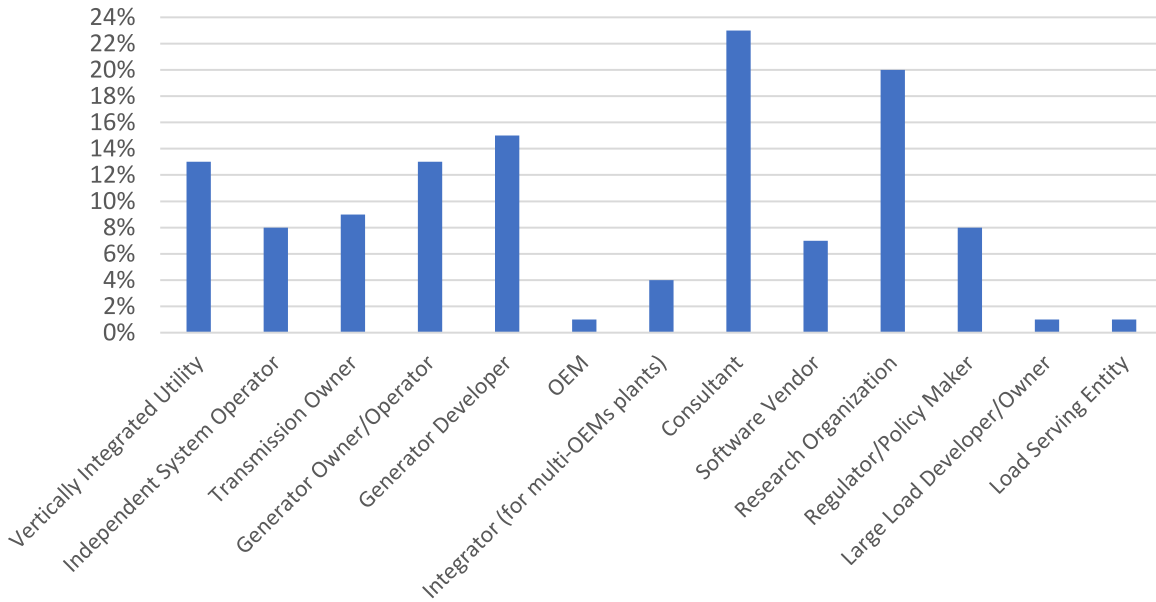


Figure 1: Meeting attendees by industry sector

This inaugural meeting introduced the DOE i2X FIRST initiative and plans for a series of virtual meetings to convene industry stakeholders and explore pathways to enable practical and harmonized implementation of interconnection standards, particularly the IEEE 2800-2022 standard for IBRs connecting to the transmission and sub-transmission networks. Presentations included:

- **Cynthia Bothwell, DOE Wind Energy Technologies Office (WETO):** Cynthia presented the recently published DOE i2X Roadmap[4] that is seeking to enable a simpler, faster, and fairer interconnection process for clean energy resources while maintaining reliability, resilience, and security (see Figure 2). i2X involves four pillars – stakeholder engagement, data and analytics, technical assistance, and strategic road mapping. The transmission roadmap success targets are focused on reducing the interconnection process time, lowering cost uncertainty, increasing project completion rates, and maintaining system reliability. The forum is focused on education and building community alignment, focusing on practical implementation strategies of interconnection requirements, and other streamlining interconnection practices. Focus areas include upskilling the existing

[4] https://www.energy.gov/sites/default/files/2024-04/i2X%20Transmission%20Interconnection%20Roadmap.pdf

workforce; developing tools, technologies, and techniques; enhancing interconnection study practices; developing IBR plant conformity assessments; and enabling emerging technologies. DOE also recently released the Solar and Wind Interconnection for Future Transmission (SWIFTR) Funding Opportunity Announcement (FOA) focused on 1) improved efficiency of electromagnetic transient (EMT) simulations for interconnection studies of IBRs, and 2) dynamic stability-enhanced network assessment tools.

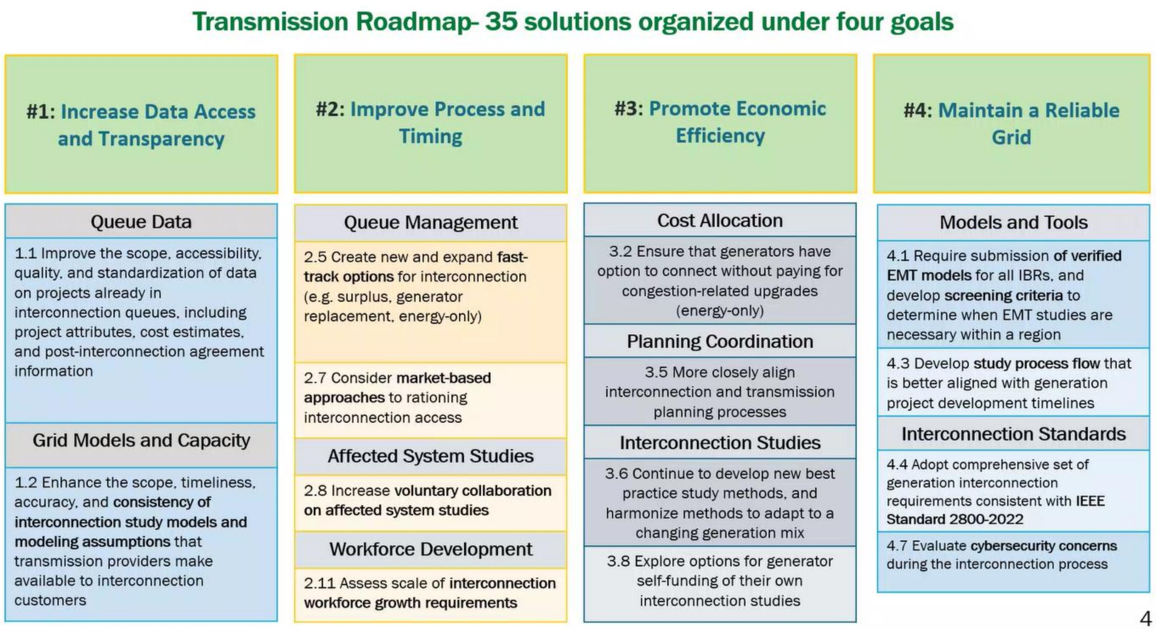
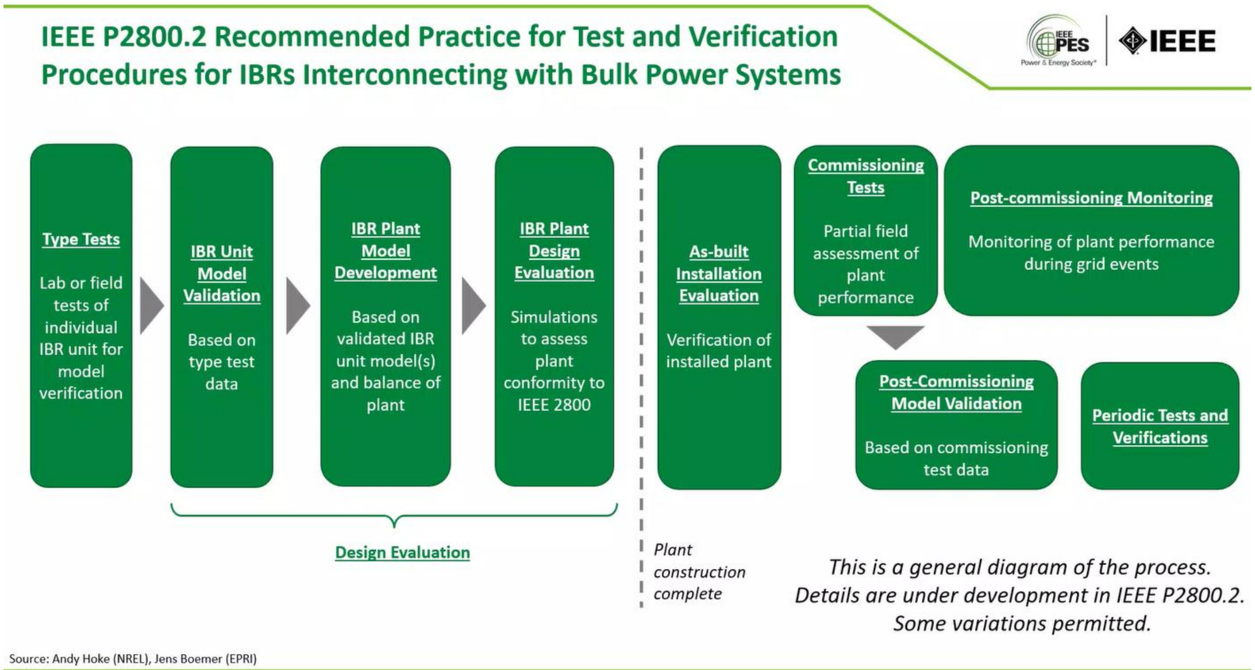


Figure 2: Pillars of the DOE i2X Roadmap

- **Julia Matevosyan, Energy Systems Integration Group (ESIG):** Julia discussed the i2X FIRST initiative in more detail as well as provided a high-level overview of IEEE 2800-2022 and its requirements pertaining to large solar PV, wind, BESS, and voltage source converter (VSC)-connected IBRs such as offshore wind. Julia highlighted that the IEEE 2800-2022 standard is not enforceable until it is adopted and implemented by authorities governing interconnection requirements; however there are a number of regions that already completed or are working on IEEE 2800-2022 adoption including MISO, ERCOT, SPP, NYISO, Southern Company, and others. The presentation also described the IEEE P2800.2 test and verification recommended practices that are currently under development that will revolutionize how IBR design evaluation, commissioning, and testing is carried out to help enable a more reliable and resilient IBR-based resource base moving forward (see Figure 3). Lastly, Julia described how policies and statutes are intertwined with the regulatory framework, interact with State and federal (i.e., Federal Energy Regulatory Commission (FERC)) rulemaking, and must be coordinated with regulations set forth by the North American Electric Reliability Corporation (NERC). These layers of complexity may be barriers or deterrents to quick action by individual system operators and utilities.



** Note: The Type Tests box should say "model validation" rather than "model verification"*

Figure 3: Vision for Implementation of IEEE P2800.2

- **Alex Shattuck, NERC:** Alex presented on NERC's IBR risk mitigation strategy (see Figure 4) and discussed past NERC disturbance reports and other guidance materials. FERC Order No. 901 has directed NERC to make sweeping changes to the NERC reliability standards to address significant gaps in the existing standards. Furthermore, FERC ordered NERC to modify their registration requirements to include smaller IBRs connected to the bulk power system (BPS) that have a material impact on BPS reliability. Alex described that much of NERC's activities are stakeholder-based and offer excellent opportunities for all types of stakeholders to get engaged and influence the impeding regulations being put forth. The presentation emphasized that industry is not taking *voluntary* steps to adequately address reliability risks and therefore the regulator entities are now stepping in more directly to invoke change.

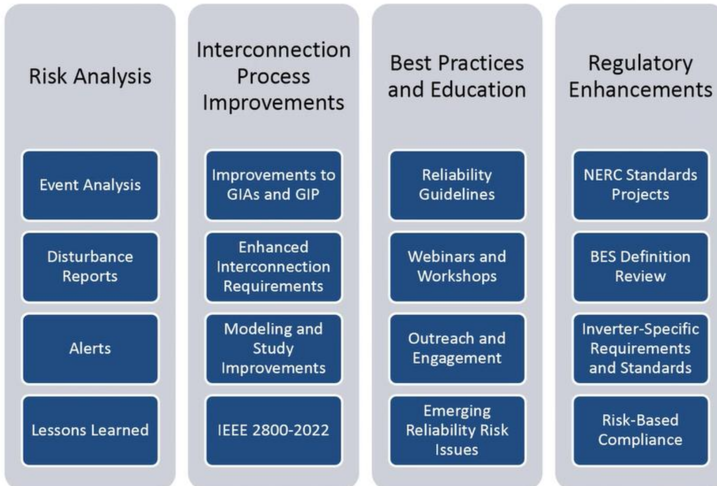


Figure 4: NERC IBR Risk Mitigation Strategy

- **Jens Boemer, EPRI:** Jens discussed IEEE 2800-2022 as a harmonized set of technical minimum interconnection *capability and performance* requirements that "raise the bar" to make these resources more reliable and resilient yet leave sufficient space for specific regions or entities to establish requirements beyond those in the standard. The scope of requirements was introduced in more detail (see Figure 5); each category of requirements will be explored in more detail in subsequent i2X FIRST meetings. Jens highlighted that there are no notable concerns from IBR original equipment manufacturers (OEMs) to meet these new requirements for future resources; however, some degree of flexibility in terms of timing will likely be needed for conformance testing. Furthermore, existing resources likely do have limitations where they cannot meet the new requirements and would need at least some exemptions if these requirements were imposed on them. Most transmission providers implementing IEEE 2800-2022 are not seeking retroactive applicability to existing resources for this reason.

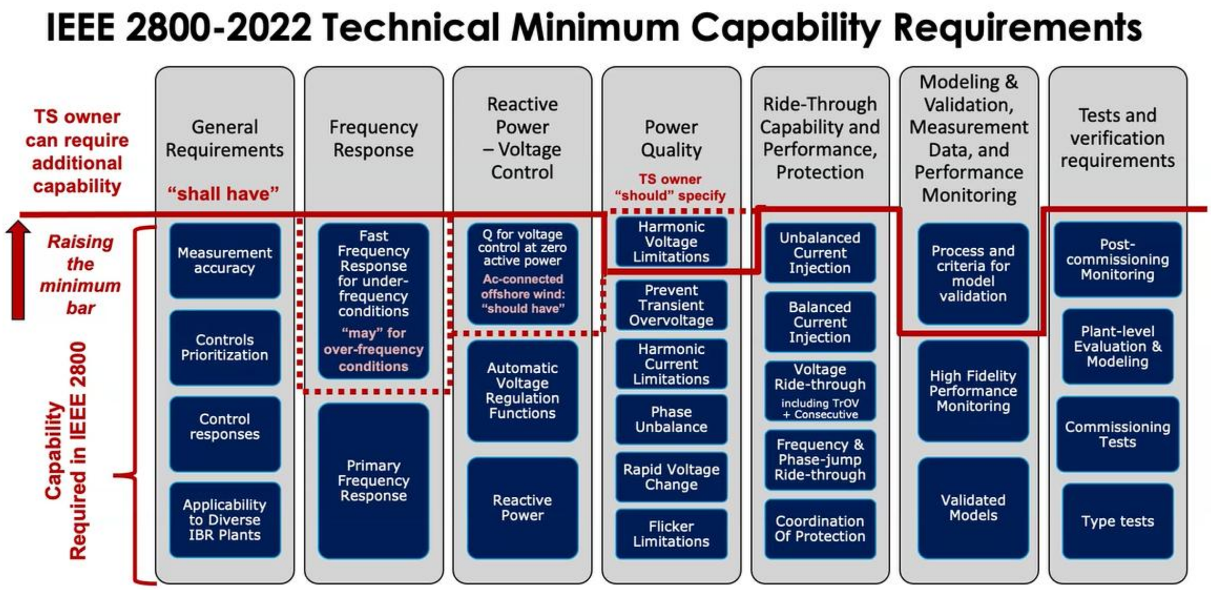


Figure 5: IEEE 2800-2022 Technical Minimum Capability Requirements

- **Andy Hoke, National Renewable Energy Laboratory (NREL):** Andy introduced IEEE P2800.2 which is establishing a set of uniform test and verification procedures for demonstrating IBR plant conformity with IEEE 2800-2022 requirements. IEEE P2800.2 is still in development and will be published as a set of recommended practices that can be integrated into existing industry practices once published. Unlike IEEE 1547 where type testing in a laboratory is the primary focus of proving conformity, IEEE 2800 focuses on plant-level conformity which requires unit-level test and verification as well as overall IBR plant design evaluations, modeling and studies, plant commissioning practices, and post-commissioning performance monitoring and validation throughout the lifecycle of an IBR plant. Andy recognized that adoption and implementation of IEEE 2800.2 once published will not be an easy endeavor but will continue moving industry toward more standardized and reliable practices. IEEE P200.2 is intended to be published some time in 2025; however, this should not preclude industry from starting their adoption and implementation of IEEE 2800-2022 requirements in the interim timeframe.

Presentation recording and slides are available to download here.

Interactive Group Discussion

The following topics were briefly discussed during the group discussion (including responses posted on Slido):

- **Why has industry taken such a long time to improve interconnection requirements:**
    - **Training Needs:** Broad lack of knowledge in the field of IBRs and advanced inverter technologies, particularly given the ongoing technological evolutions occurring over the past decade.

  - **Workforce Resourcing:** Lack of skilled and experienced staff; significant demands and workload on existing workforce with a large volume of generator interconnection requests; limited ability to focus on emerging issues and the need for sweeping changes to requirements that would impact timelines in the near-term.
  - **OEM Engagement:** Need more engagement from the OEMs (both inverter and power plant controller (PPC)) and systems integrators.
  - **Lack of Proactive Action by Industry Stakeholders:** No incentives for project developers or OEMs to proactively seek enhancements to requirements due to fear of non-compliance or delayed interconnection requests; prioritization issues with system operators and utilities to make this a priority given other risks and challenges; possible prioritization of near-term needs versus long-term needs.
  - **Regulatory Lag:** Slow action by regulatory entities (FERC and NERC) to make broad-reaching changes to regulations that would impact these types of decisions.

- **Can interconnection requirements for transmission/sub-transmission connected IBRs be harmonized across North America?**
  - There is a clear and definitive need to push harmonization efforts across North America to the highest level possible (i.e., Federal level); however, there is also need to retain some degree of flexibility for local system-specific needs.
  - There have been challenges with getting alignment from FERC and NERC in this area; both organizations have stated that they do not intend to adopt IEEE 2800-2022 directly. Focus needs to turn towards effective local utility and system operator adoption and implementation practices.
  - Harmonization efforts in Europe took many years but resulted in excellent reliability results; the U.S. can look to learn from this experience and needs a unified effort to drive that forward.
  - There are notable disparities between industry experts that engage in IEEE standards development activities and industry members that support NERC and FERC regulatory activities.

- **Role of regional interconnection requirements (including regional adoption of IEEE 2800-2022) versus NERC Reliability Standards versus FERC Orders**
  - Implementation is nonuniform because both FERC and NERC have encouraged IEEE 2800-2022 but have chosen not to explicitly adopt it in regulation; ongoing industry efforts should continue to recommend and urge a more uniform adoption approach at the NERC and/or FERC level.
  - Lack of broad knowledge and understanding of the hierarchy and layers within the U.S. electricity regulatory framework may be creating roadblocks and obstacles here with respect to Federal and State policies and mandates, FERC, NERC, system operators, utilities, renewable project developers, generator owner/operators, etc.

  - Focus needs to turn toward effective, efficient, and uniform adoption and implementation of the IEEE 2800-2022 standard at the local transmission provider or system operator level.

- **Is improving interconnection requirements sufficient for improving IBR performance in operations?**
  - Did not have time to address this question but will come back to this in the future meetings when discussing each of the requirements in detail.

Key Themes

- Transitioning the power system toward increasing levels of IBRs is an exciting engineering challenge.
- Besides the technical engineering challenges, there are significant knowledge transfer, people, and institutional challenges such as regulations, policies, training, and many other factors.
- Industry efforts need to anticipate future issues proactively and seek to address them early; this requires effective management of issues along the way, transparency and honesty and them, and fostering a collaborative learning environment.
- Technical standards play a major role in this process as they help inform and support the implementation of policy mandates, regulatory rulemaking, and stakeholder education. For that to be successful, alignment between level of the decision making process is essential.
- Technical standards can streamline and expedite the interconnection process of IBRs if developed, adopted, and implemented appropriately and in a timely manner. This can help ensure a reliable and resilient grid and reduce interconnection queue backlog.
- This all requires a significant ***mindset shift*** related to the interconnection process that will necessitate an overhaul of process, practices, and technologies from multiple parties.

June 25, 2024 Virtual Meeting

IBR Ride-Through Capability and Performance (~150 simultaneous attendees)

Figure 5 shows the makeup of the meeting attendees by industry sector:

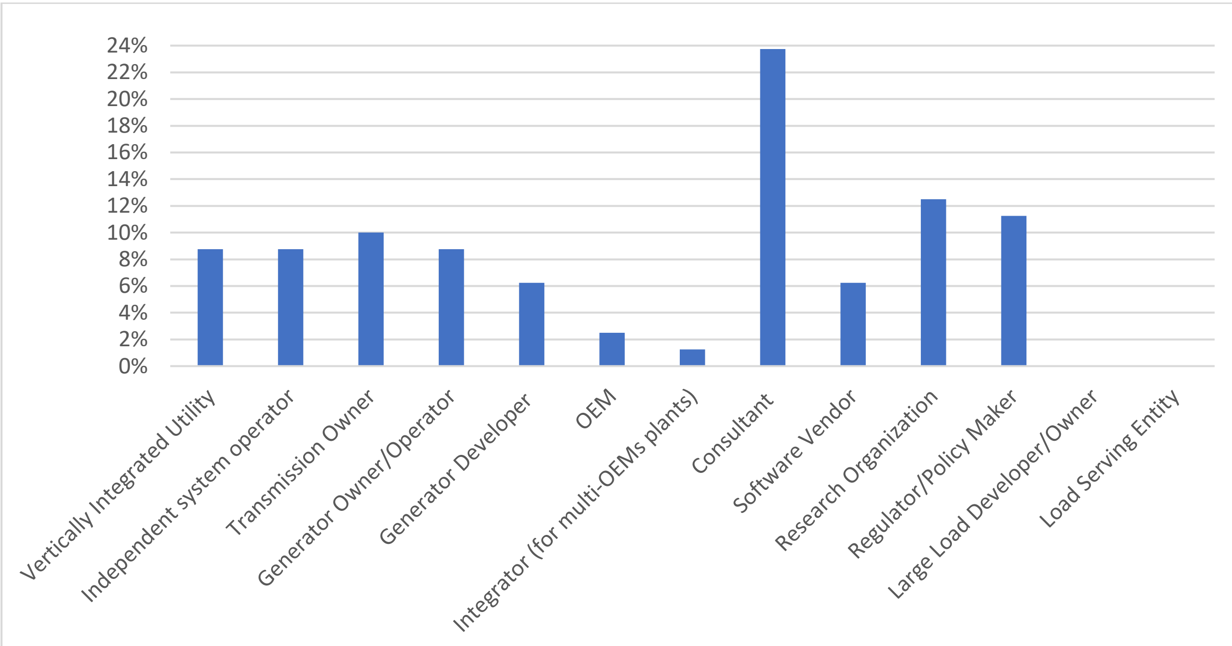


Figure 5: Meeting attendees by industry sector

This was the second meeting of the DOE i2X FIRST initiative, focused on IBR ride-through capability and performance requirements. IEEE 2800-2022 *Clause 7: Response to TS Abnormal Conditions*[5] codifies minimum technical capability and performance requirements for IBR ride-through. NERC is also developing a new Reliability Standard, NERC PRC-029, focused on IBR ride-through performance requirements for registered IBRs. Additionally, some utilities and ISO/RTOs are adopting IEEE 2800-2022 Clause 7 requirements. These topics were the main focus of the meeting. Presentations included:

- **Wes Baker, Silicon Ranch:** Wes provided a detailed review of IEEE 2800-2022[6] Clause 7 requirements. The reference point of applicability (RPA)[7] for Clause 7 is the Point of Measurement (POM) for all requirements except current injection during abnormal voltage requirements where the RPA is the Point of Connection (POC).[8] The standard includes a set of minimum voltage ride-through capability requirements that are separated based on whether the IBR plant includes auxiliary equipment limitations (Table 11,

[5] TS – Transmission System
[6] https://standards.ieee.org/ieee/2800/10453/
[7] The RPA defines the electrical location(s) within the facility where the specific requirements apply.
[8] The POC is either the high or low side of the individual IBR units (i.e., individual inverters).

typically for wind turbine generators (WTGs)) or does not (Table 12, typically for solar and BESS)). The ride-through curves include three modes of operation:

- **Continuous Operation:** continued exchange of active and reactive current between the IBR and transmission system (TS) as prescribed and while the applicable voltage and the applicable frequency is within specified parameters (i.e., normal operation)
- **Mandatory Operation:** continued exchange of active and reactive current between the IBR and the TS as prescribed notwithstanding disturbances of the TS voltage or frequency having magnitude and duration severity within defined limits.
- **Permissive Operation:** mandatory operation or current blocking[9]

Clause 7 also includes current injection during ride-through mode that specifies automatic voltage control, current injection type and magnitude dependent on voltage deviation at the POC, and positive and negative sequence current injections for balanced and unbalanced fault conditions. It also defines restore output after voltage ride-through requirements for how the active power must recover once voltage returns to within the continuous operating range, defining the dynamic response of the facility. Additionally, transient ac overvoltage ride-through requirements are also defined for fast sub-cycle switching events on the TS. The standard similarly includes frequency ride-through and performance requirements for the same ride-through regions including rate-of-change-of-frequency (ROCOF) and voltage phase angle change ride-through requirements. Clause 7 includes performance specifications for voltage and frequency ride-through performance in terms of step response time, settling time, and settling band. It also defines consecutive voltage ride-through conditions where multiple faults may occur within a relatively short time window.

- **Jens Boemer, EPRI:** Jens provided an overview of the draft of NERC PRC-029 standard, currently under development in NERC Standards Project 2020-02 *Modifications to PRC-024 (Generator Ride-Through)*,[10] which was part of the NERC Standards Development Work Plan[11] to address FERC Order No. 901[12] directives that have a filing deadline of November 2024. The standard defines IBR ride-through requirements that include voltage and frequency ride-through. Jens described some areas where there could be misalignment between the draft PRC-029 and published IEEE 2800-2022 requirements and proposed possible remedies to those issues. Examples include definitions of IBRs and ride-through terminology and differences of the voltage and frequency capability curves and performance within those curves. Jens highlighted

[9] Current blocking in IEEE 2800-2022 is intended to capture very fast power electronic behavior and requires that the restart of current injection after returning to Mandatory or Continuous Operation regions occurs within 5 electric cycles. Current blocking is necessary for some inverters to be able to ride through very deep (below 10% retained voltage at RPA) voltage ride through events.
[10] https://www.nerc.com/pa/Stand/Pages/Project_2020-02_Transmission-connected_Resources.aspx
[11] https://www.nerc.com/news/Pages/NERC-Submits-Comprehensive-Work-Plan-Addressing-FERC-Order-901-Directives.aspx
[12] https://www.ferc.gov/media/e-1-rm22-12-000

that the draft standard is presently out for industry comment and the ballot period closes at 8 p.m. Eastern, Monday, July 8, 2024 (link).

- **Megan Pamperin, MISO:** Megan described MISO's adoption strategy for IEEE 2800-2022 requirements and highlighted that the MISO Definitive Planning Phase (DPP) 2022 and 2023 interconnection queues are comprised of 96% and 93% IBRs, respectively. MISO is using a detailed reference approach for its adoption where specific references to clauses are included in the existing MISO Generator Interconnection Agreement (GIA) requirements. Additional tariff language was included to address clarifications and decision points left open-ended in the standard. MISO's adoption efforts began in 2022 with tariff changes for select Phase 1 priority requirements filed in February 2024 and approved by FERC in June 2024.[13]
- MISO used a gap analysis approach between the IEEE 2800-2022 and MISO GIA requirements which led to 21 areas of further focus and prioritization. Phase 1 included ride-through requirements, current injection, enter service performance, and measurement accuracy. Phases 2 and 3 will focus on core system support and expanded system support topics. Three subclauses of IEEE 2800-2022 Clause 7 were not adopted by MISO in the Phase 1 filing including the following:
  - **Clause 7.2.1 Voltage Protection:** References requirements for applying voltage protection, which MISO deemed out of scope.
  - **Clause 7.2.2.4 Consecutive Voltage Deviations Ride-Through:** Requires IBRs to ride through multiple voltage excursions and MISO stakeholders had concerns with technology readiness and the ability to demonstrate compatibility with this requirement.
  - **Clause 7.3.1 Mandatory Frequency Tripping:** References requirements for applying frequency and ROCOF protection, which MISO deemed out of scope.
- MISO allows DPP-2022 cycle queue requests to seek exceptions to specific IEEE 2800-2022 requirements for GIAs signed before January 1, 2025. The need for exceptions shall be confirmed by original equipment manufacturers. For DPP-2023 cycle queue and beyond, IBR plants will be required to fully comply with the MISO-adopted IEEE 2800-2022 requirements. Megan stressed that MISO sees development of conformity assessments as a critical next step after implementation of the requirements.

Presentation recording and slides are available to download here.

[13] https://elibrary.ferc.gov/eLibrary/filelist?accession_num=20240607-3041

Interactive Group Discussion

The following topics were briefly discussed during the group discussion (including responses posted on Slido):

- **What are the BPS needs that drive IBR ride-through requirements?**
  - **Grid Reliability Needs:** Generator ride-through performance is a BPS essential reliability service that must be provided to ensure grid reliability and resilience. The ability for an IBR to ride through large system disturbances is paramount for that resource to provide essential reliability services such as fault current injection, dynamic reactive power-voltage support, active power-frequency support (i.e., primary or fast frequency response), and key stability attributes. Continuity of generating resources during grid events is critical for ensuring stable and reliable delivery of electricity to end-use customers. Avoiding ride-through performance issues (e.g., inadvertent tripping, dynamic control interactions, momentary cessation) will help avoid degrading system reliability, minimize restrictive operating limits, reduce renewables curtailments, and potentially offset costly transmission infrastructure builds.
  - **Inverter Technology:** Conventional synchronous generators inherently respond dynamically to a grid event and their protection and controls are coordinated to ensure ride-through performance. Conversely, IBRs are power electronic by nature and therefore must be intentionally programmed with the desired (or required) performance characteristics the grid needs to stably and reliably operate.
  - **Minimizing Human Error, Built-In Capability Limitations, and Misoperations:** The configuration of IBRs may be one of the most significant areas requiring clear standardization because programming power electronics is prone to human error, mistakes, incorrect assumptions, etc. Changing certain settings unexpected or unknowingly can have a severe adverse impact on BPS reliability is not properly studied. Lack of capability may also cause potential reliability risks and the current and future IBR fleet needs to be designed to provide the necessary capability and performance characteristics that support BPS reliability for the next 20-40 years. For example, trip settings and dynamic response characteristics may need to be modified as the industry continues learning about IBR technology; however, the capability should be built into the IBRs to enable modifications in the future. Furthermore, industry is still learning about IBR current injection during faults and recommended practices will likely evolve rather quickly in the coming years. Therefore, more advanced inverter capability and performance requirements should be adopted with due diligence.

- **Avoiding Retrofits:** Thoughtful implementation of IBR capability and performance requirements will help minimize and avoid more costly IBR retrofits in the future as well as reduce the need for costly transmission infrastructure investments to manage unreliable IBR performance issues that could otherwise be mitigated with improved IBR capabilities.
- **Linkage to Past Standards:** NERC PRC-024 is a generator relay settings standard and is not focused on performance requirements to-date. However, the new NERC PRC-029 is a performance-based requirement and therefore it is in the best interest of all IBR Generator Owners (GOs) and Generator Operators (GOPs) to leverage modern inverter technology to the fullest to minimize any compliance risks associated with potential unexpected IBR tripping or ride-through performance failures as have been observed in past events analyzed by NERC. It is important for new standards developments to align with industry standards like IEEE 2800-2022 to the greatest extent possible. Furthermore, proactive adoption will help avoid potential pitfalls such as those experienced in Germany decades ago.
- **Timing:** The right time to start integrating enhanced IBR performance requirements is immediately. As mentioned, experience in Germany proved that by the time that determination had been made, the IBR penetration levels rose too high too quickly with insufficient technical minimum requirements in place. This subsequently led to retrofitting settings, reconfiguring devices, and replacing equipment. One important lesson was to have certainty regarding when capabilities will be needed and to proactively plan for that time. Building capabilities into plant designs will minimize the need for costly retrofits but may require software-based equipment settings modifications in the future.

- **Adoption of IEEE 2800 Clause 7**
  - **Rapid Adoption of IEEE 2800 (Including Clause 7):** There was a clear and resounding message reiterated during discussion and via questions that industry needs to adopt IEEE 2800-2022 in a consistent manner and relatively quickly to help ensure a reliable and resilient BPS moving forward when faced with increasing levels of IBRs across the system.
  - **Full Adoption Recommended; Clause 7 High Priority:** Full adoption of IEEE 2800-2022, particularly Clause 7 requirements for ride-through performance is strongly recommended. The NERC PRC-029 standards development activities should seek to align with IEEE 2800-2022 requirements, and specifically should consider adoption the IEEE 2800-2022 standard directly for broader industry uniformity, consistent, and a more effective and efficient regulatory compliance approach.

- **Engage IBR OEM Community:** The IBR OEM community should express their support (or recommendations for improvements) and advocate for the adoption and implementation of the IEEE 2800-2022 standard in a consistent manner as this will help utilities, system operators, and regulatory bodies understand the alignment within the equipment community so as to not cause any unnecessary supply chain issues.
- **Align Regulatory Requirements with IEEE 2800-2022:** Requirements developed by local transmission providers, system operators, or regulatory bodies that go beyond IEEE 2800-2022 with insufficient technical basis create an unjust and discriminatory barrier for IBRs entering the market. This further complicates the generator interconnection process, leads to regulatory uncertainty, and could result in further generator interconnection queue backlogs. Deviations from IEEE 2800-2022 requirements are possible; however, they should be backed by reliability-centered quantitative technical evidence.

Additional Q&A for Presenters in Slido

- Why does the permissive operating range allow current blocking (i.e., momentary cessation)? What percentage of IBRs today need current blocking within the permissive operating range?
    - No information regarding the percentage of IBRs using current blocking within the permissive operating range. This topic was debated heavily within the IEEE 2800-2022 working group. Some members sought current injection requirements down to 0 volts; however, others argued that there is no grid voltage for the IBR to synchronize to at that point which can lead to inadvertent negative consequences such as incorrect current injections with the wrong phasor relationship (i.e., spurious active and reactive power injections). This is a very challenging topic and thus the team decided to provide some flexibility to OEMs. However, these conditions are expected to be very localized in nature since near-zero voltages are only centered very close to the (bolted) fault location.
- Is the technical justification and analysis regarding using current blocking documented anywhere for industry reference?
    - Footnote 91 of IEEE 2800-2022 provides technical reasoning regarding current blocking:

      "While it seems intuitive to require an IBR plant to continue to exchange current when the applicable voltage at the RPA is below 10% from a system protection perspective (since current injection at low voltage may aid protection schemes in detecting and clearing faults), it is necessary to understand risks and benefits to help ensure that the ultimate objective, which is successful ride-through of the IBR plant, is not jeopardized. If required to inject current for low voltages at the RPA, the IBR plant may ultimately trip due to consequences arising from loss of synchronism, temporary overvoltage upon fault clearance and challenges in controlling dc-side voltage of the converter. Mutual consultation, and where appropriate studies, among all stakeholders is encouraged to understand the implications of the permissive operation on system performance."

- Do the ride-through performance capabilities change for grid forming (GFM) inverters? If so, is current blocking mode/momentary cessation eliminated?
  - IEEE 2800 is not specific to GFM. There will be a need for additional GFM-specific requirements and exclusions to some of the IEEE 2800-2022 requirements that could conflict with the technology. A gap analysis between IEEE 2800-2022 and GFM requirements is available from the UNIFI Consortium[14] and MISO's draft GFM requirements recently published also lists the exceptions that are needed from IEEE 2800-2022.[15]
- Is there any recommendation about sequence component extraction method (i.e. delay, etc.)?
  - To verify conformity, Table 13 Note C specifies how the phasor domain components of the current (e.g., positive and negative sequence) are calculated from the sampled measurements. "The discrete Fourier transform (DFT) with a one-cycle moving average window is used to derive phasor quantities such as active, reactive, positive-sequence, negative-sequence currents, etc. The time delay required for the DFT measurements is included in the step response time and settling time specified in this table."
- Can you expand on what is meant by cumulative time for ride-through requirements?
  - Refer to Annex D of IEEE 2800-2022 which includes pictorial descriptions of the cumulative time requirements. Essentially, if operating conditions go in and out of the ride-through threshold limits, the time starts accumulating when outside that threshold within a moving 10 second window (illustrated with Figure 6 from footnote 110 of IEEE 2800-2022).

[14] https://unificonsortium.org/resources/

[15] https://cdn.misoenergy.org/20240604%20IPWG%20Item%2004b%20Draft%20GFM%20BESS%20Performance%20Requirements%20Whitepaper%20(PAC-2024-2)633112.pdf

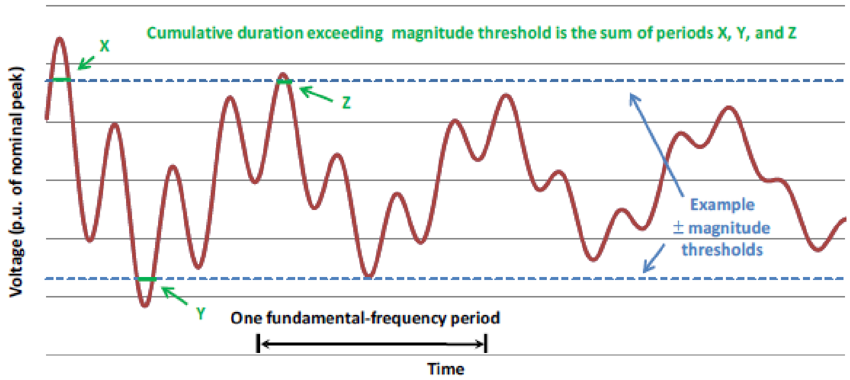


Figure 6: Cumulative Duration Illustration

- Can existing IBRs meet IEEE 2800-2022 ride-through requirements? Should these requirements be mandatory for IBRs currently entering service?
    - Existing IBRs may be able to meet many of the IEEE 2800-2022 ride-through requirements and software-based equipment modifications may be able to help IBR ride-through performance today. However, there are some requirements that will be difficult to verify whether existing IBRs can meet such as consecutive voltage excursion requirements, transient ac overvoltage requirements, and even the frequency and voltage ride-through capability requirements for older legacy IBRs. IBRs entering commercial operation in the near-term should be granted some flexibility in meeting the new IEEE 2800-2022 requirements, particularly since the IEEE P2800.2 working group is still developing the test and verification procedures. Transmission providers and/or system operators adopting IEEE 2800-2022 have specific requirements regarding modifications to existing facilities and how those are treated in terms of standards applicability; special attention should be given to the feasibility of applying IEEE 2800-2022 to existing assets without requiring costly hardware replacements.
- Is it difficult to verify compliance (conformity) with IEEE 2800-2022 requirements for new and existing IBRs? Why or why not?
    - Many of the requirements of IEEE 2800-2022 are plant-level requirements that apply at the POM/POI. This requires careful design evaluations as well as plant performance monitoring equipment capturing the IBR plant's response to grid events. Some requirements in the standard may be more difficult for new IBR to demonstrate (e.g., transient ac overvoltage requirements applying at the POM/plant-level, requiring adequate insulation coordination across the collector system and all protection systems coordinated throughout the plant). Furthermore, applying conformity assessments to existing IBR facilities may be challenging and some

flexibility should be given to attempting to apply these test and verification requirements retroactively to existing resources.

- What percentage of existing or legacy IBR will not be following the adoption of IEEE 2800-2022?
  - It is not expected that existing or legacy IBRs meet the IEEE 2800-2022 requirements; however, these resources may be configured to comply with some of the requirements presently and software-based changes to IBRs may be able to further ensure they can provide essential reliability services to the BPS.
- Has there been discussion about penalties for IBR that cannot meet new requirements or incentive to motivate older sites to invest in new inverter technology?
  - This was not discussed at this meeting.
- Should draft NERC PRC-029 or the BAL-003 standard include requirements for primary and/or fast frequency response?
  - NERC PRC-029 is intended to establish IBR ride-through performance requirements; therefore, primary or fast frequency response requirements are likely to be established in a different standard, at least as of presently given the current NERC drafting team efforts and scope of work. NERC BAL-003 could be modified to include IBR requirements for primary or fast frequency response, or an IBR-specific standard could be developed/modified to include these requirements. However, NERC could focus on cohesive adoption of IEEE 2800-2022 requirements in full to streamline its standards development efforts.
  - This topic will be discussed further at a future i2X FIRST meeting dedicated to frequency support.
- What efforts, if any, are being taken to ensure that the IEEE 2800-2022 requirements as adopted by ISO/RTOs do not conflict with PRC-029 requirements?
  - From MISO's perspective, they are closely tracking NERC PRC-029 activities, where the draft standard aligns with the IEEE 2800-2022 requirements and where it does not, and are also including language in the GIA to clarify that any applicable NERC Reliability Standards must also be met in addition to the requirements set forth in the MISO GIA.
- Industry is having challenges requiring IBRs to provide reactive power support when there is no active power. How should industry tackle this?
  - This topic will be discussed further at a future i2X FIRST meeting dedicated to reactive power support.
- Does FERC Order No. 1920 impact IBR ride-through requirements in any way?

    - Not aware of any impacts or conflicts with IBR ride-through requirements.

- Any idea when IEEE or other standards bodies will tackle performance requirements (e.g., ride-through issues) for large BPS-connected loads?
    - This is certainly an important topic; however, the presenters were not aware of any IEEE efforts to develop large load interconnection standards or performance requirements. Some discussion has occurred at the NERC stakeholder meetings; however, no major action has been taken by NERC or FERC to address large load requirements to-date.
- What considerations are being given for electricity market mechanisms to provide compensation to IBRs for providing these services? Is this necessary moving forward?
    - In general, ride-through capability is considered an essential reliability service needed from every generating resource while in operation. Other services that can be delivered by a subset of resources can potentially be produced through market mechanisms. For example, ERCOT is procuring a portion of their frequency response (e.g., a mix of primary and fast frequency response) through a market product called Responsive Reserve Service. This is done to ensure availability of sufficient frequency responsive headroom at all times, while all transmission-connected resources are required to have frequency responsive capability enabled and are providing additional frequency support when headroom is available (e.g., from curtailed state).
- Are there any plans for IEEE 2800-2022 to include GFM-specific requirements?
    - The goal is to not create a GFM-specific standard that is different from IEEE 2800-2022. IEEE 2800-2022 is one step towards enabling IBRs to have capabilities to operate and contribute to system reliability at very high penetration of IBRs; however, additional efforts will be needed. The next revision of IEEE 2800-2022 could address any technical barriers or conflicts that may exist with GFM technology and performance, and subsequent versions of IEEE 2800-2022 could include additional GFM-specific requirements where needed, including operation at 100% penetration level of IBRs.

Key Themes

- Adoption of IEEE 2800-2022 is a critical step in ensuring reliability of the BPS with increasing levels of IBRs, and specifically Clause 7 is a high-priority set of requirements that should be implemented by industry at-large. A unified adoption approach such as the FERC/NERC level would provide uniformity and consistency across regions and areas of the North American BPS. However, NERC and FERC have generally avoided adoption of IEEE 2800-2022 in their standards development directives and activities. Therefore, transmission providers and ISO/RTOs should seek to adopt IEEE 2800-2022 in a uniform manner where possible.

- Industry is strongly encouraged to participate in the NERC Standards development process as these are open processes where all stakeholders can participate, engage, and provide comments on the drafting team efforts, draft standards language, and open ballots to help refine the NERC Standards as they evolve related to IBRs.
- There is presently a rather significant duplication of effort in the NERC PRC-029 drafting activities yet with notable inconsistencies with IEEE 2800-2022 requirements pertaining to IBR ride-through capability and performance. This stems from NERC and FERC unwillingness to implement IEEE 2800-2022 requirements directly. Aligning new NERC Reliability Standards developments with IEEE 2800-2022, where applicable, to the greatest extent possible should be considered the most effective and efficient path forward especially since a number of regions have already adopted or are in the process of adopting IEEE2800-2022.
- There are still many technical questions pertaining to the IEEE 2800-2022 Clause 7 ride-through requirements, as illustrated in the meeting and the list of questions asked by stakeholders. Therefore, continued outreach, education, and training across industry stakeholders will help with effective adoption and implementation of the standard both in terms of requirements language developments and demonstrating conformity with the requirements established.
- Design evaluations and IEEE 2800-2022 conformity assessments during the interconnection process and during the lifetime of IBR plants will be an essential component of effective IEEE 2800-2022 requirements implementation. Enhancement of requirements language will support both the utility/system operators as well as renewables developers and generator owner/operators establish clearer expectations for IBR performance moving forward; however, how to implement and demonstrate conformity with those requirements is the next major obstacle.

July 30, 2024 Virtual Meeting

IBR Ride-Through Requirements and Original Equipment Manufacturer (OEM) Readiness (~195 simultaneous attendees)

Figure 7 shows the makeup of the meeting attendees by industry sector:

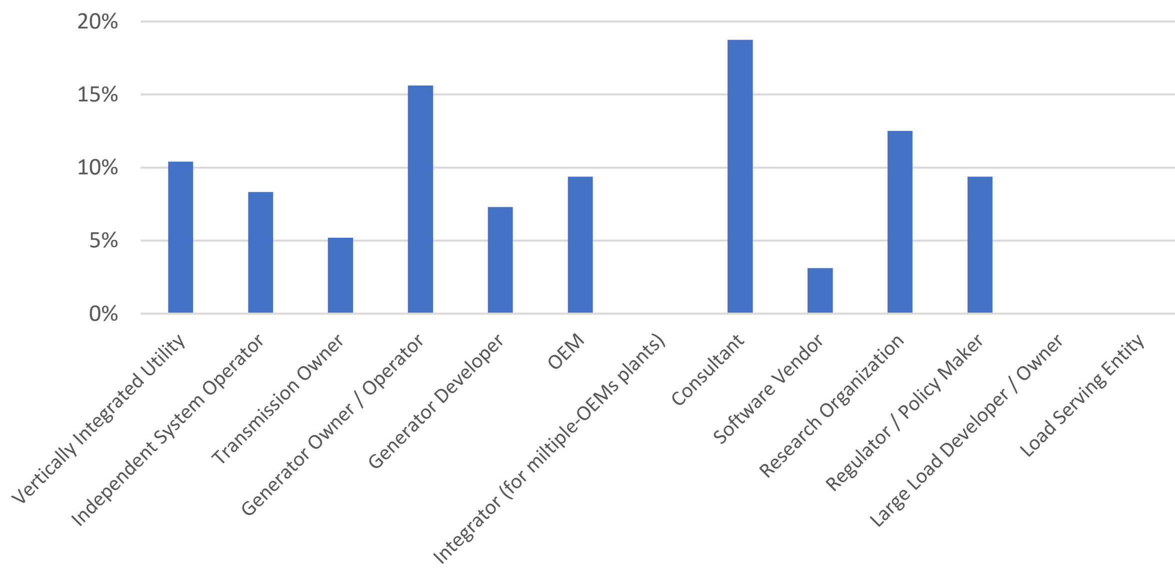


Figure 7: Meeting attendees by industry sector

This was the third meeting of the DOE i2X FIRST initiative, focused on IBR ride-through requirements and original equipment manufacturer (OEM) readiness to meet the IEEE 2800-2022 *Clause 7: Response to TS Abnormal Conditions* requirements. As industry continues to adopt and implement IEEE 2800-2022, understanding OEM readiness and plans for supporting IBR plant conformity with IEEE 2800-2022 is critical. Presentations included:

- **Dinesh Pattabiraman, TMEIC:** Dinesh shared TMEIC perspectives related to IEEE 2800-2022 Clause 7 requirements, particularly for the Solar Ware Ninja™ inverters which are widely used for utility-scale solar PV projects in the US. Dinesh described that Underwriters Laboratories (UL) certification, particularly UL1741-SA and -SB, is essential from a TMEIC perspective since it is necessary for sale of inverters in the US. These are historically distribution-centric certifications applicable for, say, rooftop solar installations; however, inverter OEMs may require adherence to these requirements even for transmission-connected IBRs which can cause complications. TMEIC views compliance with UL1741-SB as an intermediate step in meeting IEEE 2800-2022 requirements given that many requirements are synonymous yet may have different thresholds or settings. Dinesh highlighted that currently installed technology does not have some of the capabilities that IEEE 2800-2022 requires such as active current priority option, negative sequence current injection, and maybe some of the response time and accuracy requirements. Dinesh also highlighted that some requirements such as transient AC overvoltage ride-through are more of a balance of plant issue rather than an inverter OEM issue and so more focus is needed on the overall IBR and needs to be codified in IEEE P2800.2 efforts where possible. Furthermore, Dinesh also stressed that many of the past reliability issues observed and reported by NERC are based on old perspectives stemming from the distribution system such as "do no harm and get off the system" as well as a lack of EMT modeling and study work to verify plant ride-through performance and grid reliability.

- **Ravi Dodballapur, SMA:** Ravi presented on SMA readiness for IEEE 2800-2022 Clause 7 requirements, stressing that all requirements are met except for some further considerations that should be given to *Clause 7.2.2 Voltage Disturbance Ride-Through Requirements*. Ravi highlighted that frequency and voltage ride-through, rate-of-change-of-frequency (ROCOF), phase angle jump, and fault recording are all met with appropriate parameterization and have been thoroughly tested in the laboratory. However, some of the response characteristics such as rise time and settling time[16] may be difficult to meet under *all* system conditions. These types of performance characteristics are dependent on the depth of the voltage excursion, the system short-circuit strength in which the resource is being connected to, etc. So there may be situations where, for example, a weak grid interconnection may require slowing of those controls to maintain stability yet would not meet the requirements as specified in IEEE 2800-2022 under all conditions. Furthermore, multiple fault scenarios in combination with other issues could create difficulties. Lastly, Ravi highlighted that the current products for new installations are able to meet most or all of the requirements if configured correctly. Upgrades would be required for existing projects that were not configured correctly, which could involve both software and hardware upgrades needed ("engineered kits"). Older products pre-2015 are under review currently. IEEE P2800.2 needs to be completed and fully approved by industry at-large for full self-declarations from OEMs. Flexibility is needed in the interim related to conformity with IEEE 2800-2022 requirements.
- **Miguel Angel Cova Acosta, Vestas:** Miguel shared Vestas' perspectives related to IEEE 2800-2022 and particularly OEM implementation of Clause 7 requirements. He highlighted that the type testing, compliance evaluations, exemptions, and other factors all need careful consideration as these areas continue to evolve for OEMs. There are multiple ways in which compliance or conformity with IEEE 2800-2022 can be demonstrated. Examples may include field tests, EMT/positive sequence (RMS) modeling and simulations, hardware-in-the-loop (HIL) verification and validation, OEM confirmations and attestations, park performance during commissioning, and

[16] This refers to Table 13 in IEEE 2800-2022 that defines rise time, settling time and settling band of *IBR unit* current response during voltage ride-through events.

considerations of exemptions where needed (see Figure 8). Certainty around demonstrating conformity with some of the requirements is still low such as consecutive voltage deviations, transient overvoltage ride-through, and ROCOF ride-through. Miguel also highlighted that grid strength and hardware details play a critical role in IBR performance in these areas, particularly for wind turbine technology. Industry needs significant attention toward developing a definitive understanding of the evidence required by generator owners and project developers as well as OEMs to demonstrate compliance with IEEE 2800-2022.

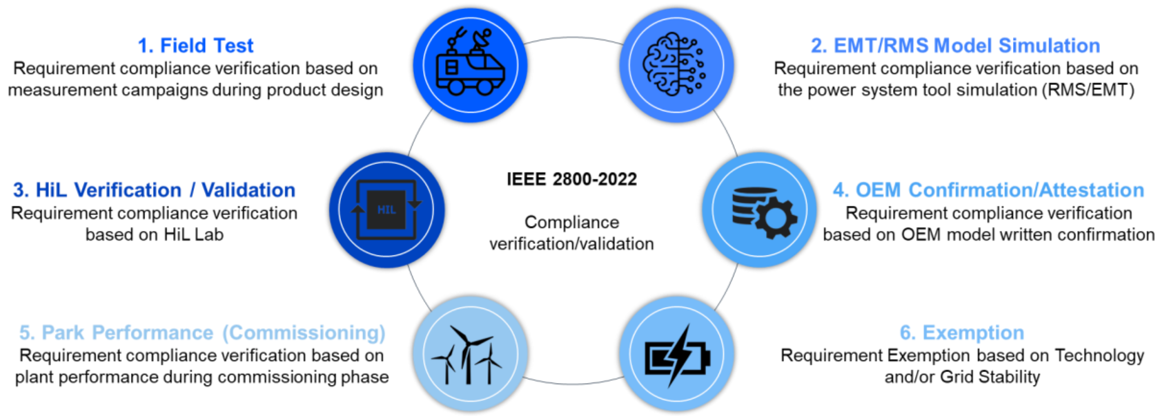


Figure 8: How to Demonstrate IEEE 2800-2022 Compliance [Source: Vestas]

- **Jens Boemer, EPRI:** Jens provided an update on the compatibility of some legacy IBR units as well as new IBR units with IEEE 2800-2022 clauses based on EPRI discussions with industry stakeholders and OEMs (see Figure 9 and Figure 10). He highlighted that balance of plant (BOP) surge arrestor design may help with OEM capability/design to meet the IEEE 2800-2022 requirements for transient overvoltage ride-through and that some conformity evidence would be part of design evaluation studies during IBR plant design and engineering.[17] Jens also stressed that consecutive VRT is rather complicated in the IEEE 2800-2022 and is likely a candidate for future revision.

[17] Surge arrestor design is often conservative in nature to protect against significant transient overvoltages and focuses on the instantaneous peak voltage quantities rather than root-mean-square (RMS) quantities. This design is also dependent on transformer winding connection and system grounding.

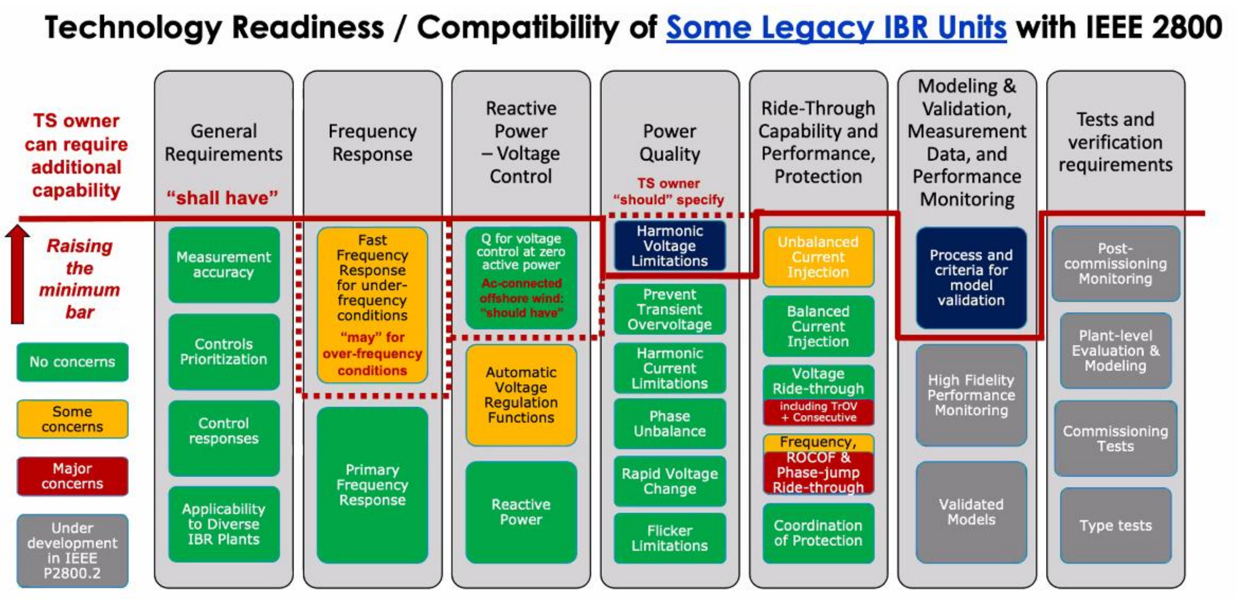


Figure 9: Compatibility of Some Existing and New IBR Units with IEEE 2800-2022 [Source: EPRI]

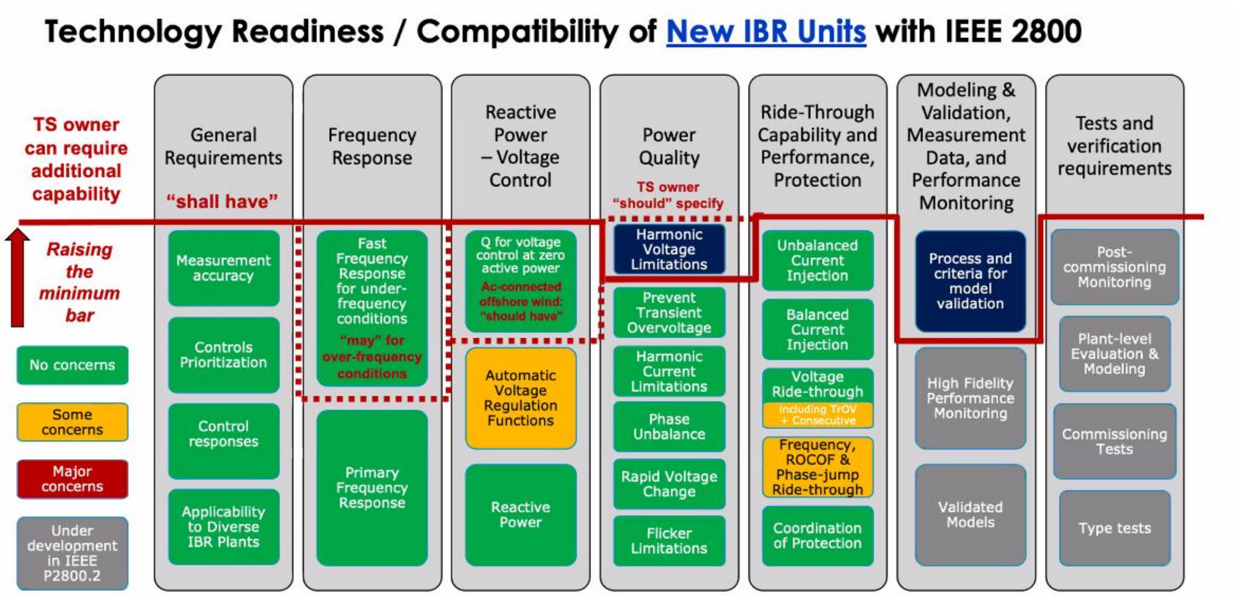


Figure 10: Compatibility of New IBR Units with IEEE 2800-2022 [Source: EPRI]

Presentation recording and slides are available to download here.

Interactive Group Discussion

The following topics were briefly discussed during the group discussion (including responses posted on Slido):

- **Backward-Compatibility of IBR Plants with New Ride-Through Requirements**
  - **Do you see the need for compatibility of existing / under construction plants with new ride-through requirements (e.g., IEEE 2800-2022 Clause 7)?** Plants undergoing signed interconnection agreements or construction presently may need to be granted exemptions to new requirements since OEMs are still developing their practices and capabilities to comply with these new requirements, particularly since IEEE P2800.2 is still in development. Transmission providers should be cautious when trying to enforce new requirements on these vintage of resources as there may be notable uncertainties that are not yet well understood during this evolution of IBR requirements enhancements.
  - **Should ride-through capability be configured to meet a set of performance requirements/curves or simply based on maximum equipment capability?** Both concepts can play an important role in reliable design and operation of the bulk power system. Capability and performance requirements help define how equipment should be designed, developed, constructed, and eventually operated. Without these requirements that defined the expected performance of an IBR plant, industry may continue experiencing the unexpected and abnormal performance of IBRs moving forward. Similarly, IBR plants can also be designed to operate with "maximized equipment capability" within the equipment ratings, design decisions from OEMs, and using sound engineering judgment. This can also help minimize the risks of unexpected IBR performance while still adequately protecting the IBR plant and its components from any equipment damage or lifespan degradation.
  - **How should we be thinking about ride-through capability and performance for legacy (existing) resources? What are good practices being deployed to mitigate ride-through risks for the existing fleet?** There are technology-specific considerations that need to be given; the behavior of different technologies will be different for various operating conditions on the bulk power system. As the grid evolves and system strength may decline, existing plants may experience challenges meeting specific performance requirements that did not apply at the time of interconnection. As equipment capabilities and technology evolves, newer performance requirements can more effectively be met. However, applying new requirements retroactively to existing equipment can be extremely problematic and costly. For example, trying to apply new transient AC overvoltage requirements to an existing IBR plant may require costly hardware upgrades or a "rip and replace" for the inverters themselves, which would not be effective and could put the entire

IBR plant in jeopardy of staying commercially operational. Maximizing ride-through capability and mitigating known performance issues with software-based updates such as firmware changes or settings/parameter changes can help improve ride-through performance of IBR plants immensely. Note that these changes to ride-through performance may trigger other obligations and requirements such as model validation or model quality test reports being re-submitted, OEM or developer attestations, etc. Conversely, there is an opportunity to enhance the ride-through performance of existing solar PV sites if and when the inverters are replaced at the end of their lifespan. Careful consideration and study of system needs in terms of retroactive ride-through requirements applicability should be used in the context of newly connecting resources that will have improved ride-through requirements.

- **Conformity of IBR Plants with New Ride Through Requirements**
    - **Do you see any barriers for future IBR plants (not yet in the interconnection queue) to comply with new ride through requirements (e.g., per IEEE 2800-2022 Clause 7)?** Most OEMs generally agreed that newer IBR plants will be able to meet most, if not all, of the IEEE 2800-2022 requirements over time. Until IEEE P2800.2 is fully approved, and sufficient time has been given for OEMs and IBR developers to fully understand and implement the test and verification procedures contained within IEEE P2800.2, some latitude is needed.
    - **What is the current best practice to get assurance from OEMs and plant developers/owners that they can meet applicable ride through requirements (e.g. IEEE 2800 Clause 7): attestations, simulation results, physical etc.?** It is becoming increasingly common[18] for attestations to be required from the project developer or OEMs that the product supports conformity with IEEE 2800-2022 as well as attestations that ensure that the as-designed or as-left equipment matches the information and models submitted during the interconnection process. It must be recognized that the inverter or wind turbine OEM can only confirm performance to their point of connection at the inverter terminals and the OEM is not well-suited to justify the performance of the entire IBR plant. However, the OEM can play a key role in helping a developer or third-party firm ensure accuracy of the information and models supplied. Transmission providers should be cautious and thoughtful when requiring OEM attestations as part of interconnection requirements because they may overcommit one party to providing information they cannot verify as well as create undue burden on multiple entities throughout the process if not used appropriately. The plant developer and plant designer (i.e., third-party engineering firm) are best equipped to attest to the accuracy of the information provided for the IBR plant as a whole, including balance of plant (BOP) and PPC controls, etc. Collaboration among

[18] For example, NYISO requires attestations from the developers regarding IBR plant conformity with IEEE 2800 requirements: https://www.nyiso.com/documents/20142/43564982/Draft%20NYSRC%20Rule%20B.5%20Attestation.pdf/69867a88-9da7-73cf-922e-ef95ae55e2e6.

multiple parties is critical throughout the entire interconnection process and through commissioning.

- **Are you planning to develop your own conformity assessment process for ride through requirements or wait until IEEE P2800.2 is completed?** Some OEMs are actively preparing for conformity with IEEE 2800-2022 using, for example, self-certification methods until IEEE P2800.2 is approved. Others, however, are waiting for the completion of IEEE P2800.2 before making any more significant changes to the test and verification methods used presently. Specifically, one OEM highlighted that they are "waiting for guidance on how certain parts of the [IEEE 2800-2022] standard will be adopted and how the performance will be verified with test procedures. For example, the OEM may be able to provide fault current injection but the amount of fault current and how that will be verified needs to be defined; the OEMs seek further guidance from transmission providers and ISO/RTOs on this subject. Another example is that one OEM is able to provide negative sequence current injection but this feature is disabled by default "due to lack of clear evidence that such an injection is helpful to the grid and not harmful to the inverter." They "will wait for more detailed specifications on these conditions from ISOs."

Additional Q&A for Presenters in Slido

- **UL Certification:** One OEM highlighted that all inverters must be Underwriters Laboratory (UL)-certified as a prerequisite for use in non-utility installations, which is a significant portion of the fleet. These requirements stem from the National Electric Code and distributed energy resources (DERs). Therefore, UL 1741 is mainly focused on IEEE 1547 testing and conformity and not bulk power system applications. NERC previously addressed this issue in a past Reliability Guideline,[19] highlighting that UL 1741 certification does not preclude a bulk power system-connected inverter from being configured to meet other requirements like IEEE 2800-2022 or local interconnection requirements or NERC Reliability Standards. However, some OEMs are still basing their conformity testing and verification practices off of UL 1741-SA or UL 1741-SB criteria. Until IEEE P2800.2 is complete, some OEMs may not be making notable changes to their verification efforts since further clarity is needed on how to certify whether a resource or component within an IBR plant supports conformity with the IEEE 2800-2022 requirements.

- **OEM Support in IBR Plant Modeling during Interconnection Process:** Questions were raised about the best ways to get OEM input and support throughout the interconnection study process and up through commissioning. While OEMs are not responsible for the entire IBR plant model overall, they play a critical role in ensuring

[19] NERC Inverter-Based Resource Performance Guideline, see Chapter 5 regarding UL 1741 confusion and clarifications addressed by NERC: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Inverter-Based_Resource_Performance_Guideline.pdf

that what got commissioned matches the model studied during the interconnection process. Site-specific modeling of IBRs is essential for making reliability decisions; generic parameterization of models should be avoided as much as possible. Experience in Australia has proven effective where the inverter OEM does testing and develops reports on the inverter models at various short-circuit ratio (SCR) levels. For every plant, an independent modeling consultant also develops site-specific models of the IBR plant and all accompanying documentation is provided to the transmission provider. OEMs highlighted that their involvement requires lots of "runway and very early involvement of the OEM(s) in the design and EMT model development of the facility." One support model is having the OEM support a third-party firm contracted by the developer to perform model development wherein the OEM supports parameterization tuning, plant sizing, and other aspects of model development and verification. Another approach is having the OEM develop the entire IBR plant model although this is less common in the US. OEM engagement, particularly on parameterizing the model to meet specific ISO/transmission provider performance requirement or system strength stability requirements, is critical. One major challenge identified is that the models used in the interconnection studies with the finalized set of parameters that should be commissioned are often not received by the OEM before commissioning and therefore generic parameterization may be programmed for the as-built facility. This leads the facility operating in a mode that was not previously studied, which could present reliability risks. Having the power plant controller (PPC) OEM and any other dynamic reactive device OEMs involved early in the process is also a best practice.

Key Themes

- OEMs continue to advance ride-through capability of IBR facilities, and OEMs are focused on developing future products that support conformity with IEEE 2800-2022 requirements. OEMs are preparing for widespread adoption of IEEE 2800-2022.
- Some OEMs are waiting for IEEE P2800.2 test and verification procedures to be vetted, approved, and adopted before they can fully certify that their equipment support conformity with IEEE 2800-2022.
- OEMs are also seeking further guidance from transmission providers and ISO/RTOs regarding how to configure and set IBRs. IEEE 2800-2022 leaves some of these options in terms of performance open-ended (intentionally) and this requires additional specificity to be provided by the transmission provider. For example, fault current injections, speed of response, and other factors need to be defined.
- Applying IEEE 2800-2022 retroactively can be problematic because it may require existing assets designed under past interconnection requirements to implement software and hardware upgrades. Hardware upgrades can be costly and may require replacing inverters and other devices within the IBR facility; however, opportunities may arise for

improved ride-through performance if inverters are replaced toward the end of their lifecycle. Ride-through capability maximization that only requires software upgrades for existing resources can deliver improvements to reliability at minimal costs, assuming sufficient caveats and exemptions for equipment limitations that may exist due to previous design decisions.

- Some of the Clause 7 requirements may be difficult to meet for some OEMs under specific grid conditions (e.g., low SCR conditions). This will need to be handled with technical exemptions or modifications to the IEEE 2800-2022 requirement as industry learns more during implementation and enforcement.

August 20, 2024 Virtual Meeting

IBR Ride-Through Requirements and OEM Readiness – Part II (~170 simultaneous attendees)

Figure 11 shows the makeup of the meeting attendees by industry sector:

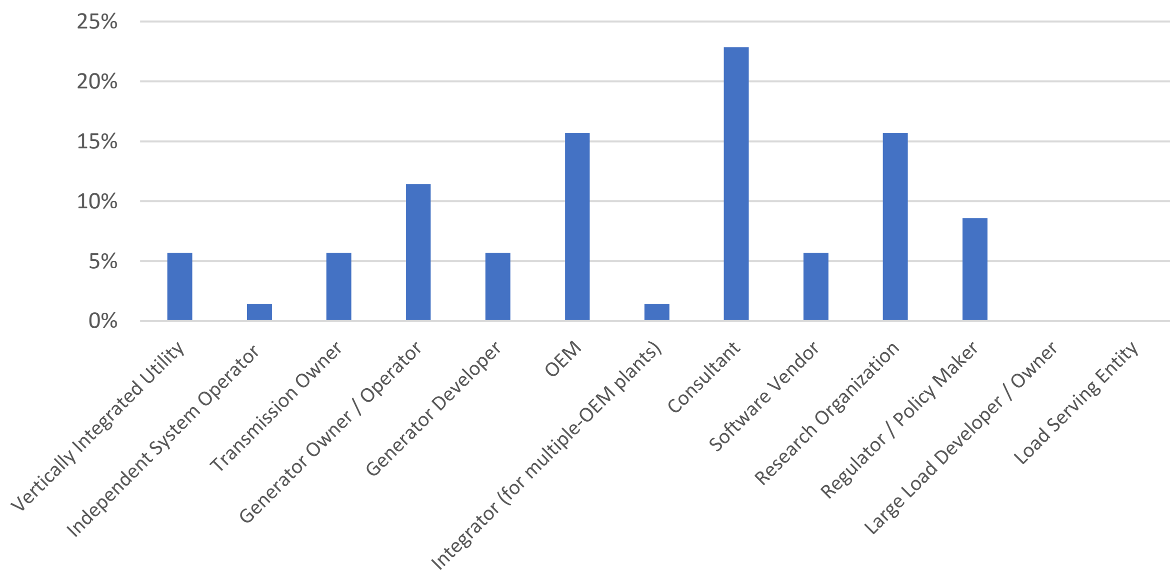


Figure 11: Meeting attendees by industry sector

This was the fourth meeting of the DOE i2X FIRST initiative, and a continuation of the topic of IBR ride-through requirements and OEM readiness to meet the IEEE 2800-2022 *Clause 7: Response to TS Abnormal Conditions* requirements. This meeting extended the presentations from OEMs regarding readiness to adopt IEEE 2800-2022 requirements, additional OEM perspectives or challenges with IEEE 2800-2022, and other industry efforts underway. Presentations included:

- **Mariana Binda Pereira and Dustin Howard, GE Vernova:** Mariana and Dustin shared GE Vernova perspectives specifically related to their onshore wind technologies and their readiness for IEEE 2800-2022 Clause 7 requirements. Positive perspectives pertaining to IEEE 2800-2022 adoption included harmonization of interconnection requirements across North America, enabling faster and more reliable integration of IBRs, supporting alignment between field settings and modeled behavior, and capabilities for performance monitoring. Mariana stressed that GE Vernova has sought harmonized IBR standardization for years and generally welcomed such as standard as IEEE 2800-2022, but would like to see this standard adopted at more of a national level. They shared some challenges with current IEEE 2800-2022 adoption strategy such as requirements being adopted in various shapes and forms (i.e., non-standardized adoption of the IEEE 2800-

2022 standard), unknown and uncertain compliance evaluations particularly as IEEE P2800.2 evolves, retroactive application of requirements, and disparity of requirements versus grid needs (see Figure 12).

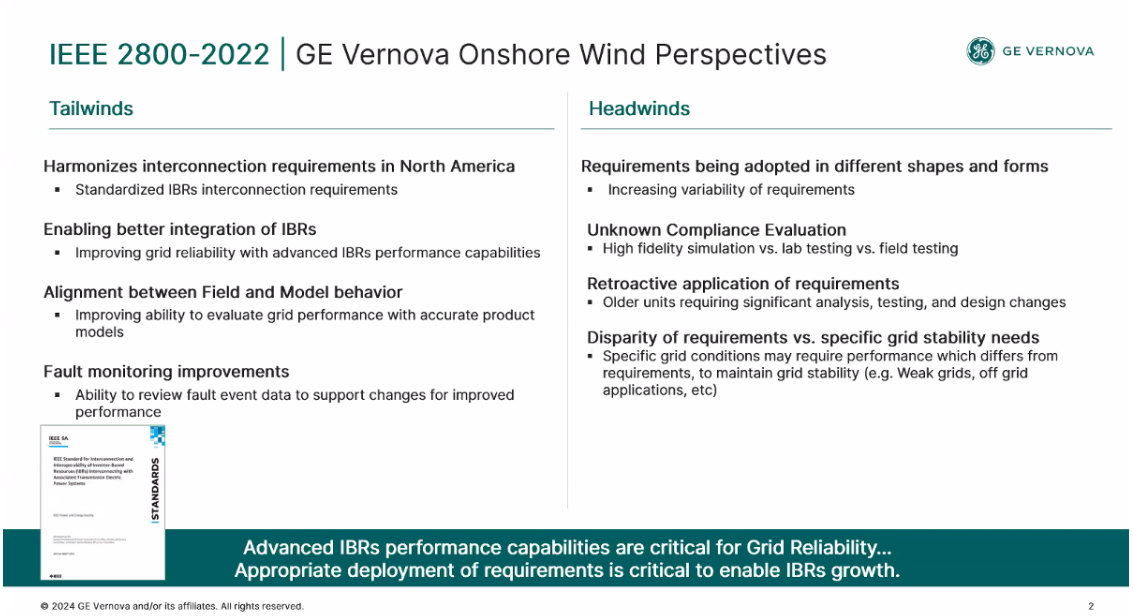


Figure 12: GE Vernova Onshore Wind Perspectives on IEEE 2800-2022 Adoption [Source: GE Vernova]

Dustin explained that there are notable differences between Type 3 and Type 4 wind turbine technology that impact the behavior and ability to comply with IEEE 2800-2022 requirements. Type 3 turbines have a natural response to fault and fault recovery since the stator is connected directly to the AC network. Torque transients during faults need to be absorbed by the mechanical drive train, unlike Type 4 turbines that use a chopper circuit to dissipate energy. Type 3 turbines are naturally suited for weak grid conditions since they drive train can tolerate and benefit from slower power recovery times. However, IEEE 2800-2022 requirements do not consider the system needs and are more designed for "current source devices" that are fully power electronic-interfaced. Therefore, Type 3 technology may be challenged to meet some of the on-fault and/or post-fault recovery and settling times for active and reactive currents (Table 13 in IEEE 2800-2022).[20] Special consideration may be required for Type 3 technology as the IEEE 2800-2022 standard may not adequately account for these nuances. Transmission providers will need to make these considerations when developing their adoption techniques. Lastly, Mariana stressed that the proposed frequency ride-through requirements in the draft NERC PRC-029 exceed IEEE 2800-2022 and other current standards; therefore, OEMs are concerned with expanded requirements for existing assets

[20] The requirement is intended more for the inverter/turbine-level capability and does not translate to performance expectations at the Point of Measurement/Point of Interconnection. IEEE P2800.2 is developing additional guidance on this issue and the plan is to review and revise this requirement in the next version of IEEE 2800.

not designed to these standards and the fact that there are presently no allowed exemptions for existing resources, which is not aligned with the existing NERC PRC-024-3 exemption process for other types of resources.

- **Henry Aribisala, Sungrow:** Henry shared Sungrow's perspectives related to IEEE 2800-2022, focusing specifically on Clauses 4–6 and Clause 7. Regarding reactive power capability, Henry stressed that IBR plant design should be coordinated with the extra reactive power compensation devices within the facility to ensure sufficient composite reactive capability curve. Regarding Clause 7, Sungrow equipment can meet the voltage ride-through requirements and can support negative sequence current injection. They have recently released a software/firmware update to support compliance with these requirements; however, it is acknowledged that older legacy equipment may not be able to meet these requirements. Additionally, Sungrow is designing to the transient AC overvoltage curves specified in IEEE 2800-2022 but highlights that conformity with these requirements requires close coordination with inverter ride-through capability and IBR plant design, specifically surge arrester protection coordination. This underlines and emphasizes once again that IEEE 2800-2022 requirements are plant-level requirements, and conformity can only be achieved through careful design and coordination of all plant components and site-specific control settings. Henry stressed that past events have a major common root cause related to poor parameterization of installed equipment and that the models must match the actual equipment in the field. Sungrow has experienced instances where the models do not match the commissioned equipment and settings used in studies, which can be corrected with closer coordination between the transmission provider and/or transmission planner, IBR developer, and OEM(s).
- **Jamie Calderon, NERC:** Jamie presented on the status of FERC Order No. 901 standards development activities, which includes four milestones through November 2026. Milestone 2 obligations are due November 4, 2024 in which standards must be developed and filed with FERC to address IBR performance requirements, IBR performance/disturbance monitoring capability, and IBR post-event performance validation for registered IBRs. Most recently, the proposed IBR Definitions[21] and PRC-028,[22] PRC-029,[23] and PRC-030[24] standards went out for a final ballot (see Figure 13).[25] All sufficiently passed except for PRC-029; PRC-030 has some minor revisions needed that will require a re-ballot. The proposed PRC-029 regarding IBR ride-through requirements failed its final ballot with 53% approval (66.67% needed for passing vote). Therefore, NERC invoked its Section 321 Rules of Procedure authority and is now planning a technical conference scheduled for September 4-5, 2024, in the Washington,

[21] https://www.nerc.com/pa/Stand/Pages/Project-2020_06-Verifications-of-Models-and-Data-for-Generators.aspx
[22] https://www.nerc.com/pa/Stand/Pages/Project-2021-04-Modifications-to-PRC-002-2.aspx
[23] https://www.nerc.com/pa/Stand/Pages/Project_2020-02_Transmission-connected_Resources.aspx
[24] https://www.nerc.com/pa/Stand/Pages/Project-2023-02-Performance-of-IBRs.aspx
[25] https://sbs.nerc.net/

DC area. The goal of this technical conference[26] is to gather information such that the NERC Standards Committee can direct revisions to the draft standard and re-ballot with the goal of achieving a passing vote. Areas of focus for the technical conference include frequency ride-through requirements which currently deviate significantly from IEEE 2800-2022 requirements, the need for exemptions for existing IBRs to meet frequency ride-through requirements, and other pertinent topics based on comments from previous ballots.

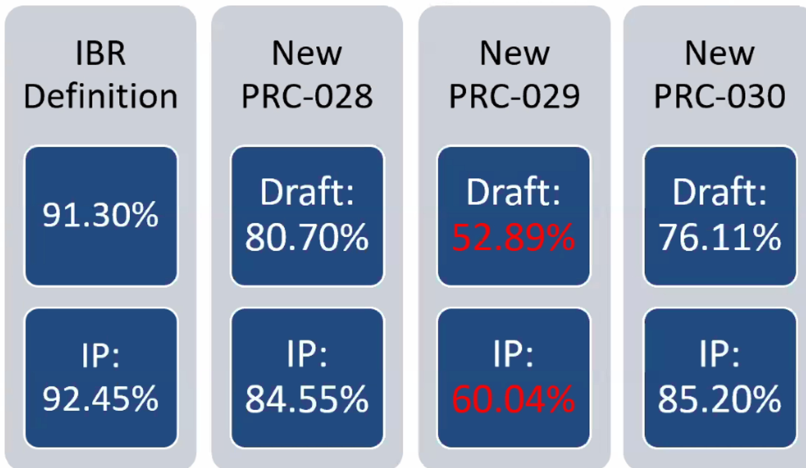


Figure 13: NERC Milestone 2 Project Ballot Scores Related to FERC Order 901 Directives [Source: NERC]

- **Ryan Quint, Elevate Energy Consulting:** Ryan shared perspectives pertaining to "maximizing" IBR ride-through with least-cost, high-value updates to software, firmware, and settings within an IBR facility. Ryan stressed that generator ride-through is an essential reliability service and has a significant impact on grid stability and reliability. IEEE 2800-2022 is generally applied forward-looking because retroactivity of any new requirements on asset owners can have significant challenges and costs. Equipment is designed and installed to meet the requirements in place at the time. So, applying new requirements retroactively without adequate exemptions can introduce regulatory and financial uncertainty to IBR asset owners. This challenge introduces the concept of "maximization" that seeks to minimize incremental costs while getting the most ride-through capability out of existing assets. Any application of new requirements retroactively, including maximization of software/firmware should use a risk-based approach based on modeling and studies of current and future BPS reliability risks; there are tradeoffs with approaches in this area (see Figure 14). Ryan discussed examples of maximization within the inverter/turbines, power plant controller, balance of plant protections, and other factors for consideration. Lastly, Ryan stressed the need to ensure dynamic models are updated to reflect any changes and that maximization assessments

[26] https://www.eventbrite.com/e/nerc-ride-through-technical-conference-registration-995391521837?aff=oddtdtcreator

follow a thoughtful and methodical process for evaluation and eventual change (see Figure 15).

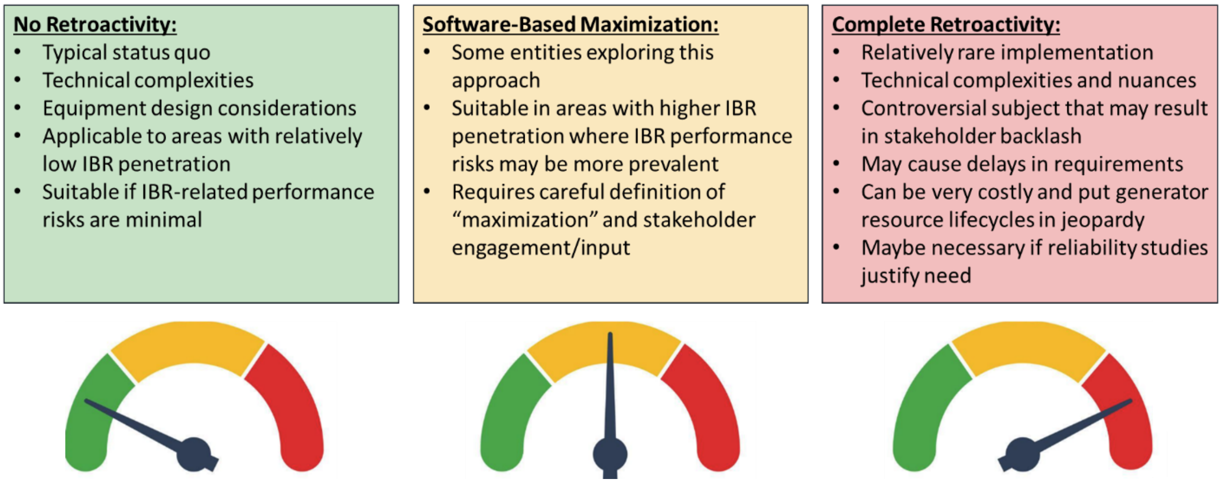


Figure 14: Concept of Maximization as a Compromise [Source: Elevate Energy Consulting]

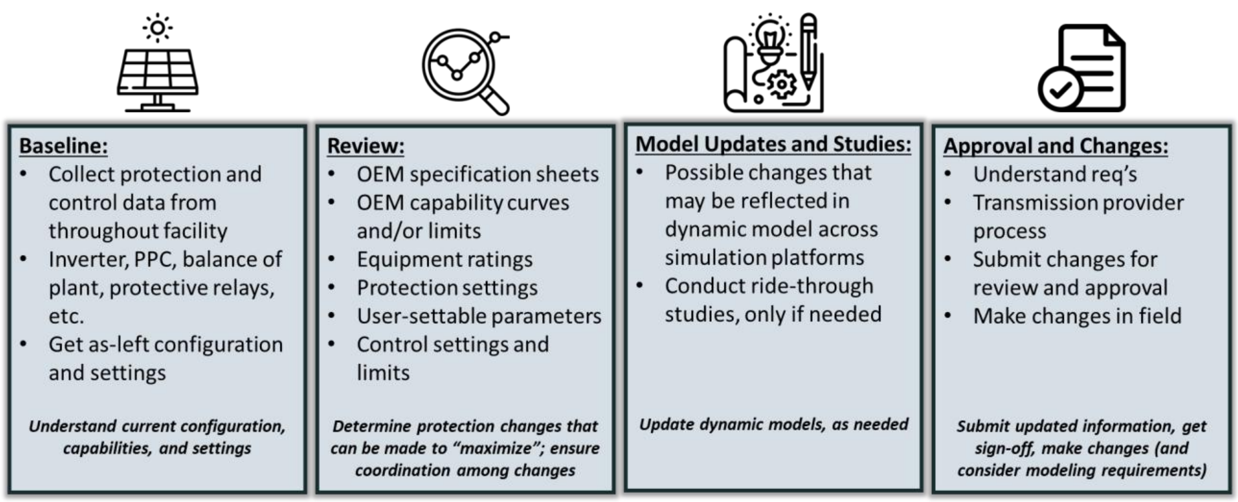


Figure 15: Maximization Process Concept [Source: Elevate Energy Consulting]

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Rule of Thumb Fault Current Levels:** GE Vernova shared that the rule of thumb for peak fault current levels from Type 4 wind turbines is around 1.1–1.2 pu and from Type 3 wind turbines is around 2 pu for deep faults. After the initial transient, fault current levels from Type 3 wind are more in the 1.1–1.3 pu range. This is all based on the nature of the electrical connectivity of the machine to the AC grid for Type 3 relative to a fully power electronic-interfaced turbine for Type 4.

- **Equipment Standards versus Grid Needs:** A question arose regarding what happens when a Type 3 wind turbine cannot meet the requirements of IEEE 2800-2022. One OEM highlighted that this may be why there are concerns with portions of IEEE 2800-2022 particularly for wind technology that may need to be addressed in future revisions. For example, meeting a very fast dynamic response characteristic and settling current response within certain limits is more applicable for fully power electronic-interfaced devices and may not be suitable for Type 3 wind technology. However, Type 3 wind may perform better in some system conditions to support grid reliability even if they do not conform to the IEEE 2800-2022 requirements. So careful consideration is needed to balance conformity with equipment requirements versus understanding the specific grid reliability challenges for a particular system. Type 3 wind may need careful consideration regarding adoption and conformity assessments of IEEE 2800-2022 moving forward. GE Vernova stressed that requiring a certain performance from wind to make it "perform like a current source" can "seal your fate" in terms of having the grid get "weaker" over time. Enhancements to IEEE 2800-2022 are likely need for new technologies like grid forming inverters but also for existing technologies like Type 3 wind that may provide certain attributes for the grid.
- **UL Certification and Conflicts with IEEE 2800-2022:** A question was raised regarding whether UL 1741 certification conflicts with OEMs implementing IEEE 2800-2022 requirements. Sungrow reassured the audience that the UL certifications and conformity with IEEE 2800-2022 requirements are more of an overlap in requirements as opposed to a conflict. Sungrow explained that they will often overlay the requirements from various regions and determine an "envelope" of most severe or most strict requirements and then seek to design a product that conforms to the most strict envelope of requirements. This minimizes the need to have one product for each region and bolsters the reliability and performance of the product. Equipment should be set site-specific to support local reliability needs rather than being installed with default settings based on equipment certifications alone.
- **OEM Concerns with Draft NERC PRC-029:** Multiple OEMs stressed that PRC-029 establishes a much wider frequency ride-through range than any existing requirements in North America, including the new frequency ride-through requirements in IEEE 2800-2022. This goes directly against harmonization of requirements across North America and is very problematic for OEMs. Existing IBR assets on the system today as well as equipment already in the interconnection pipeline (particularly with signed interconnection agreements) may not be able to be modified to meet these new requirements without significant retrofits (i.e., replacement of turbines); new IBRs technologies may not even be able to meet these requirements in the near-term. A technical basis for the ranges chosen is not justified by the NERC drafting team at this time, which is concerning for OEMs.

- **OEM Perspectives on Retroactivity of Requirements:** OEMs expressed concerns regarding the retroactivity of new requirements without sufficient exemptions that align with equipment capabilities. The OEMs stressed that retrofit kits may be developed to meet updated requirements but they may not exist today; dedicating OEM resources to focusing on retrofit kits can inadvertently take valuable engineering resources away from improving technology for future IBR plants. Those types of retrofit kits are only designed if there is a market need for them, which is typically based off a new requirement imposed. So there is a bit of a "chicken and egg" problem here with technological capability to meet new requirements (imposed retroactively).
- **NERC Standards Development Updates:** NERC will be hosting a technical conference on September 4–5 to further discuss the NERC PRC-029 draft and related topics. The NERC Standards Committee is delegated the responsibility to hold the technical conference (as opposed to the NERC Technical Committees). NERC will be releasing additional details on the event on August 21, 2024, including how in-person and virtual participation will be handled. Individuals who would like to be considered for panelist roles may submit their information to NERC Standards staff (Jamie.Calderon@nerc.net). After the technical conference, the NERC Standards Committee will work with NERC to use the results of the conference to draft a memo to the NERC Board and re-ballot a revised standard for public vote. NERC highlighted that both NERC and FERC will be at the conference listening to insights from industry representatives on the various issues with the current draft standard.

Key Themes

- OEMs readiness for IEEE 2800-2022 requirements appears to be advancing significantly, although there are unique considerations for possibly Type 3 wind turbine technology as well as newer technology like grid forming inverters. OEMs continue to prepare for widespread adoption and implementation of IEEE 2800-2022 across North America.
- OEMs are concerned with blanket application of IEEE 2800-2022 or other related standards (e.g., the draft NERC PRC-029) to existing assets since there were not designed with these requirements in mind. Any standard being applied retroactively needs careful consideration of the costs and impacts on existing fleet asset owners. This likely requires reasonable exemptions for technological limitations, and standards updates should be based on what is technologically feasible.
- A potential solution to this challenge is the concept of "IBR ride-through maximization," which is specifically focused on maximizing the ride-through performance of IBRs using software/firmware related updates or upgrades including changing protection and control settings and parameters to enhance IBR performance. Reviewing the various large-scale IBR-related events reported by NERC, this may be a viable solution to minimize risk on

the BPS while also minimizing costs to asset owners and avoid costly retrofits or replacements of existing technology.

- NERC standards developments related to FERC Order 901 continue to evolve, with some standards receiving successful ballot (e.g., PRC-028 and PRC-030) and other failing ballot which now invokes Section 321 of the NERC Rules of Procedures and is leading to an industry technical conference on IBR ride-through performance and issues with the draft PRC-029 standard.

September 24, 2024 Virtual Meeting

Measurement Data for Performance Monitoring and Model Validation (~180 simultaneous attendees)

Figure 16 shows the makeup of the meeting attendees by industry sector:

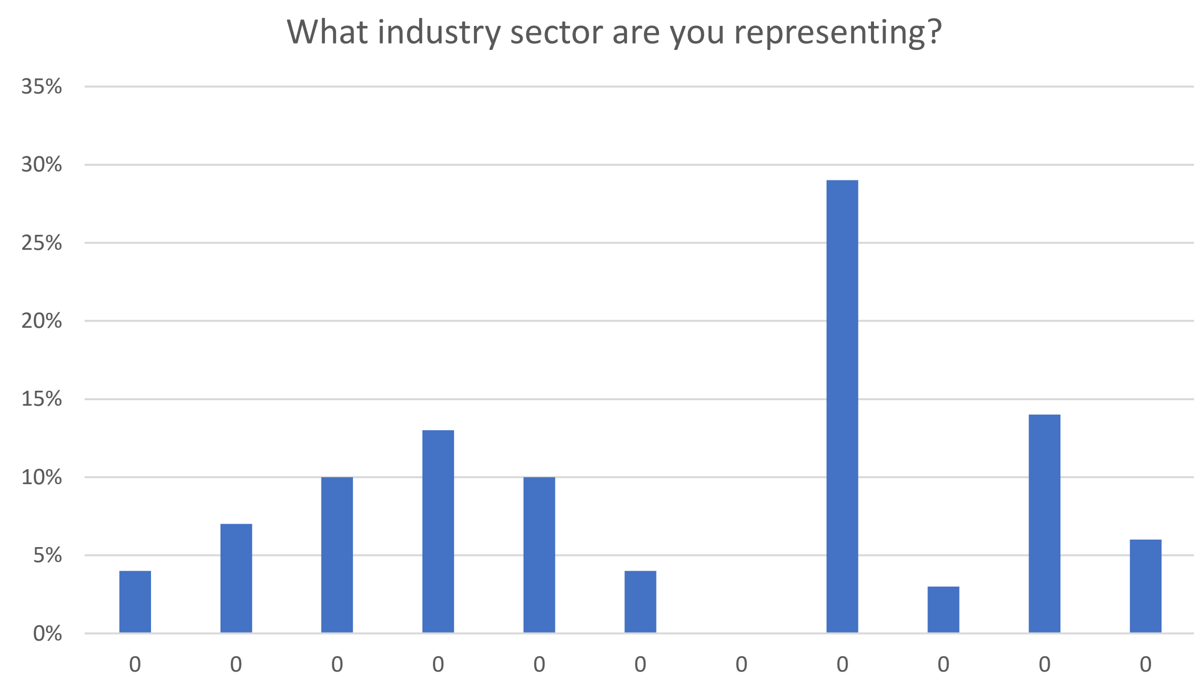


Figure 16: Meeting attendees by industry sector

This was the fifth meeting of the DOE i2X FIRST initiative, focused on IBR monitoring and measurement data related to IEEE 2800-2022 *Clause 11: Measurement Data for Performance Monitoring and Validation* and NERC PRC-028.[27] The meeting also included an informational presentation on updates from the recent NERC Technical Conference on IBR Ride-Through and modifications to NERC PRC-029 since this was the primary focus of the last two i2X FIRST meetings. Presentations included:

- **Kyle Thomas, Elevate Energy Consulting:** Kyle shared updates from the recent NERC IBR Ride-Through Technical Conference[28,29] and recent revisions to NERC PRC-029 which will go out for final industry ballot shortly. NERC PRC-029 is part of the FERC Order No. 901 directives and must be filed with FERC by November 4, 2024. The draft

[27] https://www.nerc.com/pa/Stand/Pages/Project-2021-04-Modifications-to-PRC-002-2.aspx
[28] https://www.nerc.com/pa/Stand/Documents/Agenda-Standards%20Committee%20and%20NERC%20Ride-through%20Technical%20Conference.pdf
[29] https://www.nerc.com/pa/Stand/Documents/Panel%20Questions%20-Standards%20Committee%20and%20NERC%20Ride-through%20Technical%20Conference.pdf

has gone out for industry comment and ballot three times and failed each ballot. Thus, the NERC Board of Trustees invoked Rule 321 of NERC's Rules of Procedure, which led to the technical conference to gather industry insights, feedback, and concerns with the standard. The conference was well attended by a wide range of stakeholders including utilities, IBR developers and owner/operators, regulatory bodies, and IBR OEMs. Key discussion topics included:

- Challenges developing a definition for ride-through, and industry polling led supermajority voting to adopt the ride-through definition used in IEEE 2800-2022.
- Frequency ride-through curves in draft PRC-029 far exceed IEEE 2800-2022 requirements and other current industry requirements. This would result in new and existing resources failing to meet these performance requirements. Industry expressed concerns with the lack of technical justification behind these proposed expanded curves.
- The lack of exemptions for frequency ride-through, particularly for hardware-based limitations that cannot be effectively addressed without costly retrofits or replacement of turbines or inverters. This, combined with the issue above regarding expanded frequency ride-through curves, was a serious concern for industry stakeholders.

Draft 4 of NERC PRC-029 was released for comment on September 17, 2024 and out for final ballot until September 30, 2024.[30] The updated draft includes a definition of ride-through that removes ambiguity and adds clarity. The frequency ride-through curves are aligned with IEEE 2800-2022 criteria. For existing IBRs, frequency ride-through exemptions were included for hardware-based limitations when sufficient technical justification is provided. Thus, the updated PRC-029 is much more closely aligned with IEEE 2800-2022 performance curves and has addressed the major industry concerns to-date.

- **Alex Shattuck, NERC:** Alex described the need for IBR monitoring and measurement data, particularly for forensic event analysis and root cause investigations. Alex stressed that the higher resolution data one can acquire within the facility will result in deeper forensics being uncovered as part of the analysis. Limited event analysis can be conducted with low resolution SCADA data such as area control error (ACE) or total IBR output trends. Plant-level SCADA data can help understand the general behavior of an IBR during a grid event to help guide the next steps in analysis. Plant-level digital fault recorder (DFR) data can help provide a much clearer understanding of the IBR dynamics during a large grid event such as a fault or generator trip. Inverter-level fault codes are needed to understand tripping and abnormal performance at the unit-level. Finally, high resolution inverter-level oscillography data is the best source of information to understand how the individual inverters respond to grid events relative to the electrical

[30] https://www.nerc.com/pa/Stand/Pages/Project_2020-02_Transmission-connected_Resources.aspx

quantities in the rest of the plant. This data is often stored in the inverters for access by the OEMs but is not made readily available to the IBR owner/operator and thus needs to be retrieved quickly for event analysis purposes. Figure 17 shows some illustrations of high resolution data from past event analyses.

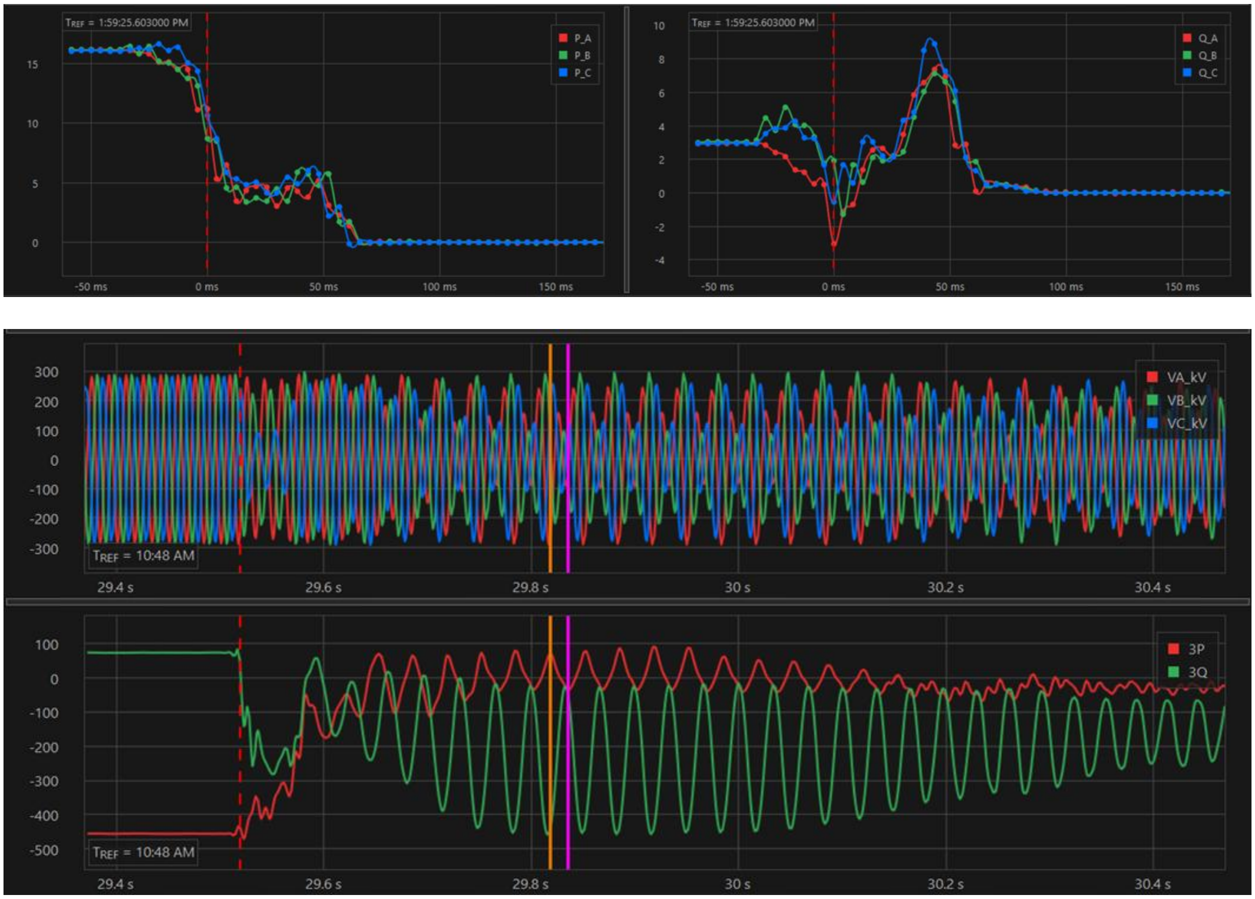


Figure 17: High Resolution Data Examples from Past Event Analyses [Source: NERC]

- **Manish Patel, EPRI:** Manish outlined the disturbance monitoring requirements in IEEE 2800-2022 and NERC PRC-028.[31] There are notable differences between the two standards (see Figure 18) in terms of the types of data required, resolution of data collected, duration of measurement quantities collected, retention of data stored, and time synchronization accuracy. IEEE 2800-2022 requirements tend to far exceed the requirements set forth in NERC PRC-028 from a technical perspective. For example, IEEE 2800-2022 requires IBR unit-level DFR data (high speed oscillography data) from each inverter whereas NERC PRC-028 does not include these provisions in any way. IEEE 2800-2022 requires plant-level DFR data of at least 128 samples per electrical cycle stored for at least 90 days; NERC PRC-028 requires the same type of data at 64 samples per cycle stored for at least 20 days. These types of differences are likely due to

[31] https://www.nerc.com/pa/Stand/Pages/Project-2021-04-Modifications-to-PRC-002-2.aspx

the fact that IEEE 2800-2022 is intended to be a forward-looking standard (generally not applied retroactively to existing assets) whereas NERC PRC-028 will apply to all existing and new IBRs that meet NERC's jurisdiction.

	IEEE 2800-2022 Clause 11 (Measurement Data for Performance Monitoring and Validation)	PRC-028 Disturbance Monitoring and Reporting Requirements for IBRs	Comments
	Forward looking standard	Applicable to existing and new IBRs (BES and non-BES)	
SCADA Data	Yes	No	
Plant Level SER Data	Yes	Yes	Requirements in PRC-028 may be brief but serves purpose
Unit Level SER Data	Yes	Yes	
Plant Level DFR & DDR Data	Yes	Yes	
Unit Level DFR Data	Yes	No	In PRC-028, FR data from collector feeder breaker is required instead
Unit Level DDR Data	No	No	
Measurement Accuracy	Yes, except for unit level data	No	

Figure 18: Requirements in IEEE 2800-2022 versus NERC PRC-028 [Source: EPRI]

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Challenges for Existing Assets:** Presenters highlighted that existing IBRs will likely need to add additional monitoring equipment to be able to capture data within an IBR plant. There are some costs associated with this, although at the IBR plant-level they are expected to be minimal since PPCs and microprocessor-based relays can often be configured to capture this type of data. However, IBR unit-level data may be more challenging to collect for legacy resources and some exceptions may be needed. This is likely a significant factor as to why the NERC PRC-028 requirements are significantly less stringent than IEEE 2800-2022.
- **Developer Perspective Regarding Monitoring Equipment:** One audience member from an IBR developer/owner highlighted that having mandatory requirements for monitoring will dramatically improve business practices within the IBR developer/owner community. The audience member highlighted that they have had little success or traction getting costs allocated to install and upkeep monitoring equipment for their fleet. The new requirements will force the business to take this type of activity more seriously, dedicate resources to supporting this, and will likely improve overall fleet performance. Past experience has shown that without these requirements the equipment, servers, and/or

communications channels are not working properly since they are not regularly maintained.

- **Go Beyond NERC PRC-028 Where Possible and Cost Effective:** Multiple presenters highlighted that NERC PRC-028 was developed considering the significant limitations of existing IBRs in terms of their measurement capabilities. Therefore, new IBRs should seek to align more closely with IEEE 2800-2022 (or adopt it where possible and/or required). For example, NERC PRC-028 does not include requirements for IBR unit-level oscillography data; however, this data can be very valuable for forensic root cause analysis, performance monitoring, and dynamic model validation. Therefore, rather than employ this monitoring at every inverter (which is much more costly), IBR owners may consider enabling it at a few inverters throughout the plant so that the data is available if ever needed. There is little financial impact, if any, to enable this capability in new inverters today and the data can be effectively retrieved when needed.
- **Implementation Timelines:** Manish explained the implementation timeline for NERC PRC-028. Per the FERC Order No. 901 directive, the standard must be fully implemented and enforceable before 2030. The implementation plan include a provision for 50% of an owner's fleet to be compliant within 36 months of the effective date of the standard and the entire fleet must be compliant by 2030. This timeline should be adequate to design new monitoring systems, procure equipment, schedule outages for installation, and begin storing the measurement data necessary. Extensions may be granted, if needed, on a case-by-case basis if IBR owners work with their respective compliance enforcement authority.
- **Software-Based versus Hardware-Based Improvements:** The panelists discussed leveraging the fullest extent of software-based upgrades to equipment, whether for ride-through performance or for monitoring equipment. This can help minimize costs and maximize performance.[32] When hardware-based upgrades are required (e.g., retrofitting or replacing entire inverters or turbines), the costs to asset owners increases by orders of magnitude and therefore these complications need to be adequately considered by standards development bodies and respective entities enforcing the standards.

Key Themes

- Strong industry engagement, particularly from asset owners and OEMs, at the NERC IBR Ride-Through Technical Conference with real-world technical examples of equipment limitations, costs, and other feedback led to an effective discussions and meaningful changes to the regulatory requirements to align with industry needs. The updated version of NERC PRC-029 following the conference included aligning the NERC PRC-029

[32] See related presentation from Ryan Quint from Elevate Energy Consulting on the Concept of "Maximizing" Ride-Through at August 20th i2x FIRST meeting. Presentation recording and slides are available to download here.

frequency ride-through-curves with IEEE 2800-2022 as well as allowing for exemptions based on technically justified hardware limitations.

- IBR measurement data has been invaluable for industry to gain a deeper understanding of the technology, design decisions, risks, and technical solutions to improve IBR performance over the past decade. NERC, transmission providers, and asset owners have leveraged high-speed data, particularly at the plant-level and inverter-level, to improve the reliability of inverter technology. Availability of higher resolution data results in deeper insights for better forensic analysis.
- There are significant differences between the requirements set forth in IEEE 2800-2022 and NERC PRC-028. This is mostly due to the fact that IEEE 2800-2022 was intended to be applied for newly connecting IBRs whereas NERC PRC-028 will apply to all IBRs within NERC's jurisdiction including existing and new IBRs. Existing IBRs will likely be unable to meet stringent IBR monitoring requirements, particularly for unit-level monitoring. Therefore, the NERC PRC-028 drafting team took that into consideration when developing requirements and decided not to differentiate between existing and new IBRs in terms of the requirements applied.
- Existing assets will be required to meet the new NERC PRC-028, where applicable, and reasonable implementation times (and extensions) were intentionally included by the drafting team. New assets should seek to meet IEEE 2800-2022 requirements (of course, particularly where those requirements are mandatory). This approach will also help new assets comply with the technical requirements of NERC PRC-028 since IEEE 2800-2022 monitoring requirements are notably more stringent than the NERC requirements.

October 24, 2024 (Hybrid Event at ESIG Fall Workshop)

IEEE P2800.2 IBR Plant Conformity Assessment (~50 in-person and ~80 virtual attendees)

Figure 19 shows the makeup of the meeting attendees by industry sector:

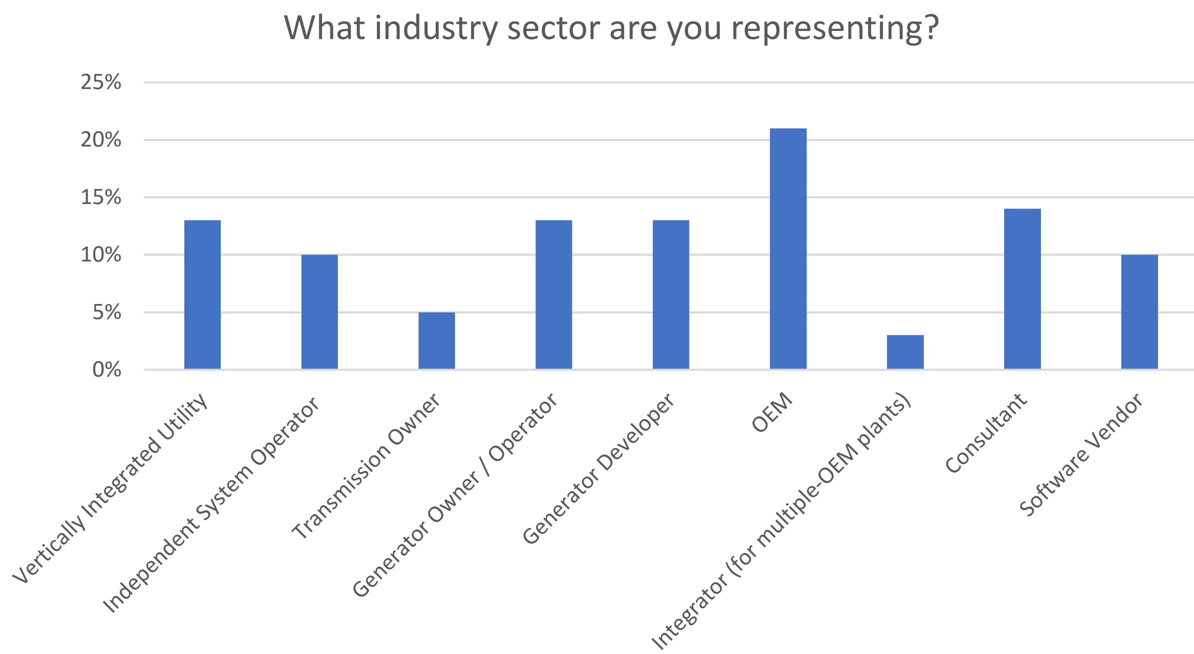


Figure 19: Meeting attendees by industry sector

This was the sixth meeting of the DOE i2X FIRST initiative, focused on IEEE P2800.2 *Draft Recommended Practice for Test and Verification Procedures for Inverter-Based Resources Interconnecting with Bulk Power Systems* and IBR plant performance conformity assessments.[33] The meeting was held in conjunction with the Energy Systems Integration Group (ESIG) Fall Technical Workshop in Rhode Island. Presentations included:

Session 1: Opening Remarks and Background Information

- **Julia Matevosyan, ESIG – Introduction to DOE i2x FIRST and the Workshop:** Julia provided a high-level overview of the i2X initiative, key themes from past meetings, and the goals of the hybrid workshop.
- **Ryan Quint, Elevate Energy Consulting – Need for IBR Plant Conformity Assessment:** Ryan provided background regarding adoption needs and strategies for IEEE 2800-2022 as a starting point for evolving IBR plant conformity assessments. He highlighted the recently released ESIG brief *IBR Interconnection Requirements: Status*

[33] https://standards.ieee.org/ieee/2800.2/10616/

and Needs,[34] which included a call to action for ISO/RTOs, transmission providers, and their customers adopting large parts of voluntary industry standards such as IEEE 2800-2022. Additionally, Ryan highlighted how improving IBR plant conformity assessments would likely help address systemic risks observed by NERC in past large-scale events and potentially speed up interconnection processes. However, speed of interconnection must be balanced with the depth and breadth of IBR plant conformity assessment details included in future requirements. Lastly, Ryan stressed that IEEE P2800.2 adoption by transmission providers would need careful consideration and integrated with the obligations of the FERC Large Generator Interconnection Procedures and the timelines set in FERC Order 2023.[35]

- **Andy Hoke, NREL – IEEE 2800.2 Progress Update:** Andy emphasized that the IEEE 2800-2022 and IEEE P2800.2 teams encourage entities to adopt IEEE 2800-2022 even before IEEE P2800.2 is complete and approved. He explained how IEEE 2800-2022 Clause 12 includes a framework for test and verification of IBR plant requirements which can help entities get started in this area; IEEE P2800.2 includes the details of how to conduct the tests and checks to know if an IBR plant is conforming to IEEE 2800-2022. Andy also announced that draft 2.0 of IEEE P2800.2 was released to drafting standards team members for commenting. The drafting team is targeting completion, approval, and publishing of IEEE P2800.2 some time in late 2025 or early 2026. Andy also gave an overview of the process flowchart for IEEE P2800.2 (see Figure 20) which lays out the specific clauses of the recommended practice and how they integrate together. This includes:
    - **Type tests** that include lab or field tests of individual IBR units that generate actual IBR unit performance data for subsequent model validation
    - **IBR unit model validation** that ensures that the models of individual IBR units are validated to match the actual product across a range of conditions.
    - **IBR plant model development** involving the creation of a full IBR plant model that includes the IBR unit(s) as well as balance of plant elements.
    - **IBR plant design evaluation** where simulations are used to assess IBR plant conformity to specific IEEE 2800-2022 requirements
    - **As-built installation evaluation** where the installed equipment and their respective configuration (controls, protections, settings, parameterization) are verified to ensure they match what was studied
    - **Commissioning tests** that include partial field assessment of plant performance, where possible

[34] https://www.esig.energy/wp-content/uploads/2024/10/ESIG-IBR-Interconnection-Requirements-brief-2024.pdf
[35] https://www.ferc.gov/media/pro-forma-lgip

- **Post-commissioning model validation** where the results of commissioning tests are used to validate the IBR plant model matches actual installed equipment
- **Operational monitoring** where the response and performance of the IBR plant is monitored during grid events and any issues are corrected as needed
- **Periodic tests and verifications** where subsequent tests and verifications are conducted during the operational lifecycle of the IBR plant

The first six topics are discussed in subsequent presentations of this workshop, while the last three topics related to the period after an IBR plant has been commissioned will be discussed in the next hybrid workshop during ESIG Spring Workshop in March 2025.

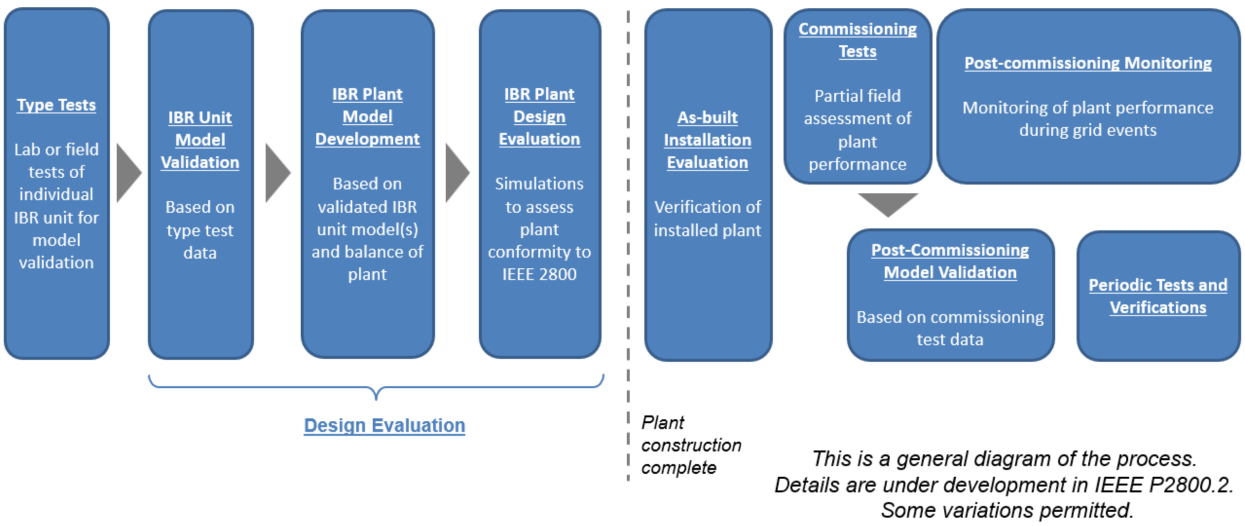


Figure 20: High-Level Process Flowchart of IEEE P2800.2 and its Clauses [Source: IEEE©2024]

Lastly, Andy shared some key terms used throughout IEEE P2800.2 that are important to understand for implementation of the clauses. These include the following:

- **Model Validation:** The process of comparing measurements with simulation results for the assessment of whether a model response sufficiently matches the measured response.
- **Model Benchmarking:** the process of comparing simulation results from two models for the assessment whether a response from one model sufficiently matches the response from the other model for the same disturbance and external power system conditions.
- **Model verification:** The process of checking documents and files or equipment and respective settings (e.g., controls & protection), and comparing them to model parameters or model structure.

- **Aung Thant, NERC – Importance of IBR Modeling and Design Evaluation:** Aung shared perspectives from NERC regarding the need to address systemic IBR performance issues and risks that have been observed by NERC. He shared that these issues stem from poor model representation and that industry has a "modeling pandemic" overall; Aung urged for improved IBR modeling practices to improve the accuracy of engineering and reliability studies conducted during the interconnection process and in planning and operations horizons. NERC has been challenged in gathering data and information from IBR owners in recent Alerts that have been issued.[36] Aung shared that NERC is planning to release its first-ever Level 3 Alert[37] which will be focused on IBR modeling and performance issues. Lastly, Aung shared an overview of ongoing NERC activities related to IBRs and how that work aligns with the IEEE P2800.2 proposed design evaluation steps. Aung stressed that adoption and implementation of IEEE P2800.2 would likely address the systemic risks identified as well as improve data availability for IBR owners.

Session 2: IBR Plant Modelling and IEEE P2800.2 Design Evaluation

- Alex Shattuck, NERC – Review of Design Evaluation Requirements and Recommended Best Practices in IEEE 2800-2022 and IEEE P2800.2: Alex focused on design evaluation recommended practices in IEEE P2800.2, which specifically includes IBR unit model validation, IBR plant model development, and IBR plant design evaluation. Figure 21 shows the process flow for these steps. The IBR unit model is validated and an IBR plant model is developed and verified. That model, or a best available model (for early in the interconnection process) is then run through IBR plant model quality tests and a series of simulation-based IBR capability and performance verification tests to determine if the IBR plant design meets the IEEE 2800-2022 requirements (where applicable requirements can be assessed). Alex then covered the scope and procedures for the various tests and illustrated what some of these tests could look like in terms determining conformity. In essence, Alex stressed that if these procedures are followed appropriately and correctly during the interconnection modeling and study process, then more accurate IBR models will result in and lead to better IBR design evaluations and more accurate reliability studies.

[36] https://www.nerc.com/pa/rrm/bpsa/Alerts%20DL/NERC%20Alert%20Level%202%20-%20Inverter-Based%20Resource%20Model%20Quality%20Deficiencies.pdf
[37] Level 3 Alerts are "Essential Action" alerts which are intended to identify actions deemed to be "essential" to BPS reliability and requires approval by the NERC Board of Trustees prior to issuance. Like recommendations, essential actions require applicable NERC-registered recipients to respond as defined in the alert.

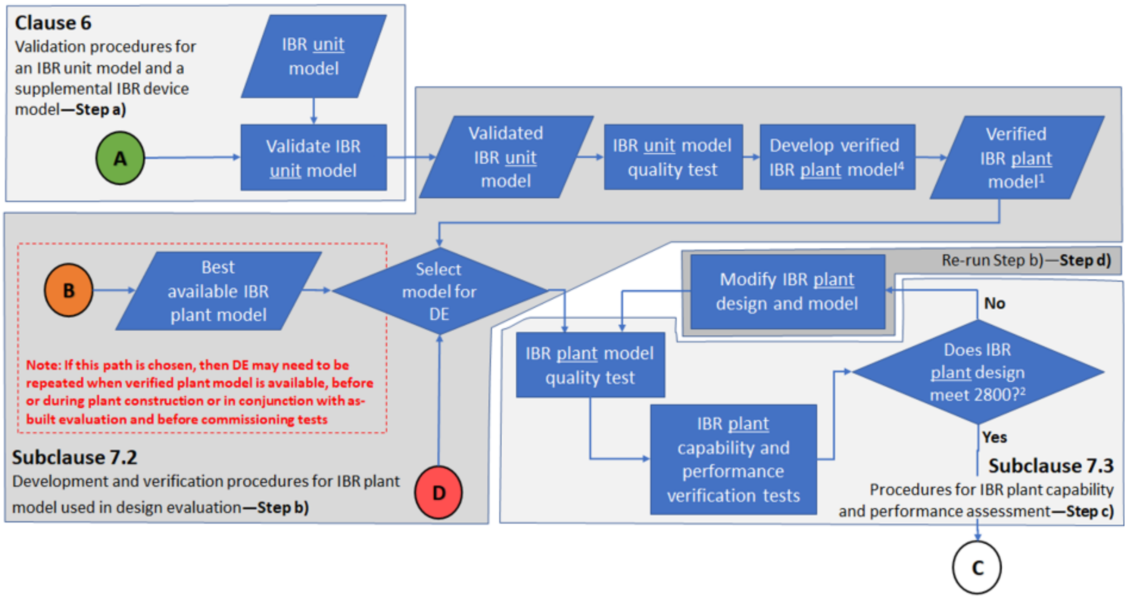


Figure 21: Overview of IEEE P2800.2 Clause 6 and Clause 7 [Source: IEEE©2024]

- **Miguel Cova Acosta, Vestas: OEM Perspective: IBR Plant Design Evaluation through Testing and Modeling:** Miguel shared considerations and perspectives from an OEM regarding IBR plant design evaluations. He emphasized that presently there is a lack of defined accountability in assessing if the IBR plant is conforming or compliant with requirements that may exist (see Figure 22). The OEM does not own the plant and may not have information regarding balance of plant design and configuration. The GO lacks a comprehensive understanding of OEM equipment capabilities due to proprietary information and other factors. The transmission provider is concerned with compliance to requirements but can only assess the information provided to them through assessment documentation.

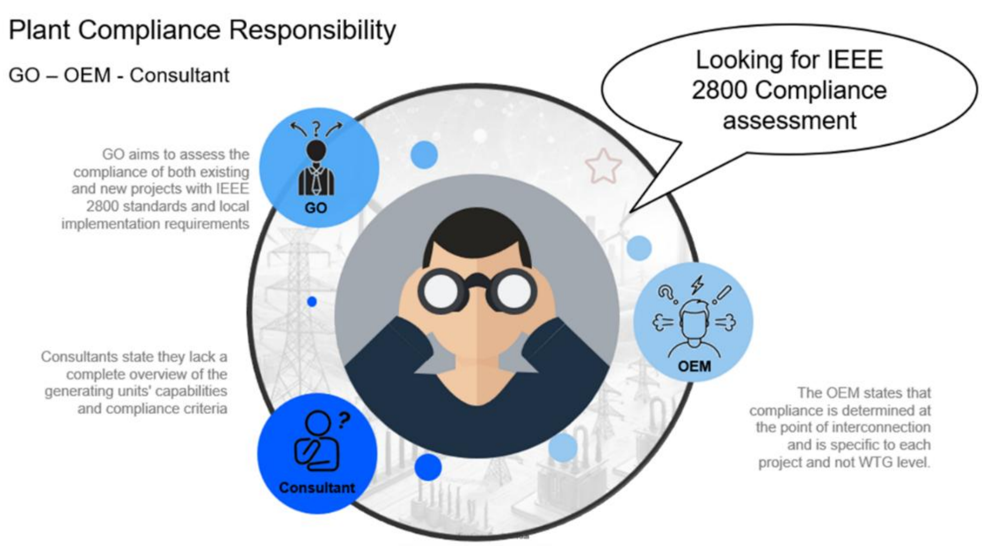


Figure 22: IBR Plant Conformity Assessment or Compliance Responsibilities [Source: Vestas]

The process is also highly iterative with preliminary models often used early in the interconnection process, updates being made throughout the study process, model bug fixes and corrections occurring regularly, cycles of due diligence on design and tuning, and validation/verification at commissioning and into commercial operation (see Figure 23). Miguel also highlighted that full implementation of IEEE P2800.2 could result in thousands of simulation test results being conducted over the interconnection process of a single IBR plant, which will dramatically increase workload and could cause delays in interconnection; therefore, a staged and systematic approach to IEEE P2800.2 is likely needed. Miguel shared that all models have limitations but that automation and thoughtful OEM model development can help eliminate the possibility of human error or unnecessary issues as long as sufficient engineering oversight is provided for any automation tool use.

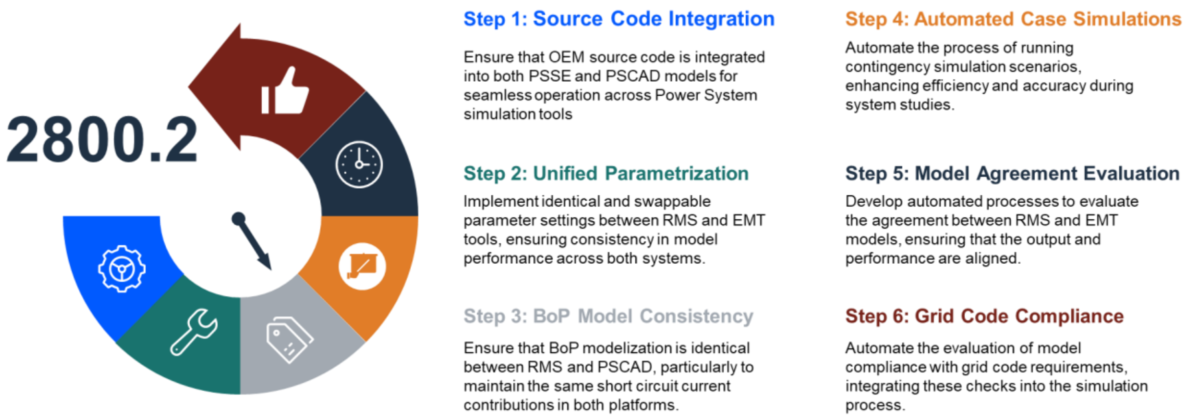


Figure 23: Aspects of OEM Involvement in P2800.2 IBR Unit Model Creation and Conformity Assessment [Source: Vestas]

- **Billy Yancey, EPE – Present-Day Design Evaluations Analysis and Challenges:** Billy shared experience with developing IBR plant models and meeting regulatory and ISO/utility requirements throughout the interconnection process. The processes introduce challenges for both the OEM and the developer, and are also difficult to strictly adhere to while the IBR plant model and design evolves throughout the process. This can lead to short decision timelines and difficulties getting accurate IBR model information to meet key milestones, which may put third-party consultants or other entities in a bind to deliver something for the project with few alternative solutions explored collaboratively between the IBR plant developer and the transmission provider. Billy stressed that collaboration is needed between the IBR plant developer, OEM, and transmission provider throughout the process. He also talked about various design evaluation types for an IBR plant including a test single-machine-infinite-bus system or equivalenced network and the IBR plant being subjected to a defined set of tests that evaluate its performance.

Session 3: IEEE 2800.2 Design Evaluation, Model Validation and Benchmarking Deep Dive

- **Andrew Isaacs, Electranix – IEEE P2800.2: The Trouble with Model Validation!:** Andrew focused more closely on the technical details of model validation and some of challenges that the IEEE P2800.2 team is contemplating. IBR unit-level hardware tests and model tests are used to create a validated IBR unit model. Those models are combined with the balance of plant components to create an IBR plant model, specifically in EMT domain. That EMT model is then expected to represent the IBR plant in as best detail as possible. The phasor domain model can then be created and benchmarked against the EMT model for specific tests to prove it sufficiently matches, where possible (see Figure 24).

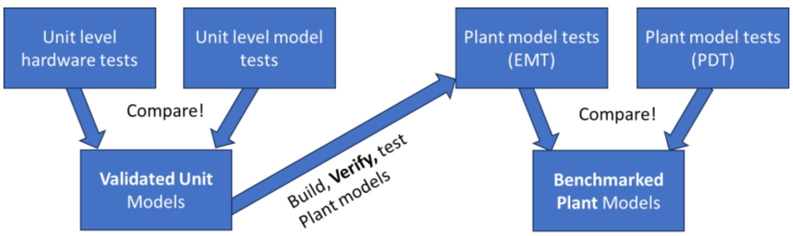


Figure 24: Steps of Model Development, Validation, Testing, and Benchmarking [Source: IEEE©2024]

Type tests are typically performed by the OEM on a specific unit of equipment in a controlled facility (i.e., these tests are not intended to be conducted on every piece of equipment or repeated for every IBR plant). Challenges arise on determining which types of validation test setups and specific test procedures shall be used to validate the models and how the simulation results will be compared and assessed. A list of tests are specified for comparing the IBR unit EMT model versus type tests. Practically, however, insufficient care in model development and uncertainties in test system conditions may result in some degree of error in the models, which can propagate throughout the process. There can be serious complications in strictly comparing model response versus actual hardware response; some discrepancies are acceptable while others are not. This requires relatively expert engineering judgment to discern and also takes significant time (i.e., very hard to automate this step). On the other hand, qualitative assessment (i.e., opinions) is necessary in some cases. Therefore, the IEEE P2800.2, at the time of presentation has devised a validation approach that includes multiple steps wherein quantitative comparisons *should* be done followed by qualitative analysis that *shall* be done (see Figure 25).

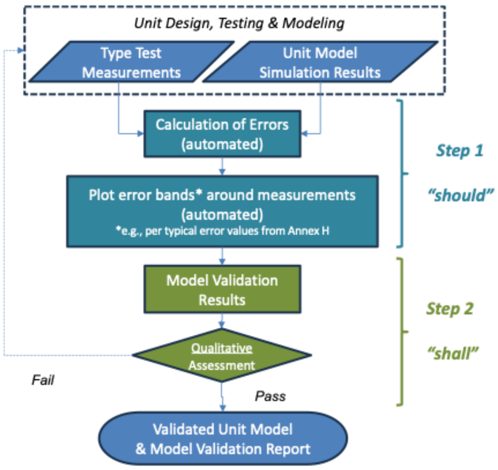


Figure 25: Proposed IEEE 2800.2 Model Validation Assessment Process [Source: IEEE©2024]

- **Miguel Cova Acosta, Vestas – OEM Perspective: IBR Unit Model Validation:** Miguel shared OEM perspectives regarding IBR unit model validation, covering how product software is ultimately converted into simulation models used in commercial platforms (see Figure 26). Vestas uses a "one library, many simulation tools" approach where the product software source code used in the WTG and PPC is converted to a sharable .dll file that can be integrated with various models across software platforms. Therefore, this is one "seed" representation of that specific inverter that can be traceable throughout the process. This is used in the OEM product design process and model validation process.

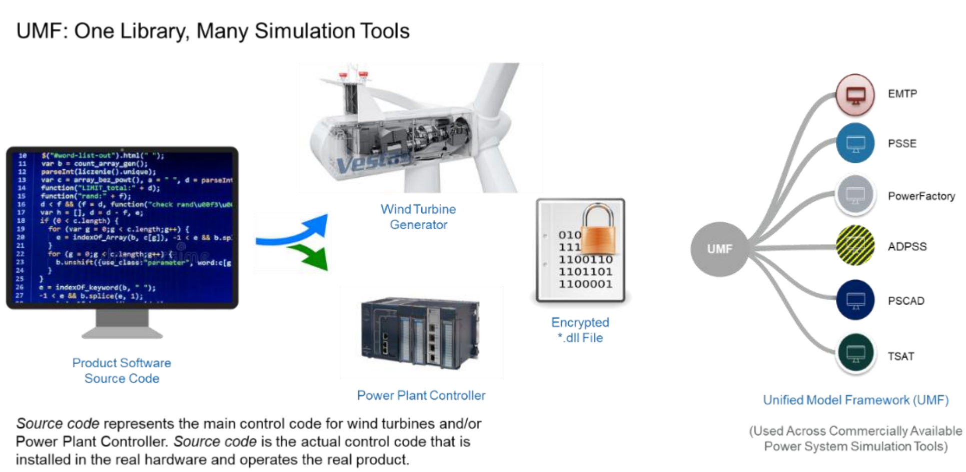


Figure 26: Vestas Process of Converting Product into Models [Source: Vestas]

Miguel also described how different types of model validation are used in different stages of the process (see Figure 27). Model versus hardware-in-the-loop (HIL) testing is used to compare an IBR unit model against hardware tests but this only represents a single WTG or inverter. Therefore, software-in-the-loop (SIL) can be used to expand that to an IBR plant. Models can also be compared against field tests or IBR plant performance during commissioning. Additionally, models can be compared against each other (i.e., benchmarking) and tested after IBR plant commissioning when actual grid disturbances occur.

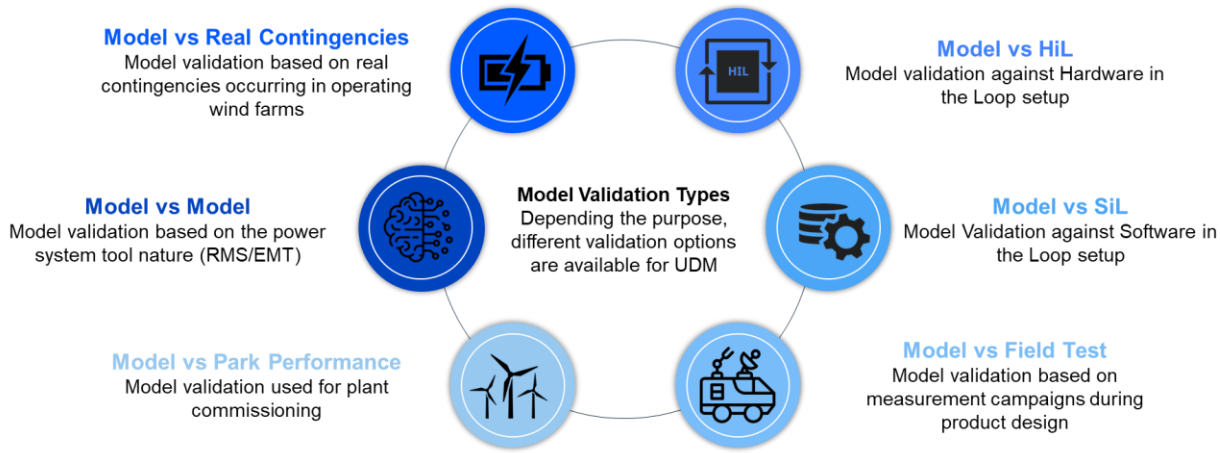


Figure 27: Vestas Model Validation Variances [Source: Vestas]

- **Andrew Isaacs, Electranix – IEEE P2800.2 Design Evaluation Tests – A Deep Dive:** Andrew described how the design evaluation fits into the overall IBR plant conformity assessment. Ultimately, design evaluation consists of reviewing validation report(s), ensuring the model passes a set of quality checks, is accompanied by sufficiently accurate and comprehensive documentation, and passes a set of IBR plant performance tests. The performance tests use the IBR plant model against a pre-defined simulation test system and simulation procedure (see Figure 28 for some examples). The focus is on using a controllable voltage source equivalent (i.e., system side representation) in the simulation test bench to subject the plant to specific conditions that can be used to compare the performance against the IEEE 2800-2022 requirements. Some of the more "controversial" IEEE 2800-2022 requirements, as described in previous i2X FIRST meetings, are not included in the IEEE P2800.2 test and verification clauses – namely, transient AC overvoltage conditions and consecutive voltage deviations. This is predominantly due to difficulties in conclusively testing these requirements since they are dominated by the IBR unit capability yet the IBR plant design (collector system, arrestor coordination etc.) all play critical factors .Ensuring the IBR plant passes the defined performance requirements is a critical step in the interconnection process and can be adapted to the requirements in place for any transmission provider; however, the benefit of IEEE P2800.2 is that the tests are standardized which enables a more harmonized and automated process for reviewing results.

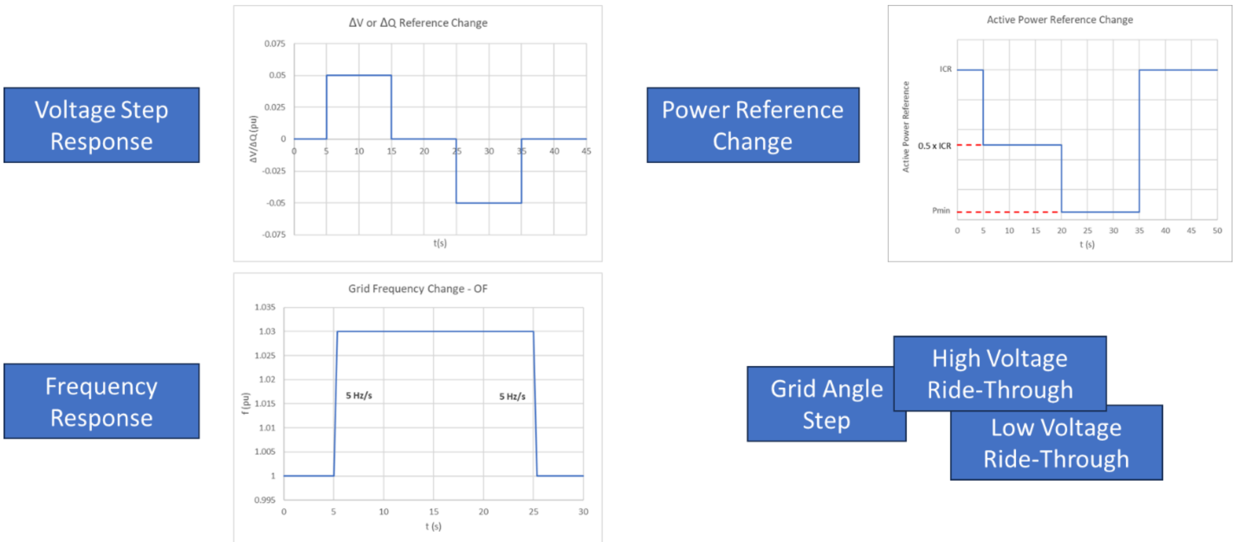


Figure 28: Proposed IEEE 2800.2 Design Evaluation Simulation Test Examples [Source: IEEE©2024]

Session 4: "As-Built" Evaluation and Commissioning Testing

- Chris Milan, CrestCura – Review and Examples of "As-Built" Evaluation and Commissioning Testing Requirements and Recommended Best Practices in IEEE 2800-2022 and IEEE P2800.2: Chris described how the as-built evaluation is an on-site process at the time of commissioning to verify that the IBR units, the collector system, supplemental IBR devices, and other balance of plant components and protections that comprise an IBR plant are delivered and installed to meet or exceed the design as defined in the IBR plant design evaluation. If significant changes are made to controls, protection, or design that potentially change IBR plant performance, then a design reevaluation and conformity reassessment may be needed. These additional steps could add significant delays and should be avoided; however, ensuring a thorough as-built evaluation is conducted is critical in ensuring that what gets installed matches what was studied and that any discrepancies are addressed for the benefit of all parties involved. Similarly, commissioning tests are not intended to check that the plant meets the capability and performance requirements specified since it is unlikely that commissioning tests can actually test IBR plant capability and the full extent of its performance range. Therefore, these tests are used to provide data of the actual response of the IBR plant such that model validation can be done on the entire facility using measured data. IBR plant commissioning test procedure should be written and approved by the transmission provider before initiating. Chris reviewed each of the clauses of IEEE P2800.2 for both these topics at the meeting.

Concluding Remarks

- **Ryan Quint, Elevate Energy Consulting:** Ryan offered some concluding remarks and observations for the suite of presentations covering IEEE P2800.2 and related IBR plant conformity assessment activities. First and foremost, Ryan emphasized that adopting and implementing IEEE 2800-2022 is a resounding message from industry experts and that the recommended approach given activities at the various regulatory levels is for transmission providers (ISO/RTOs or transmission utilities) to implement the standard as uniformly as possible to harmonize with other regions. As part of the ESIG brief on IEEE 2800-2022, Elevate, ESIG, and EPRI have led a renewed alignment of how the adoption methods are described and recommend a hybrid integration approach (Figure 29) since it allows for some degree of flexibility (targeted enhancements, phased approach, etc.) and also includes the key system-specific information necessary for interconnection customers to effectively demonstrate conformity with the standard without significant back-and-forth with the transmission provider.

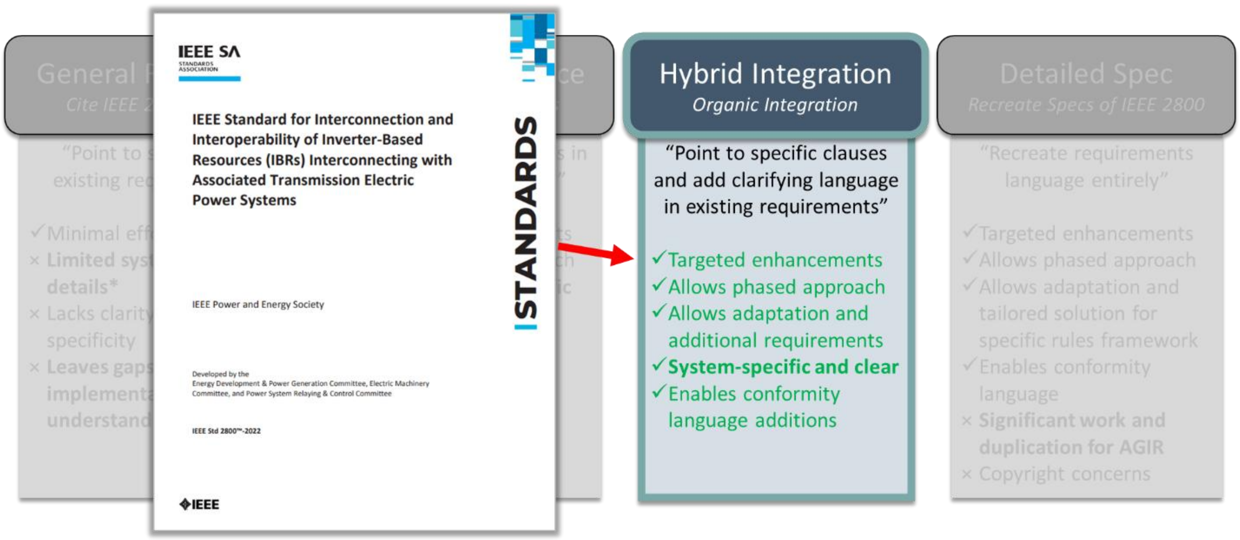


Figure 29: Recommended IEEE 2800-2022 Adoption Approach [Source: Elevate Energy Consulting]

Additionally, when integrating the recommended practices in IEEE P2800.2 (once approved), consider how those fits with other activities or areas of improvement under consideration. Utilities and ISO/RTOs may be updating their interconnection requirements with IEEE 2800-2022 requirement, they may be developing enhanced IBR plant modeling requirements, they may be thinking about how to bolster IBR plant evaluations, and they may be considering ways to generate more collaboration and accountability from the OEM (e.g., HIL testing results, attestations, etc.). All of these concepts are components of a comprehensive IBR performance conformity assessment process that ideally should be developed and integrated into the interconnection study processes.

Figure 30: Alignment of Areas of Interconnection Process Improvement [Source: Elevate Energy Consulting]

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Quantitative versus Qualitative Criteria for Model Validation:** This topic was discussed at length in the workshop, in terms of the pros and cons of each approach and how a balance must be struck in developing requirements and implementing these requirements. The audience recognized that quantitative criteria allows for a more objective and automated approach that a less experienced workforce can handle (which is necessary given the significant workload associated with processing the interconnection queue and insufficient experienced technical engineering staff in this area). Conversely, using strictly quantitative success criteria could lead to some OEMs not being able to effectively pass tests or could even lead to less innovation in the space, particularly during transient conditions where these mismatches may be explained by modeling or simulation software limitations. The current draft IEEE P2800.2 approach is to use "may" language in the informative Annex I for quantitative validation while using "should" language for qualitative validation with additional recommendations in Annex H. Additional training and education will be needed in this area in the near future to expedite effective implementation of IEEE P2800.2 testing and verification and IBR plant conformity assessment reviews.
- **Model Maturity Through Interconnection Process:** It is recognized in IEEE P2800.2 that an accurate model of the IBR plant may not be available early in the process before design decisions are made. There are specific call-outs in the standard where "best available model" is used and a more accurate model is obtained later. However, this becomes a risk management question for IBR plant developers and IBR owners and highlights the importance of automation of IBR plant conformity assessment. Some

"preliminary" model-based plant verifications paired with some form of IBR plant equipment capability verification early could reduce risks. Using "general" models early in the process that are not reflective of actual equipment to be installed will likely require re-verification and re-evaluation of IBR plant design throughout the process, which could slow down the interconnection queue processing and delay the project. Updates to the IBR model, which are fundamentally used to conduct these assessments, require re-work across all parties involved. Therefore, there is a balance and tradeoff for both the IBR plant developer and the transmission provider. Requiring these tests early on in the process may result in more re-work than necessary; IBR plant conformity assessments should likely be implemented once IBR plant design evaluations can be conducted on the actual selected equipment. This may be closer to signing of the interconnection agreement and considered a "final design evaluation".

Key Themes

- **Harmonization of Interconnection Standards:** Harmonization of interconnection standards and requirements will significantly help speed up the interconnection process and result in more accurate IBR plant models, more reliable IBR plant designs, and more thorough conformity assessments. Standards such as IEEE 2800-2022 and IEEE P2800.2 can serve as effective tools to improve interconnection requirements in a standardized and harmonized manner.
- **Enhancing IBR Plant Conformity Assessments:** IEEE P2800.2 is likely to be complete in 2026 and industry will likely begin adopting it after this time. However, many ISO/RTO and transmission providers are already requiring some degree of model validation, model quality checks, IBR plant design evaluations, IBR plant performance conformity assessments, and other similar concepts in existing requirements. Therefore, in many areas, the requirements will likely continue to evolve and hopefully be implemented in a harmonized manner. However, the adoption of these requirements needs to be balanced with the resourcing, effort, and time involved, as described throughout this report.
- **IBR Unit and IBR Plant Model Validation:** Having an accurate and validated IBR unit model (and other equipment unit-level models) establishes a foundation for creating the IBR plant EMT model which serves as the most accurate reflection of the expected performance of the IBR plant. Once created, this model can be used for conducting subsequent IBR plant design evaluations. Creation of these models to conform with IEEE 2800-2022 requirements call for close coordination between the OEMs and the IBR plant developer. Qualitative and quantitative testing should be used to develop the models and create supporting documentation that justifies model performance. Using models with generic parameters early in the process likely requires re-work later in the process.

- **Design Evaluations:** IBR plant design evaluations should generally be done in EMT domain and are essentially a series of tests that must be passed by the IBR plant model to justify that the capability and performance of the model meets the applicable requirements. Therefore, these tests should be conducted on the "final design" of the IBR plant to avoid re-work. The tests are being developed by the IEEE P2800.2 drafting team to align with the IEEE 2800-2022 requirements as well as a set of additional informational tests to help more deeply understand the performance of the IBR plant. Testing can be automated to a large extent; however, review of testing results should be done with caution and engineering judgment in some cases.
- **Balancing Comprehensiveness, Speed, and Engineering:** The implementation of all the IEEE P2800.2 test and verification practices will significantly increase workload on all parties throughout the interconnection process and should be implemented thoughtfully and systematically. Improving testing will result in a more reliable interconnection of IBR plants; however, it could slow down the interconnection process. Furthermore, reliance on automation tools to support quicker IBR plant conformity assessments will be necessary to keep pace with the increased workload but should be done with caution since engineering judgment is still needed in many cases.
- **As-Built Evaluations and Commissioning Tests:** As-built evaluations and IBR plant commissioning tests are not intended to test the full capability of the IBR plant. Rather, they are intended to ensure that the IBR plant is installed and configured to match the IBR plant design evaluation steps and to ensure the model can be validated, to some extent, after commissioning. This is a critical step that creates a feedback loop and justifies that the IBR plant model is reflective of reality.

November 26, 2024 Virtual Meeting

Active Power-Frequency Response Requirements (~180 simultaneous attendees)

Figure 31 shows the makeup of the meeting attendees by industry sector:

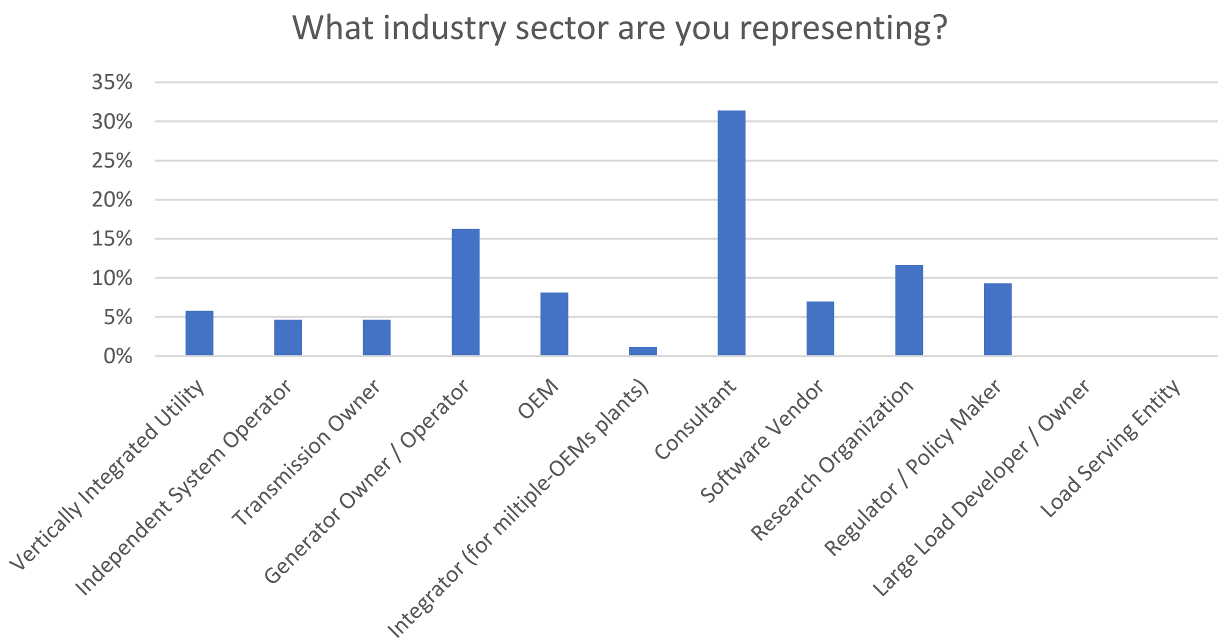


Figure 31: Meeting attendees by industry sector

This was the seventh meeting of the DOE i2X FIRST initiative, focused on IEEE 2800-2022 *Clause 6: Active-Power–Frequency Response Requirements*. Presentations included:

- **Mahesh Morjaria, Terabase Energy:** Mahesh described the fundamentals of active power-frequency response controls including both primary frequency response (PFR) and fast frequency response (FFR). Mahesh explained how PFR and FFR (for underfrequency conditions) are required capabilities in IEEE 2800-2022. He also described the concepts of droop and deadband settings, which have default settings and ranges of adjustability. They can be configured uniquely for underfrequency and overfrequency conditions. The standard also includes parameters for PFR dynamic response performance characteristics in terms for reactive time, rise time, settling time, damping ratio, and settling band. See Figure 32 for more details.

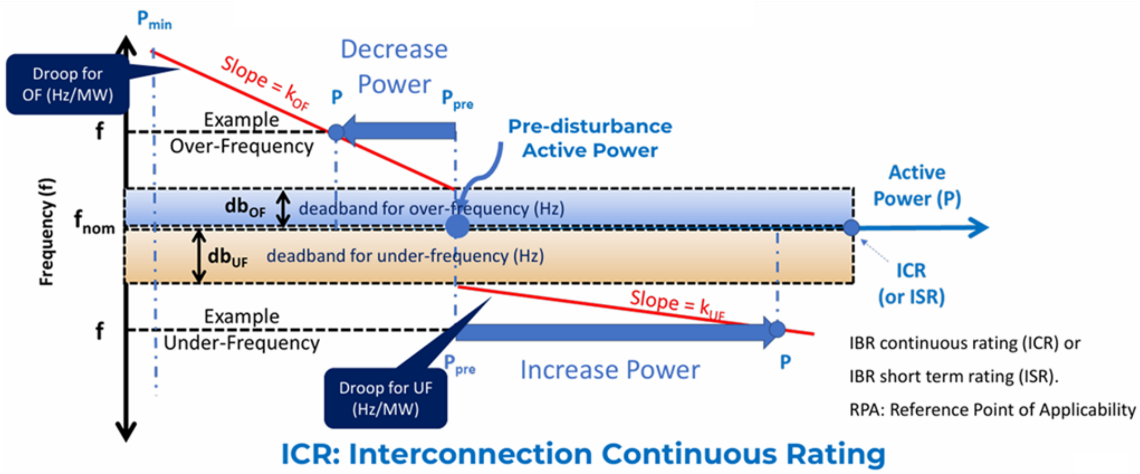


Table 9— Parameters of primary frequency response for *IBR plant*

	units	Default Value	Minimum	Maximum
db_{uf}	Hz	0.06% x f_{nom}	0.025% x f_{nom}	1.6% x f_{nom}
db_{of}	Hz	0.06% x f_{nom}	0.025% x f_{nom}	1.6% x f_{nom}
k_{uf}[66]		5%	2%[67]	5%
k_{of}		5%	2%	5%

Table 10—Parameters of active power-frequency response dynamic performance for *IBR plant*

	Units	Default Value	Minimum	Maximum
Reaction time	seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	seconds	10.0	10	30
Damping Ratio	% of Change	0.3	0.2	1.0
Settling band	% of Change	Max (2.5% of change or 0.5% of ICR)	1	5

Figure 32: PFR Droop, Deadband, and Dynamic Performance Ranges in IEEE 2800-2022 [Source: ©IEEE]

PFR and FFR must actuate independently from each other and must complement each other, per the standard (particularly for wind). IBR active power output is the minimum of the available power before the event, PFR, and other kinds of FFR. FFR may be proportional to frequency deviation or trigger-based using rate-of-change-of-frequency (ROCOF) or other quantities. Proportional response, defined as "FFR1" in the standard, is the most common form of FFR today. The standard also defines FFR from WTGs in more detail.

IEEE 2800-2022 specifies the capability of what functions are available and the range of settings and the minimum specification of how they should behave. However, the standard does not define how those capabilities are used or operationalized in the grid (especially FFR). This may be required by interconnection agreements (e.g., FERC Order 842),[38] procured through ancillary service markets, or other mechanisms.

- **Miguel Duarte Campos, Vestas:** Miguel discussed wind generation technology frequency response capabilities. While IEEE 2800-2022 active power-frequency response requirements are at the Point of Measurement (POM), not at the Point of Connection (POC) at each turbine, it is important to consider the inverter/turbine capabilities as they are a predominant role in meeting the requirements. Miguel clearly described how wind turbine technology has a technical minimum power level where, below this level, the turbine must pause operation. Pausing operation is different than a disconnected state (see Figure 33). This is a challenging operational characteristic of wind technology that must be carefully addressed in standards requirements. Miguel highlighted that IEEE 2800-2022 does a clear and effective job of defining these technical minimum levels based on how it has defined PFR response characteristics. These factors are important for OEMs to be able to sufficiently and comfortably determine whether they can support conformity/compliance with the requirements. Otherwise, the ISO/RTO may be expecting PFR when it cannot or should not be provided. Thoughtful turbine design is also important because OEMs need to avoid unnecessary engaging and disengaging of mechanical components as this can put excessive wear and tear on these parts, reducing the lifespan and increasing maintenance costs. There are solutions to this challenge. Defining a minimum operating limit (DMOL) is one option and introducing a filtered or delayed/counter is another option. Both have been proven solutions, decreasing pauses and reducing fatigue.

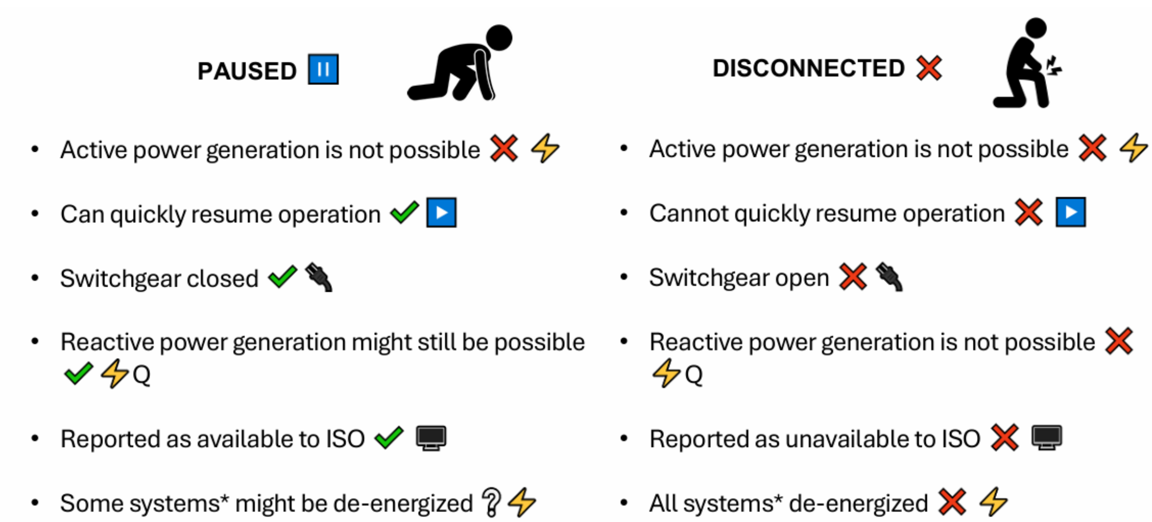


Figure 33: WTG Paused vs. Disconnected State [Source: Vestas]

- **Nitika Mago, ERCOT:** Nitika provided an overview of the ERCOT requirements regarding active power-frequency response. All resources, including IBRs, are required

[38] https://www.ferc.gov/media/order-no-842

to assist in ERCOT's frequency control and provide "governor-like" PFR when they have headroom/legroom. IBRs are required to have a +/- 17 mHz deadband and 5% droop characteristic. Figure 34 shows some examples of wind and solar resources responding to grid events going back nearly a decade.

Resource Type	Max. Deadband
Steam Turbines with Mechanical Governors	+/- 0.034 Hz
Hydro Turbines with Mechanical Governors	+/- 0.034 Hz
All Other Generating Units/Generating Facilities/ESRs	+/- 0.017 Hz
Controllable Load Resources	+/- 0.036 Hz

Generator Type	Max. Droop % Setting
Combustion Turbine (Combined Cycle)	4%
All Other Generating Units/Generating Facilities/ESRs/Controllable Load Resources	5%

Figure 34: ERCOT PFR Capability Requirements and Example Responses [Source: ERCOT]

The ERCOT Responsive Reserves Service (RRS) is procured to meet ERCOT's Interconnection Frequency Response Obligation (IFRO) under NERC BAL-003 and to ensure sufficient response to arrest frequency from reaching underfrequency load shedding (UFLS) at 59.3 Hz for the trip of the two largest units (2805 MW) in the Texas Interconnection.[39] The amount of RRS procured for any hour is set based on the expected inertia in that hour. There are three types of RRS response (see Figure 35):

- PFR, which is a governor-type response provided by generation and energy storage
- Load Resources (LR) using underfrequency relays triggered at 59.7 Hz
- FFR, which is trigger-based at a certain frequency (59.85 Hz), and response is required to be injected in its full amount within 15 electrical cycles

Having this configuration of RRS specifically for ERCOT's islanded system has allowed it to lower its minimum reliable inertia level, which they define as "critical inertia" and use as an operating limit. Without FFR, the minimum inertia is 100 GW*s; however, with 400 MW of FFR procured, ERCOT has lowered its critical inertia level to 88 GW*s.

[39] https://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-003-2.pdf

Beyond this level, ERCOT has faced additional stability and reliability challenges such as voltage stability, transient stability, and other issues, that would also need to be addressed to further lower critical inertia levels.

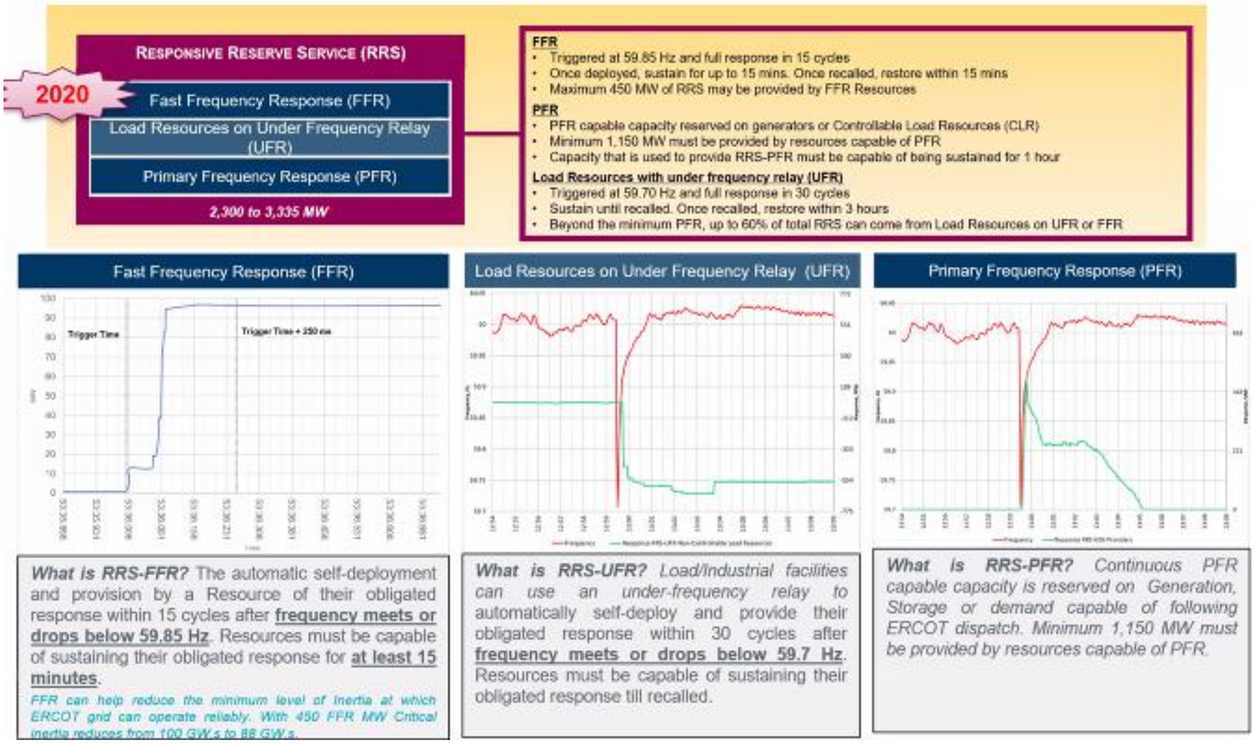


Figure 35: ERCOT RRS Types of Response [Source: ERCOT]

ERCOT has also observed over the years good response and poor response from some of its fleet and continues to assess PFR and FFR performance of the resources closely. Examples of issues observed include the resource reaching its minimum design limit and not able to respond, controls or design issues, not fully understanding ERCOT requirements, inadequate state of charge, etc. Nitika mentioned that there have been questions regarding whether resources are expected to provide PFR during a curtailed state and noted clearly that the answer is "yes." With the boom of storage resources coming online and their inherent headroom availability under most conditions, ERCOT has had very strong CPS1 performance scores, a significant improvement of ERCOT's minimum frequency nadir to grid events, recovery of frequency to nominal or within bands, and improved overall frequency response of the system.

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **FFR in WTGs:** Miguel talked about how FFR technology in WTGs inherently extract kinetic energy from the rotating mass of the turbine. This leads to a balancing of mechanical input power and electrical output power. Depending on wind speed and other factors, this may require the turbine to produce *less* power than was originally being provided before the FFR event. This energy must be restored back into the turbine; hence the reduction of power output after initial increase from FFR. In situations with relatively high wind speed, a reduction of active power after the event may not be required.

- **Balancing Types of Controls and Equipment Limits:** A question was raised as to how, in IEEE 2800-2022, IBR technology handles current limiting when PFR and FFR along with reactive power support and negative sequence current injection support and other features are also required. Panelists discussed how IEEE 2800-2022 Clause 4 includes a prioritization of functional capabilities and performance, defining which order or rank these would take if current limits are reached.
- **PFR/FFR Controls in Existing Assets:** It was reiterated that IEEE 2800-2022 is intended to be applied forward-looking and not retroactively. Existing IBRs may have PFR (and maybe FFR) control capabilities that could be leveraged but older technologies may not have these features (particularly FFR). Thus, applying the standard retroactively without exemption could require repowering or replacement of hardware, which is very costly and not recommended unless a system reliability issue exists. If the capability does exist and could be enabled without costly retrofits, tapping into this capability to improve grid reliability may be advantageous.
- **IBR PFR/FFR Modeling:** The fundamental characteristics of IBR PFR and FFR can be modeled in dynamic simulations. However, many of the stochastic characteristics of the response (in wind) and some of the more complex controls are not well-represented in dynamic models. Particularly, grid planners struggle with configuring base cases with proper levels of IBR curtailment and PFR/FFR performance "procured" since the tools are IBR models are not presently designed to capture these details effectively.

Key Themes

- 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 of this technology clearly and effectively.
- IBR FFR is a relatively newer field and continues to evolve and improve; however, FFR is predominantly a proportional or triggered response to frequency or change in frequency. Non-rotating technologies like solar and BESS can provide very fast FFR in response to grid events; wind technology has limitations given the mechanical nature of the system 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 operationally but did not specify a headroom (or legroom) requirement for these resources. Apart from ERCOT, there are no post-commissioning or post-event performance evaluation requirements in place directly on generator owners; rather, current BAL-003 practices focus on the overall performance of the balancing authorities and not the generator owners.

December 17, 2024 Virtual Meeting

Reactive Power – Voltage Control Requirements (~230 simultaneous attendees)

Figure 36 shows the makeup of the meeting attendees by industry sector:

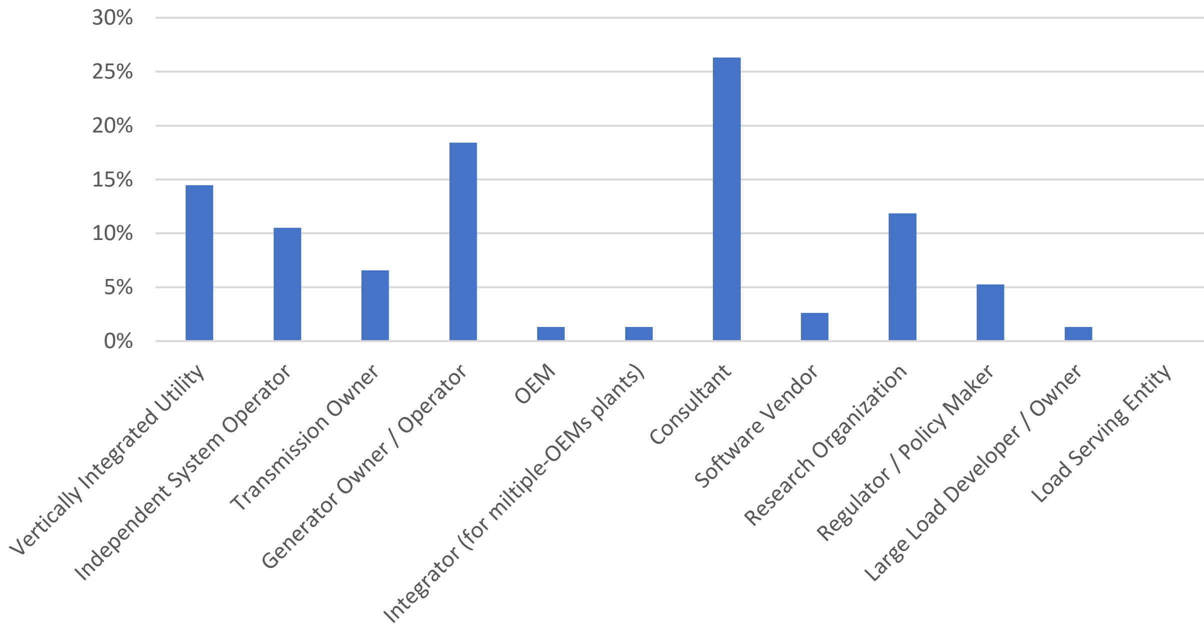


Figure 36: Meeting attendees by industry sector

This was the eighth meeting of the DOE i2X FIRST initiative, focused on IEEE 2800-2022 *Clause 5: Reactive Power–Voltage Control Requirements within the Continuous Operation Region*. Presentations included:

- **Jens Boemer, EPRI:** Jens provided an overview of IEEE 2800-2022 *Clause 5: Reactive Power-Voltage Control Requirements within the Continuous Operation Region.* Clause 5 includes minimum reactive power capability requirements of 0.95 power factor at the IBR continuous rating (Pmax). The curves are rectangular shaped as active power reduces (see Figure 37). The clause also includes minimum reactive power requirements as a function of voltage. These requirements shall be met for all active power output levels (including zero active power), with exceptions for Type 3 wind and AC-connected offshore IBR plants. The default reference point of applicability (RPA) for these requirements is the point of measurement (POM). Utilization of reactive power capability is based on mutual agreement between the IBR owner and TS owner.

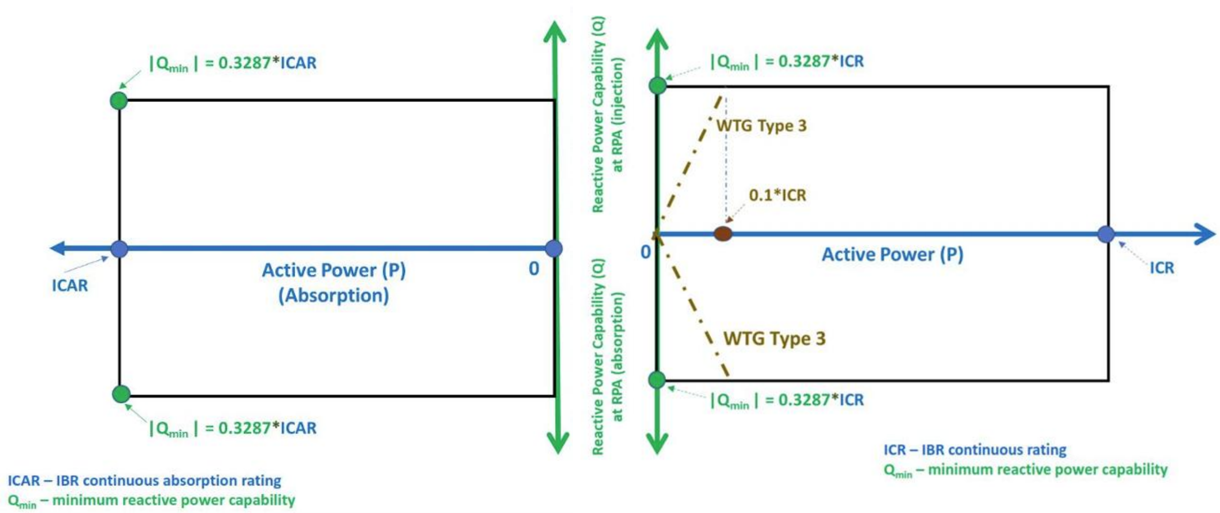


Figure 37: Reactive Power Capability versus Active Power Curves (Adapted from EPRI) [Source: ©IEEE]

The standard introduces three types of reactive power-voltage control modes (power factor control, reactive power control, and voltage control); however, RPA voltage control mode is the default and most commonly used for BPS-connected IBR plants. RPA voltage control includes a performance target range (Table 5 of the standard), as shown in Figure 38. Note that the maximum step response time shall be determined and specified by the TS operator. Jens emphasized that the reactive power capability shall be dynamic in nature, defined by the time responses in Table 5 of the standard. The IBR plant must seamlessly change and adjust reactive power output across the full range without significant steps. This implies that mechanically switched reactive power devices may not be sufficient to conform with IEEE 2800-2022 reactive power capability requirements unless their operation is coordinated through a PPC with other IBR devices within the plant that have that dynamic capability and together they provide the full capability 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.

Figure 38: Reactive Power Performance Target Requirements [Source: ©IEEE]

Lastly, Jens, illustrated how conformity assessments could be conducted, testing the reaction time, maximum response time, band of RPA voltage set point, and damping ratio, as illustrated in Figure 39.

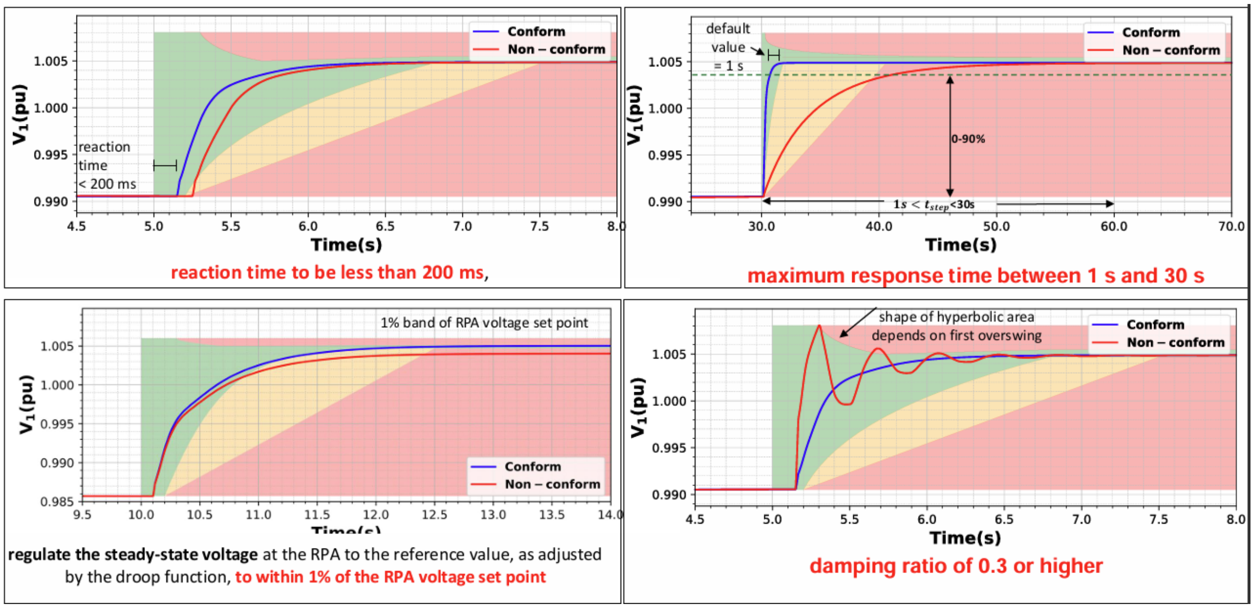


Figure 39: Reactive Power-Voltage Performance Conformity Assessment Example [Source: EPRI]

- **Patrick Dalton, MISO:** Patrick shared MISO's experience adopting IBR reactive power-voltage control requirements, highlighting that: 1) adoption of Clause 5 brings greater performance specificity to existing voltage control requirements and stakeholder-driven selection of voltage control performance characteristics. Ultimately, adoption of Clause 5 requirements was mostly a refinement of existing requirements, adding more specificity and clarity to help avoid ambiguity and help IBR developers and owners design and operate their facilities to support BPS reliability. MISO adopted the reactive power capability requirements, including at zero active power. However, MISO did not require utilization of the IEEE 2800-2022 Clause 5 reactive power capability beyond what is required in FERC Order 827. Figure 40 shows the differences between IEEE 2800-2022 capability and FERC Order 827 requirements; in essence, FERC Order 827 may be creating an unnecessary barrier[40] and underutilizing the full capabilities of IBRs if IEEE 2800-2022 Clause 5 is adopted unless new financial compensation mechanisms are developed.

[40] Concerns were expressed that there may be little to no cost associated with using reactive power capability from IBR plants when the primary energy source is available; thus, requiring compensation may create barriers.

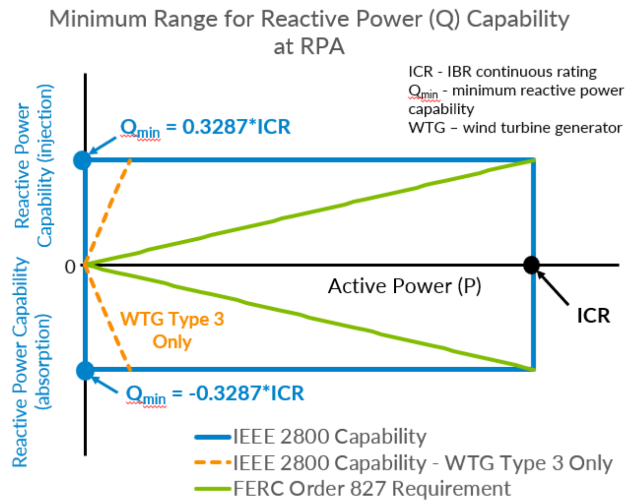


Figure 40: Comparison of IEEE 2800-2022 Reactive Power Capability Requirements and FERC Order 827 [Source: MISO]

MISO also modified the reaction time to 250 ms and selected 30 seconds for the maximum step response time, although it was recognized that this may need further analysis and consideration. The reaction time was extended based on stakeholder input from IBR developers that communication latency within an IBR plant, DC-coupled hybrid IBR issues, and issues with IBR plant designs involving IEEE 1547-compatible equipment could exist.

- **Eric Heredia and Dmitry Kosterev, BPA:** Eric and Dmitry described BPA's decades of IBR voltage control experience, dating back to the historic outages of 1996 and wind plant voltage control issues in the mid-2000s at Jones Canyon wind plant. They highlighted that planning of reactive power deliverability and voltage control improves grid performance and provides optimal transmission capacity. Experience at Jones Canyon led to improved BPA operating procedures and establishing voltage droop requirements. BPA currently does not have a reaction time requirement and uses a 5 second maximum step response time with overshoot less than 10%. Response must be positively damped (no damping ratio specified). POI voltage must be controlled with a 2% reactive droop, with reactive power normalized to maximum reactive capability required (33% of active power maximum). See Figure 41 for a visualization of the requirements.

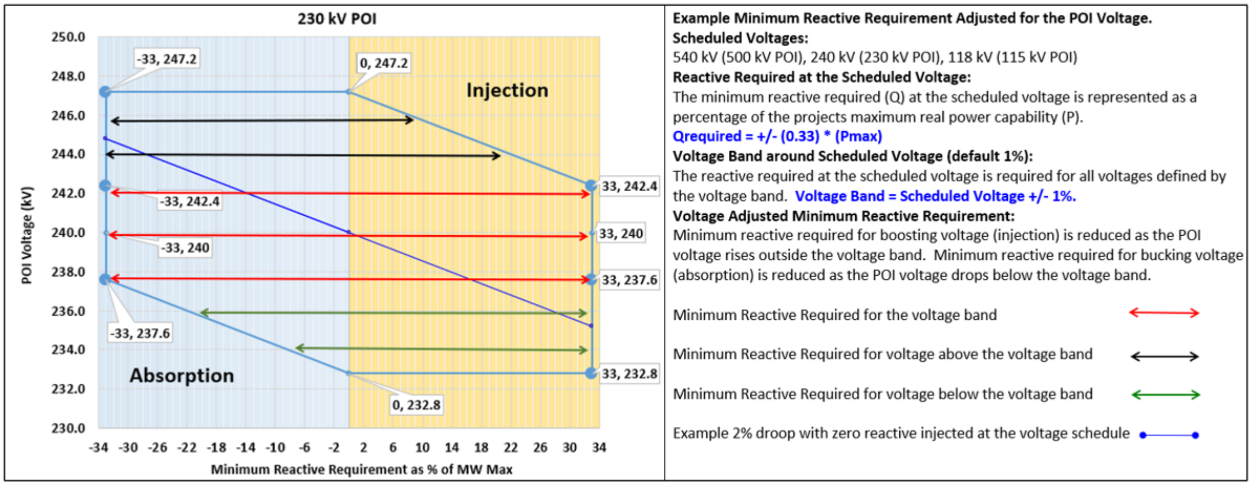


Figure 41: BPA Voltage Control and Reactive Power Requirements [Source: BPA]

BPA would like to see resources as responsive to changes in voltage as possible (i.e., fast voltage control) without causing any instability issues. BPA seeks to maintain a system strength of short circuit ratio (SCR) = 3 or higher (and weighted SCR (WSCR) may be used when multiple IBRs are in the vicinity). Performance commissioning tests have also been developed to test plant voltage control (droop, step response, overshoot, etc.), reactive power capability, and frequency control. Disturbance monitoring equipment is also used to ensure operational performance of IBR plants meet requirements.

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Speed of Reactive Power Response:** MISO was asked about their 30 second maximum reactive power step response time and if there were any concerns that this time may be too slow for reliable operation of the BPS. Patrick shared that the MISO Transmission Operators have the responsibility to control voltage and sought the 30 second response time. Fundamentally, there were concerns that weak grid conditions could cause voltage instability issues for fast reactive power injections and the Transmission Operators wanted to avoid these concerns. Conversely, BPA uses a fast reactive power response time (5 seconds) and adjusts if any instability issues arise. Thus, there are different approaches to voltage control that are up to the local Transmission Operators to determine and plan for.
- **Reactive Droop:** There were questions about how reactive power droop is selected. First, it was strongly emphasized that the base value used for calculating droop should be carefully specified. Incorrect assumptions or calculations of droop by IBR owners has led to incorrect operation of IBR voltage control for some entities. Further, studies may be needed to determine an ideal or suitable droop setting for each system. However, BPA recognized that years of experience led them to select a 2% droop characteristic and that

this was chosen "because it operationally works." Entities highlighted that 0% droop at the high side of the main power transformer(s) is rather unstable and unsustainable, particularly as IBR penetration levels rise. Droop has been a long-established solution for parallel resources trying to control a common variable (e.g., hydro plants or other resources) and is important to study carefully and implement accordingly.

- **RPA for Voltage Control:** IEEE 2800-2022 uses the POM as the RPA for Clause 5 IBR plant requirements. However, many Transmission Operators use the POI for voltage control for multiple reasons – existing tariff language, FERC Order 827, existing operational practices, etc. Thus, multiple Transmission Operators expressed that they adjusted the RPA to the POI instead of the POM for adoption of Clause 5 requirements.
- **System Strength:** System strength can have a significant impact on reactive power response characteristics and should be carefully studied. Conformity assessments may need to test an array of conditions to find a suitable IBR voltage control design. Most importantly, a conversation between the IBR developer, OEM(s), and transmission provider is needed to ensure all parties are aligned.

Key Themes

- **IEEE 2800-2022 Clause 5 Adoption:** Implementation of IEEE 2800-2022 Clause 5 requirements can help clarify and refine existing voltage control requirements that may be in existence today. Improved voltage control requirements can help in the reliable design and operation of IBR plants moving forward. Multiple entities have selected the POI rather than the POM as the RPA for these requirements.
- **Conflicts with FERC Order 827:** Some system operators may not be fully leveraging the requirements in IEEE 2800-2022 Clause 5 due to conflicts with FERC Order 827, particularly related to utilization of reactive power capability (rectangular versus triangular shaped curves). This may be leading to underutilization of IBR reactive power capability and resulting in costlier transmission reinforcements than necessary.
- **RPA Voltage Control:** RPA voltage control is the most common form voltage control for BPS-connected IBRs. IEEE 2800-2022 Clause 5 includes specifications for the performance targets for this type of control including reaction time, maximum step response time, and damping ratio. Selection of droop and deadband settings based on local BPS needs and Transmission Operator voltage control practices can also help improve grid reliability and stability as well as increase transfer capability, in some cases. System strength should be accounted for when determining performance requirements.

January 28, 2025 Virtual Meeting

Postponed

February 25, 2025 Virtual Meeting

Protection and Power Quality Requirements (~190 simultaneous attendees)

Figure 42 shows the makeup of the meeting attendees by industry sector:

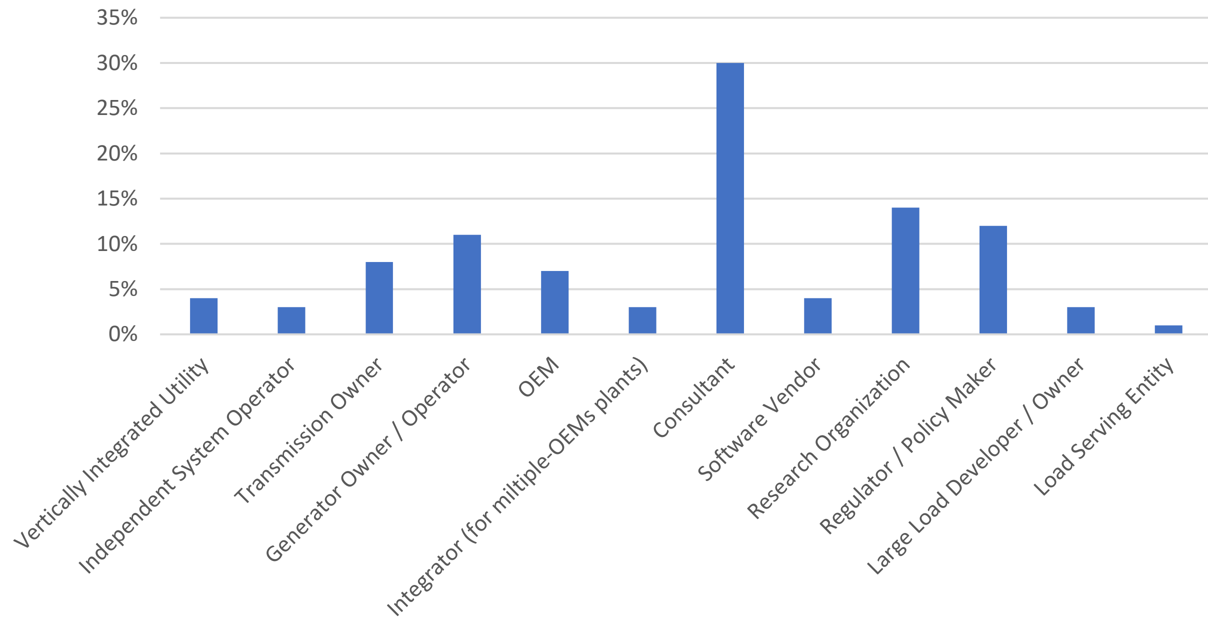


Figure 42: Meeting attendees by industry sector

This was the ninth meeting of the DOE i2X FIRST initiative, focused on IEEE 2800-2022 *Clause 9: Protection Requirements* and *Clause 8: Power Quality Requirements*. Presentations included:

- **Manish Patel, EPRI:** Manish provided an overview of IEEE 2800-2022 *Clause 9: Protection Requirements*. Generally, the protection requirements in IEEE 2800-2022 do not require any specific types of protection to be applied within an IBR plant. If protections are applied (including auxiliary systems), then they shall allow the IBR Plant to meet its ride-through requirements. There are some requirements for frequency, ROCOF, overvoltage, and overcurrent protection when used in an IBR plant.
    - Frequency protection is not required by the standard, but if applied it should enable the IBR plant to meet the frequency ride-through requirements. Frequency protection should also be coordinated with the TS frequency protection, if necessary, as well as underfrequency load shedding (UFLS) program designs. Similarly, ROCOF protection is also not required by the standard and should not affect ride-through performance. Any ROCOF measurement and associated

protection should be based on a change of frequency averaged over sufficient time to reject spurious frequency measurements caused by distortion and transients.

  - AC voltage protection in the IBR plant is also not defined by the standard and should not interfere with IBR plant ride-through capability. All instantaneous overvoltage protection used within the IBR plant must use filtered quantities to reduce the possibility of misoperation while providing protection to the desired equipment and system. Any instantaneous overvoltage protection(s) that has the possibility of disrupting the power output ***of the entire plant*** shall use at least one cycle (of fundamental frequency) measurement window. Where instantaneous overvoltage protection is applied on IBR units, it must be coordinated with transient overvoltage capability of the IBR units, coordinated with surge protection equipment, and allow the IBR plant to meet the transient overvoltage ride-through requirements.
  - AC overcurrent protection is not required by the standard. Any use of AC overcurrent protection is applicable to phase and sequence quantities and must not limit the IBR plant ride-through capability. AC overcurrent protections shall use filtered quantities as well and any of these protections that have the possibility of disrupting the power output ***of the entire plant*** shall use at least one cycle (of fundamental frequency) measurement window.
  - Unintentional islanding protection shall be implemented in accordance with the requirements set by the TS owner if islanding of the IBR plant with any portion of the TS is not allowed. This protection shall not affect IBR plant ride-through performance.
  - Protection for the interconnection system shall be implemented in accordance with the TS owner's requirements and/or the requirements of the owners of electrically joined facilities. This protection shall be coordinated with the TS protection system. Protection schemes shall not limit the IBR plant's ride-through capability with the following exceptions:
    - Faults within the interconnection system
    - Faults within protection zones identified by the TS owner that provide sole connectivity of the IBR plant to the TS
    - Faults within the IBR plant that cannot be cleared except by disconnecting the IBR plant
- **David Mueller, EnerNex:** David described the key aspects of IEEE 2800-2022 *Clause 8 Power Quality Requirements*, which include (1) limitations of voltage fluctuations induced by the IBR plant, (2) limitation of harmonic distortion, and (3) limitation of overvoltage contribution.

The standard defines maximum limits for voltage fluctuations at the RPA:

- Frequency rapid voltage change (RVC) less than 2.5% at the RPA. These are for normal, regularly occurring voltage changes such as for capacitor switching events or other common operations.
- Infrequent RVC of less than 12% at the RPA for uncommon operations such as transformer energization and maintenance.
- Flicker limits of 10-minute flicker emissions less than 0.35 and 2-hour flicker emissions less than 0.25. The

RVC analyses are often done using statistical evaluation of many simulations of point on wave faults to identify the worst possible occurrences. Additionally, the IEEE 2800-2022 team and industry at-large have recognized that flicker requirements were created based on 60 Watt incandescent light bulb technology which has been mostly replaced by light-emitting diode (LED) technology today; thus, the standards may need to be updated. Regardless, the limits set for flicker for the IBR are set such that they are about one-third of the total planning and operational limits so that no one IBR plant can take up all the flicker contributions in an area.

The standard also describes harmonic current distortion and harmonic voltage distortion. Harmonics are a particularly difficult phenomena to study and standardize because the characteristics of the grid affect the IBR plant, and the characteristics of the IBR plant affect the grid. Harmonic voltage distortion is the primary focus and what must be limited on the system. However, it is difficult to quantify pre -energization what the IBR plant would contribute in terms of voltage harmonics. Additionally, many systems greater than 161 kV today have baseline harmonics levels that exceed the IEEE 519 recommended limits prior to connecting an IBR plant. Thus, requiring that the IBR plant not contribute to limits that exceed these levels becomes impractical to implement in these systems.

Harmonic current limits are easier to apply. One can measure harmonic currents with measurement devices post-energization for a period of time, most often one or two weeks. Although, handling directionality of current (particularly for BESS) can be problematic and challenging. It is worth noting that the limits do not need to be met at all times; they must be met 95% of the time. Therefore, statistics can be applied to the measurements collected to determine cumulative harmonics levels and adherence to the requirements. David mentioned that most IBR plants meet these limits and that IBR plants are generally a low source of harmonics.

IEEE 2800-2022 also includes limitation of overvoltage contribution requirements; however, these are also less of a concern for large IBR plants as compared with smaller DERs applicable to IEEE 1547 requirements since large IBR plants have a ground source which limits overvoltage rise. However, it is worth noting that the IEEE 2800-2022 recommended to OEMs that they design their equipment to meet these requirements rather than simply set protections to ensure they avoid such contributions (i.e., don't set unnecessary trip settings just to comply with requirements).

David also shared practical experience dealing with IBR-related power quality issues, and highlighted the following issues as the most common problems at IBR plants:

- **Unit turbine or inverter transformer failure:** Transformer failures particularly when the IBR unit transformer was not designed to be coupled with a power electronic converter, which will inherently see high frequency harmonics. If the electrostatic shielding or insulation are not designed properly, this can tax the transformer and lead to early failure.
- **Converter instability:** Issues where inverter controls become unstable during certain operating conditions in which a resonance effect occurs between the inverters at the IBR units and the grid natural frequencies. (see Figure 42). This can be studied with careful EMT modeling and studies, in some cases.
- **Capacitor bank causing resonance conditions:** Situations where capacitor banks switched in at the site create resonance effects with the IBR unit, similar to the issue above. This magnifies the harmonic current levels. The IBR units may make abnormal noises and may lead to early failure of the power electronics.
- **Background harmonic voltage levels exceeding IEEE 519 limits:** As mentioned above, issues occur where the baseline background harmonic voltage levels already exceed acceptable levels. However, the cumulative requirements may be met, and the system is operating reliably. Thus, it becomes a challenge to determine how and what standards to apply at this point.

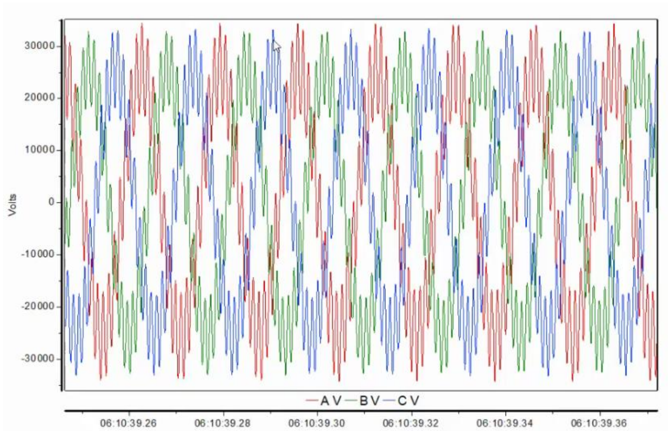


Figure 43: Resonance at Interharmonic frequencies due to converter instability (Source: EnerNex)

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Harmonization of IEEE 2800-2022 Protection and Ride-Through Requirements with NERC Requirements:** Manish highlighted that there may be one bullet in the list of explanations in NERC PRC-029 that could be interpreted as more stringent than IEEE 2800-2022. This is related to a clarification that "instantaneous trip settings based on instantaneously calculated voltage measurements with less than filtering lengths of one cycle (16.66 millisecond) are not permissible." However, overall they are aligned, particularly on the key point that IBR plant protections should not interfere with or limit the IBR plant's overall ride-through capability.
- **Harmonics for Type 3 and Type 4 Wind Turbine Generators:** David described that there are not a lot of distinctions between Type 3 and Type 4 wind turbines from the standpoint of harmonic sources and impacts on the bulk power system. Most notably, a Type 3 wind turbine has the stator electrically connected to the grid and thus changes the impedance characteristic and shifts the resonance conditions, which needs to be accounted for from a harmonics/resonance perspective.
- **Siloed Approach to IBR Plant Design and Protection Settings:** A comment was raised regarding the challenges associated with IBR plant design being a somewhat siloed activity where the IBR unit may be designed by the OEM a certain way yet the balance of plant relaying and the site configuration are established by third-parties or different departments within a developer. Thus, it can be challenging to accomplish a comprehensive and consistent approach to protection system coordination within IBR plants. This issue was recognized by panelists as a potential challenge and obstacle for IEEE P2800.2 implementation.
- **Consistency in Adoption:** A comment was raised that utility protection standards differ widely and could lead to differing protection system implementations by IBR owners. The presenters recognized that this may be the case today; however, they hope for consistency and harmonized practices with further implementation of IEEE 2800-2022 and adoption of IEEE P2800.2 recommended practices.
- **Harmonics Modeling and Analysis Pre-Commissioning:** This topic is a main focus of IEEE P2800.2 currently. The IBR plant must be modeled as a detailed representation of all the IBR units and collector feeders (i.e., no aggregated model). Additionally, detailed and accurate models of turbines and inverters are needed from OEMs that capture harmonics. Some degree of grid modeling is also required, leading to additional complications. This type of modeling is not common for typical IBR plants; however, it is common for very large inverter-based projects such as offshore wind or large HVDC projects to de-risk the facility and its impact on the grid as much as possible before commissioning.

- **Extending Harmonics Testing to Inverter Switching Frequencies:** A question was raised regarding whether harmonics testing should be extended to higher frequencies due to inverter switching; however, David explained that the test laboratories are not set up to handle this currently, and experience has shown that high frequency harmonics are not a major issue for BPS-connected IBR plants.

Key Themes

- **IBR Plant Protections Enabling Ride-Through:** Any IBR plant protection systems should be coordinated such that they do not limit the ride-through capability of the IBR plant. IEEE 2800-2022 does not specify any particular protections that must be enabled at the IBR unit or balance of plant relays. Details are provided regarding frequency, ROCOF, AC voltage, AC current, unintentional islanding protections. Protection for the interconnection system connecting the IBR plant to the TS should be coordinated with TS owner protection standards and practices.
- **Power Quality for IBRs:** IBRs are a relatively low source of harmonics; however, there are resonance effects and IBR plant design considerations that may affect the lifespan and integrity of IBR plant and TS equipment and therefore warrant careful engineering consideration. Ongoing industry efforts are focusing on improved IBR modeling for power quality analyses, generally focused on Thevenin or Norton equivalent harmonic source representations.

March 20, 2025 (Hybrid event during ESIG Spring Workshop)

Post-Commissioning Workshop (~185 virtual attendees and ~75 in person attendees)

Figure 44 shows the makeup of the meeting attendees by industry sector:

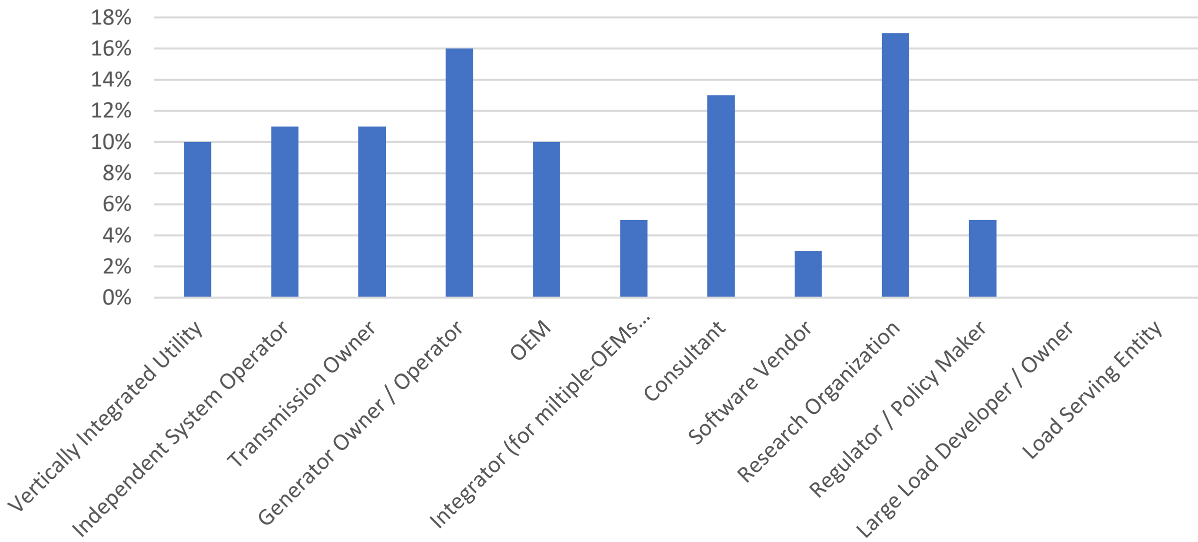


Figure 44: Meeting attendees by industry sector[41]

This was the tenth meeting of the DOE i2X FIRST initiative, and was a hybrid (in-person and online) workshop focused on IEEE 2800-2022 post-commissioning activities. The last hybrid workshop focused on aspects of the standard leading up to commissioning (including commissioning tests) whereas this workshop focused on aspects of IEEE 2800-2022 that occur post-commissioning and commercial operation. Presentations included:

- **Andy Hoke, NREL:** Andy provided an overview of IEEE P2800.2 as well as a status update regarding plans for drafting, balloting, and eventual publication of the standard. Andy reiterated that almost all the requirements of IEEE 2800-2022 apply at the Point of Measurement (POM) by default, as illustrated in Figure 45. Therefore, when considering conformity assessments, one needs to think about the entire plant and how all the different components of the plant work in harmony to meet the applicable requirements of IEEE 2800-2022.

[41] Note that this only represents the online registrants.

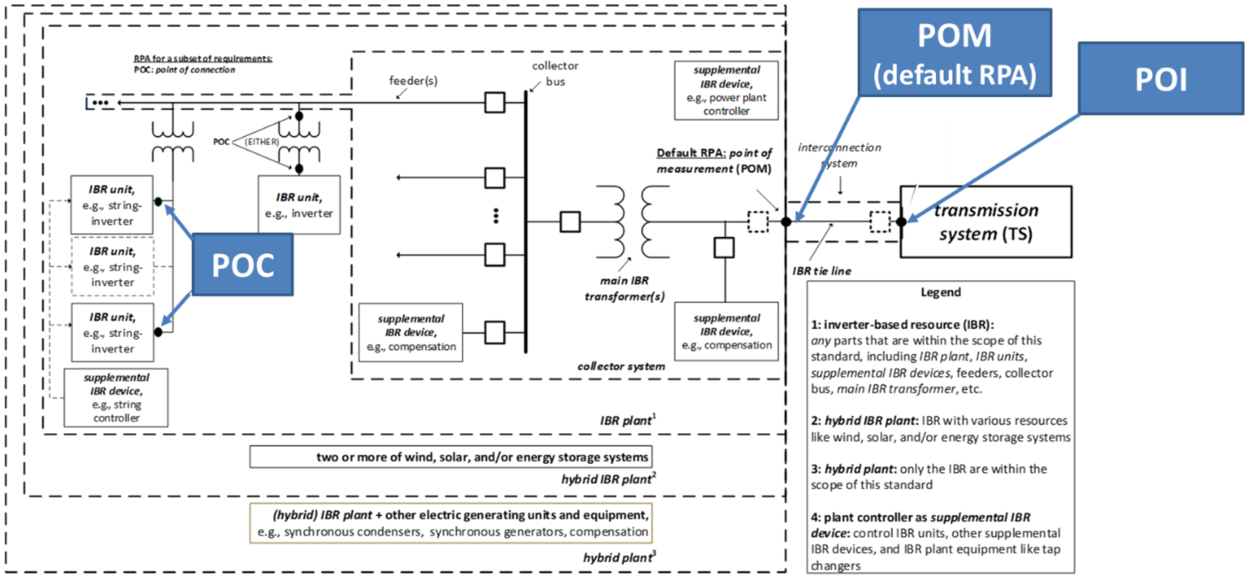


Figure 45: Illustration of the Reference Point of Applicability in IEEE 2800-2022 [Source: ©IEEE]

Andy also covered the various steps of conformity assessments that are described in IEEE P2800.2 (see Figure 46). The post-commissioning steps focus on the following:

- Post-commissioning model validation: Real-world measurement data, either from commissioning tests or grid disturbances are used to validate the model as well as ensure that the plant conforms with the IEEE 2800-2022 requirements per the processes outlined in IEEE P2800.2, to the extent possible.
- Post-commissioning monitoring: The operational performance of the IBR plant is monitored over time and its performance and response to grid conditions is collected and assessed. Measurements from events are used to gain further assurance that the plant meets the performance requirements (particularly for the transient large disturbance requirements).
- Periodic tests and verification: When and if changes are made to the facility, some test and verification activities may be required to ensure the plant continues to conform with the IEEE 2800-2022 requirements; after a designated period of time, it is recommended to conduct periodic tests and verification to ensure that performance hasn't changed unexpectedly.

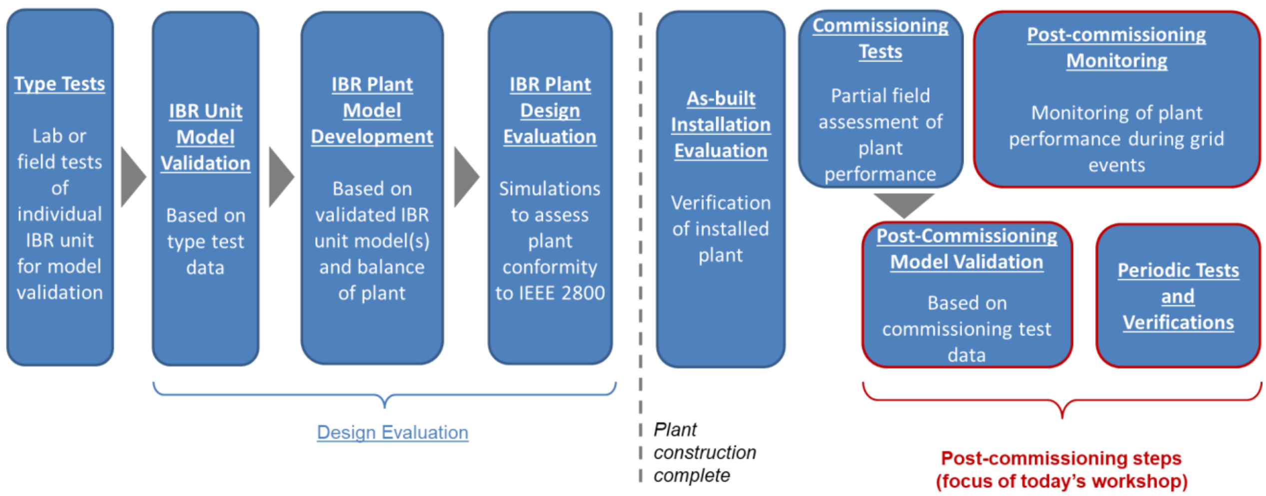


Figure 46: Overview of Conformity Assessment Steps in IEEE P2800.2

The steps of IEEE P2800.2 involved in the interconnection process relate to developing, verifying, and validating the models used to represent the IBR plant. The model can then be confidently used to assess whether the plant, at least in a simulation environment, can meet the requirements set forth. On the other hand, post-commissioning, focus turns to using real-world measurement data to verify and validate that the as-built plant responds and performs as expected (as modeled) and complies with he requirements set forth.

Andy also described the progress of the IEEE P2800.2 efforts. The drafting team had just released the Draft 3.0 for review. The team is currently seeking the IEEE P2800.2 Working Group's approval to ballot the standard for approval following IEEE processes. A two-thirds vote is required to move the standard forward for balloting. Once the draft goes out for ballot, the IEEE Standards Association members will have an opportunity to formally submit comments and a comment resolution team comprised of members of the drafting team will be created to address all comments received.

The comment resolution team will be actively working on revisions and will support ballot responses. Regardless, it is expected that IEEE P2800.2 would not be published any earlier than Q1 or Q2 of 2026 at this point. Andy encouraged folks to get engaged in the IEEE P2800.2 efforts and subsequently join the ballot pool.

- **Pouyan Pourbeik, PEACE:** Pouyan presented on post-commissioning model validation of IBR plants, which is a core focus of IEEE P2800.2 subgroup 5 activities. The individual IBR units (and supplemental devices) are all OEM type-tested and their models are validated across simulation domains. The collector system and major electrical equipment are all modeled and verified to match the actual installed equipment. Once the entire IBR plant model is developed and verified, it needs to be validated against actual field measurements that are collected during IBR plant commissioning. The goal of post-commissioning IBR plant model validation is to gain confidence that the

IBR plant model is an accurate representation of the behavior of the actual equipment in the field and then to use that validated model to ensure continuous conformity with IEEE 2800-2022 requirements.

There are many tests conducted during IBR plant commissioning to verify field settings and test conformity to IEEE 2800-2022; some of these tests can be specifically used for model validation of the IBR plant model. Example tests applicable to model validation include voltage and reactive power control mode, primary frequency response, and fast frequency response tests. Generally, these are all classified as "small disturbance" tests, hence they can be used to validate the model against small perturbations that are intentionally injected into (or generated by) the plant controls to monitor the plant response to those changes in state. Figure 47 and Figure 48 show examples of the voltage and reactive power control modes test and the primary frequency response test, respectively, illustrating how the setpoints are modified in the actual plant controller as well as in the model.

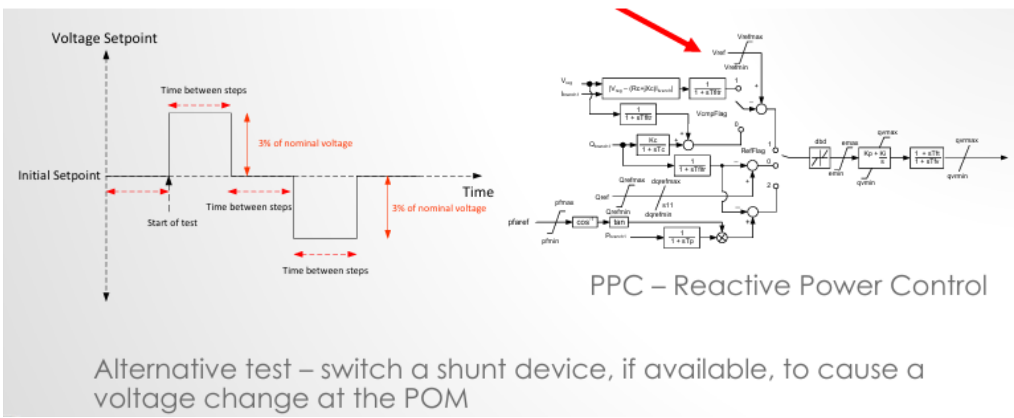


Figure 47: Voltage and Reactive Power Control Modes Test Illustration [Source: ®PEACE]

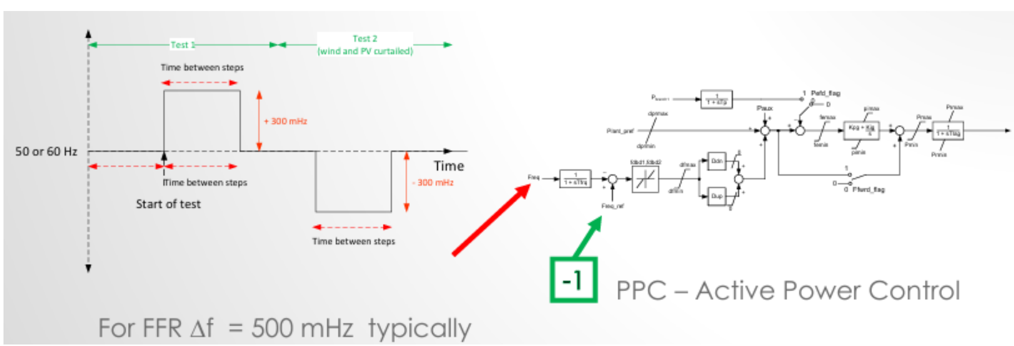


Figure 48: PFR and FFR Test Illustration [Source: ®PEACE]

There are multiple methods for IBR plant model validation. These generally include representing the IBR plant against an infinite bus with source impedance, use of a playback model, and a full (or partial) grid model although this requires data from the transmission planner which may be challenging to obtain for IBR owners. See Annex C of IEEE P2800.2 for more details. Figure 49 shows an illustrative example of a frequency step test where an artificial frequency step is injected into the PPC. Therea are multiple factors that must be considered when conducting these tests – IBR plant curtailment status, active power output level, grid operating conditions, testing approval from the transmission provider, etc. IBR plant active power is monitored as well as wind speed. The results show an overall reasonable match between simulated and actual active power. Note that the modeled response is not expected to match the simulated response exactly since there are numerous factors that are not represented in models (e.g., changing wind speed or solar irradiance). This makes applying quantitative de facto pass/fail criteria to these plots challenging; however, qualitatively, the plots should match and discrepancies should be explained.

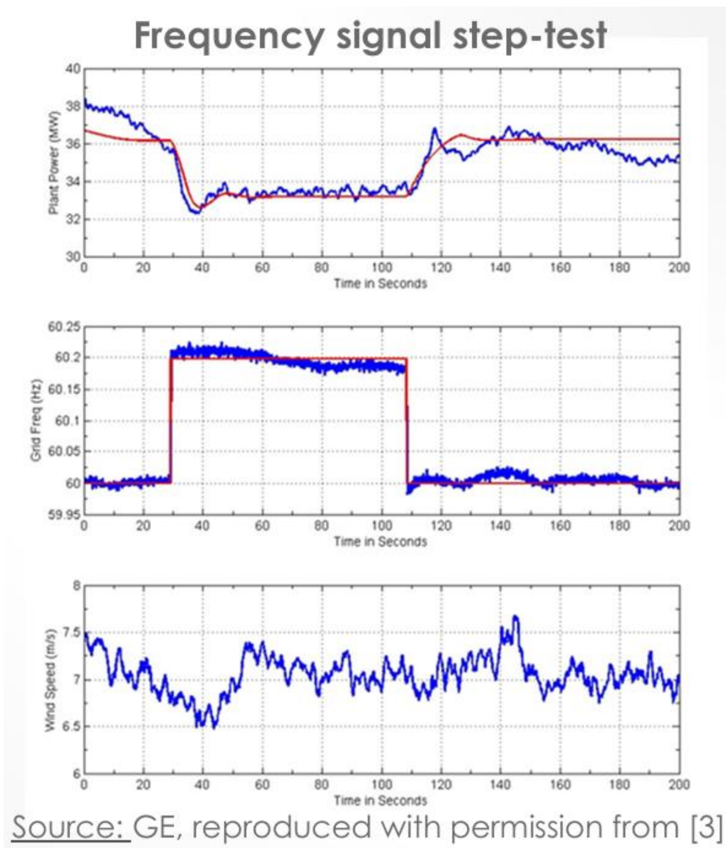


Figure 49: PFR and FFR Test Illustration [Source; ®PEACE]

- **Julia Matevosyan, ESIG:** Julia described the selection of event triggers used for capturing high-resolution measurement data for the purposes of post-commissioning model validation. Event triggers are established to capture event data which can then be used for model validation, which can then compare the response of the IBR plant model and actual equipment. Subsequent analysis can then determine whether the IBR plant is meeting IEEE 2800-2022 conformity, where possible (see Figure 50).

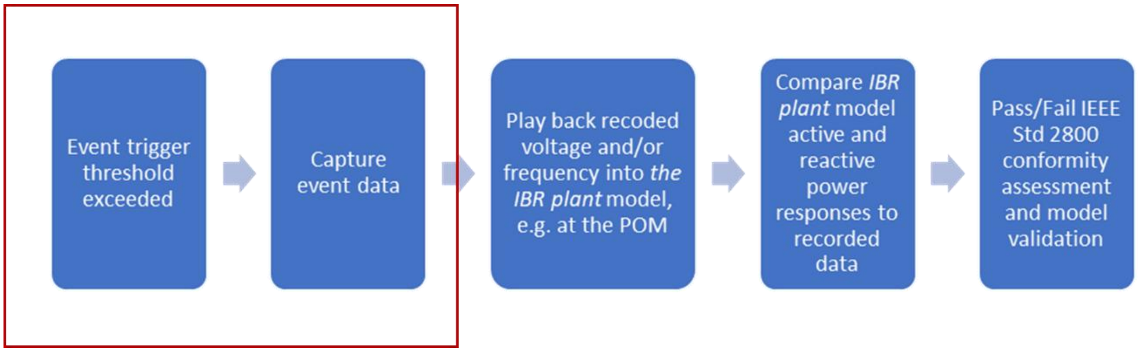


Figure 50: Post-Commissioning Monitoring Process [Source: ESIG]

Even with post-commissioning monitoring, conformity with all aspects of IEEE 2800-2022 performance requirements cannot necessarily be verified during the lifecycle of an IBR plant. Most events are relatively smaller (e.g., small change in IBR plant POM voltage or frequency); however, more severe grid events do occur and offer a great opportunity for model validation. Faults are useful for testing the volt/var response and dynamic ride-through performance of the IBR plant; frequency excursions due to loss of large generators or loads are useful for testing PFR and FFR dynamic performance.

Appropriate event triggers depend on the characteristics of the interconnection in which the plant is connected, particularly for frequency thresholds. Triggers set too narrow will record too many events and cause data storage issues and overwriting. Triggers set too wide will miss events useful for conformity assessment. Table 19 in IEEE 2800-2022 provides guidance on measurement data (type, points, sampling rate, retention, and duration), and trigger settings may need to be adjusted periodically. Consultation with the TS owner/TS operator is encouraged, particularly for configuring DFR triggers. A common time reference so that data across different DFRs can be time-aligned is also necessary for effective IBR plant model validation.

IBR plant performance evaluation, model revalidation, and conformity assessment should be performed with the relevant clauses of IEEE 2800-2022 at least once every 24 months, assuming a significant event has occurred. An entity may perform such work on a more frequent basis, as needed.

- **Julia Matevosyan, ESIG:** Julia then presented on post-commissioning monitoring and considerations for assessing conformity with various IEEE 2800-2022 requirements. It is not always feasible to fully assess conformity to some requirements of IEEE 2800-2022 through type tests, design evaluation, and commissioning tests. Post-commissioning monitoring can provide an opportunity to assess conformity to those requirements when relevant grid events occur. It is also an opportunity to validate the IBR plant models for conditions outside of the normal operation region and to capture any unintended changes in an IBR plant since commissioning. The purpose of post-commissioning monitoring is to verify, to the extent possible, that the IBR plant continues to meet the requirements of IEEE 2800-2022 over its lifetime.

The triggered and/or continuous data can be used with the playback function of simulation tools. Measured voltage and frequency are played back into the IBR plant model and active and reactive power output are monitored and compared against the actual response. Again, the user is looking for qualitative matches, and caution should be used when quantitative metrics are applied. The user is seeking to determine 1) whether the model remains accurate, and 2) whether the IBR plant conforms with the requirements. If the simulated response for the event does not match the recorded response of the actual site, one or more issues may be occurring:

- The IBR plant model is not accurately representing the actual IBR plant
- The event cannot be accurately replicated in the simulation domain for which the model is created for (e.g., issues/controls not modeled, simulation time step too large, etc.)
- The measurements from the event are not accurate
- Post-processing of raw phase voltages and currents into RMS quantities within the data recording equipment may differ from the corresponding processing of the same quantities in the simulation tool
- If a full (or partial) TS model is used for IBR plant model validation, the accuracy of the TS model may also be a reason for mismatch

Discrepancies warrant further investigation as to the root cause of errors, which may uncover issues with the model or with control modes, settings, configuration, etc., within the actual plant. Performance over a long period of time can help identify trends and identify capability points that otherwise may not be able to be tested during a specific day or condition in which that testing occurs.

The actual assessment of IBR plant conformity against the IEEE 2800-2022 requirements requires numerous caveats and other attention to detail. Examples include:

- FFR and PFR: Limitations with the provision of FFR and PFR during low active power output conditions, curtailment levels, wind speed, etc.
- Voltage Ride-Through and Current Injection: Most of the sub-requirements of Clause 7 cannot be checked with grid voltage events other than general ride-through and recovery. Conformity with requirements regarding capability and dynamic response of individual IBR units are hard to assess; however, careful analysis of the IBR plant DFR data can uncover useful indicators of whether the plant is generally meeting the IEEE 2800-2022 performance requirements. For

example, abnormally long recovery times (when not desired) could be indicative of plant-level controls interacting with the inverter ride-through mode.

Conformity with the more detailed IBR unit-level requirements of IEEE 2800-2022 regarding dynamic performance are checked using IBR unit type test measurements in a laboratory environment; however, disturbances are very useful for validating the models and ensuring the general dynamic behavior of the IBR plant is as expected.

- **Yunzhi Cheng, ERCOT:** Yunzhi presented on ERCOT experience with model validation using high resolution data captured from event data. ERCOT uses PSS®E and Powertech TSAT™ for positive sequence RMS models and PSCAD for EMT models. ERCOT's model quality test and benchmarking ("MQT") requires consistent response between the positive sequence RMS models and the EMT model. Additionally, ERCOT requires a Model Parameter Verification Report (PVR) that provides evidence that tunable model parameters match what is implemented in the field. Lastly, ERCOT also requires unit model validation for PSCAD models demonstrating validation of the PSCAD model against actual hardware measurements (i.e., hardware type test, not site-specific tests). ERCOT's MQT includes the following tests:
    - Flat start
    - Voltage step down/up 3%
    - Frequency step up 0.3 Hz
    - Frequency step down 0.3 Hz with and without headroom
    - High voltage ride-through
    - Low voltage ride-through
    - Short circuit ratio steps
    - Phase angle jump (only for EMT)

  Simulation-based MQT tools are posted publicly for PSS®E,[42] TSAT,[43] and PSCAD.[44] DMView compares the model response with the recording data to validate the PSS®E model of an IBR plant; it can play back the voltage and frequency as recorded by a phasor measurement unit (PMU). Figure 51 shows the overall process for using the DMView tool. PMView is a similar tool used for validating PSCAD models and is able to represent more details of the IBR plant as well as validate against unbalanced grid disturbances (which more events are). The tool uses both PMU and DFR data and knits them together (with some manual user intervention) in terms of playback functionality to

[42] DMView (https://sites.google.com/view/dmview/home)
[43] Powertech MQT Case Preparation Tool (https://www.dsatools.com/news)
[44] PMView (https://sites.google.com/view/pmview/home)

leverage the higher resolution data when available. This is enabled by time-synchronization across both measurement sources.

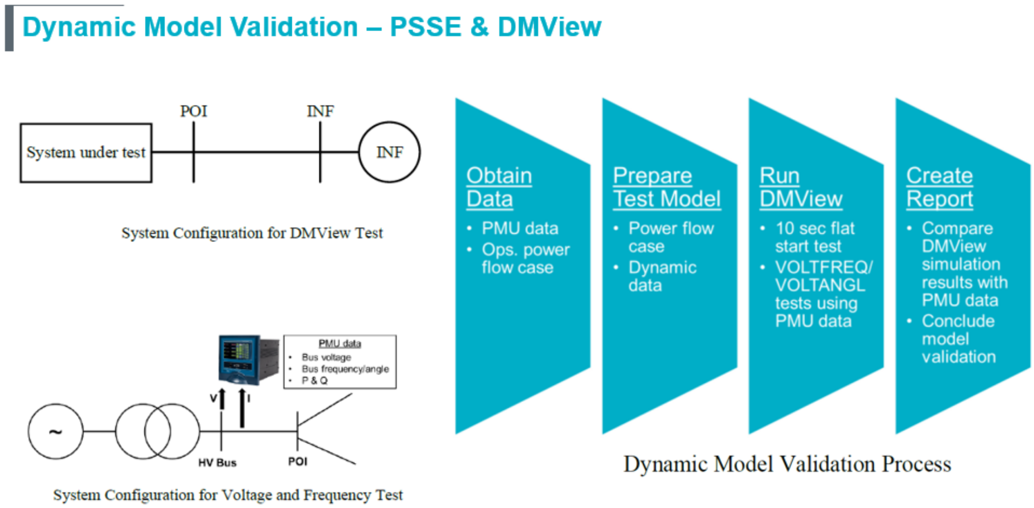


Figure 51: DMView Process Flowchart Visualization [Source: ERCOT]

Yunzhi emphasized that, in the end, the model needs to be an accurate representation of the actual equipment. Further, he stressed that it is not ERCOT's responsibility to do model tuning. ERCOT uses measurement-based approaches to ensure model accuracy. When models are deemed insufficient, ERCOT contacts the respective Resource Entity (i.e., the IBR plant owner/operator) who then must conduct additional analysis to determine the cause of the error and to then tune the model or update the site to get a more accurate match between simulation and reality.

- **Julia Matevosyan, ESIG:** Julia gave a brief presentation regarding periodic tests, which should be conducted to reassess conformity of the IBR plant with the requirements in IEEE 2800-2022. The periodic testing should be mutually agreed between the TS owner/TS operator and the IBR owner or as required by applicable regulatory standards. If during the period since last testing, and before the next periodic testing is due, IBR plant model validation and IEEE 2800-2022 conformity assessments were performance based on system disturbances, the timeline for the next periodic testing may be reset. Figure 49 shows a high-level illustration of the periodic testing timeline.

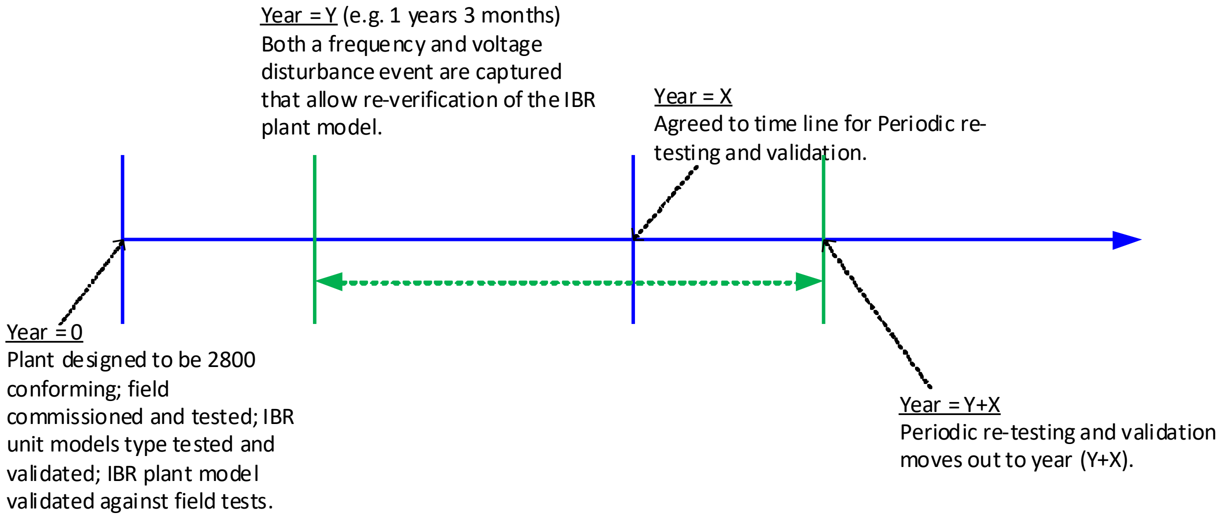


Figure 52: Illustration of Periodic Testing Timeline [Source: ESIG]

Periodic verification is another step in the conformity assessment process and takes place following any substantial changes at the IBR plant, as defined by the TS owner or the TS operator. Periodic verification confirms that the as-modified IBR plant continues to meet the requirements of IEEE 2800-2022. There are many reasons why an IBR plant may fall out of conformity with specific performance requirements following minor updates to the site. Examples include, but are not limited to, modifying dynamic response characteristics, changing operating modes purposefully or inadvertently, defaulting to factory settings accidentally, failing to return a control setting to its original value after testing, etc. After any substantial change to the IBR plant, the IBR plant model should be updated to reflect the change. Elements of the conformity assessment procedures may need to be repeated, as appropriate, to verify capability and performance requirements in case of augmentation or retrofitting of IBR plants.

Depending on the nature of an IBR plant change, engineering review should be performed to determine which, if any steps should be repeated (i.e., design evaluation, commissioning tests, IBR plant model validation, IBR plant model verification).

Care should be taken during IBR plant routine firmware updates to verify that PPC and IBR units' settings in the IBR plant do not automatically reset to default settings (as opposed to site specific "as-built" settings).

- **Manish Patel, EPRI:** Manish provided a detailed comparison of ride-through requirements in NERC PRC-029-1 and IEEE 2800-2022. FERC and NERC have acknowledged the potential value of IEEE 2800-2022 requirements and plant conformity assessment per IEEE P2800.2 but have declined to incorporate IEEE standards by reference. Rather, the NERC standards are evolving mostly driven by FERC Order 901 directives including, for example, the development of an IBR ride-through standard

NERC PRC-029, and the industry has sought to align the PRC-029 requirements as closely as possible with applicable IEEE 2800-2022 requirements. Both have very similar applicability, although IEEE 2800-2022 is more expansive since it does not have size or specific voltage thresholds. PRC-029 will apply to existing IBR plants as well as new IBR plants, with exceptions allowed for existing IBR plants with clearly documented hardware-based limitations; there are no exceptions for IBR plants already in interconnection queue or under construction.

The following are notable differences or nuances that Manish described in detail:

- PRC-029 does not specify grid conditions for which ride-through is required (e.g., system strength conditions).
- PRC-029 does specify V/Hz limitations wherein IBR plants may be able to trip and remain compliant.
- PRC-029 does not exclude interconnections at 500 kV nominal voltage, whereas IEEE 2800-2022 specifically defines how 500 kV voltage level resources should treat ride-through voltage thresholds.
- PRC-029 sets a uniform cumulative duration of 10 seconds for the ride-through region; therefore, IBR plants must withstand any number of disturbances spaced greater than 10 seconds apart. IEEE 2800-2022 specifies a shorter (120 second) and longer (30 minute) windows for consecutive voltage deviations that IBR plants must ride through.
- PRC-029 Attachment 1 Note 7 is written with an additive curve interpretation where it states "[i]f the voltage is continuously varying over time, it is necessary to add the duration within each band of Tables 1 and 2 over any 10 second time period." This may be interpreted as doubling the ride-through time obligations; however, it maybe referring to situations where voltage goes in and out of the mandatory and continuous operation regions. This is difficult to interpret and may need revision so as not to create an untenable requirement.
- PRC-029 includes some requirements that may be vague or up to interpretation. For example, "continue to deliver the pre-disturbance level of Real Power…" is technically infeasible for step changes in voltage. However, over a short period of time (within cycles) this is achievable.
- PRC-029 and IEEE 2800-2022 have different fault current injection requirements where IEEE 2800-2022 has much more details regarding current injection type, speed, capability, performance, etc. This is predominantly driven by IEEE 2800-2022 being more of a capability and performance standard whereas PRC-029 is a regulatory compliance standard.

  - PRC-029 is a bit more flexible in terms of active power recovery following faults than IEEE 2800-2022 such as speed of recovery and dynamic response characteristic.
  - PRC-029 Attachment 1 Note 10 states "instantaneous trip settings based on instantaneously calculated voltage measurements with less than filtering lengths of one cycle (16.6 millisecond) are not permissible"; however, this type of protection is very commonly employed on the IBR units and thus this requirement will likely require significant exceptions and may not be able to be met by newer technology as well. This is a significant issue in PRC-029 that needs revision. This could be included as an exception in Requirement R1 of PRC-029 above certain AC voltage levels, thus allowing IBR units to retain such protection. Or the language could more closely mirror IEEE 2800-2022 where this specific language is only applied for protection schemes that can trip the entire IBR plant (i.e., at the main power transformer and/or substation bus).

  Manish also briefly covered differences between NERC PRC-028-1 and IEEE 2800-2022. Ryan provided closing remarks for the event, highlighting the steps of the conformity assessment process per IEEE P2800.2, and those that

  - IEEE 2800-2022 is notably more comprehensive than PRC-028 in terms of required measurement data. IEEE 2800-2022 specifies SCADA data, unit-level DFR data, unit-level DDR data, and measurement accuracy requirements whereas PRC-028 does not. does not specify grid conditions for which ride-through is required (e.g., system strength conditions).
  - Recording rates and retention periods for multiple types of data are much shorter in PRC-028 than in IEEE 2800-2022.
  - Time synchronization requirements in IEEE 2800-2022 are much more stringent than in PRC-028; however, some industry representatives have highlighted that the time synchronization requirements in IEEE 2800-2022 may not be possible to meet in all instances due to transmitting clock signals within a large, dispered IBR plant.

- **Ryan Quint, Elevate Energy Consulting:** Ryan provided closing remarks for the event, highlighting the steps of the conformity assessment process per IEEE P2800.2, and those that particularly pertain to the post-commissioning activities: model validation, monitoring, and periodic tests and verifications. IEEE P2800.2 approval is still a year or more out, yet that should not preclude transmission entities from adopting IEEE 2800-2022 requirements and starting to develop conformity assessment processes. Post-commissioning model validation standards are evolving with FERC Order 901 Milestone

3 NERC Standards revisions, particularly related to MOD-026.[45] It will be important for that effort to align with IEEE 2800-2022. Disturbance monitoring equipment is now required per NERC PRC-028 and can thus be used for conducting model validations and other performance assessments when large grid events occur. Creating automated processing of model validation results to help expedite the assessment of IBR plant models and conformity with requirements is an important aspect of improving reliability and operational efficiency of these sites. Periodic verifications and testing can also help when settings, controls, and protections may be inadvertently changed or reverted to factory defaults over many years. This requires close coordination between IBR plant owners/operators and the OEMs, which may create bottlenecks and may need to be included in IBR plant procurement contracts.

Defining roles and responsibilities for establishing and enforcing requirements throughout the IBR plant lifecycle is an important aspect of effective adoption of IEEE 2800-2022. Close coordination with the NERC standards revisions currently underway is essential to minimize conflicts or contradictions that create obstacles for both IBR plant owners and TS owners/operators. Minimizing the impact on transmission providers to integrate these conformity assessments into existing business practices is key. Additionally, minimizing impacts on IBR plant owner/operators in terms of personnel; compliance burden; operational downtime; coordination with engineering, procurement, and construction contractors; coordination with OEMs; and additional external support all need to be considered.

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Metrics for IBR Model Validation:** The IEEE P2800.2 working group discussed normative quantitative model accuracy metrics at great length, but finally decided to make only qualitative evaluation normative, and quantitative metrics are in an informative annex. Other parts of the world have adopted various approaches to this and there are pros and cons to qualitative and quantitative evaluations.
- **Ongoing Conformity Testing to IEEE 2800-2022 Requirements:** Questions were raised regarding whether repeated conformity testing and compliance evaluations will be required over the lifetime of an IBR plant with IEEE P2800.2, which is often done in various markets around the world. This topic is only briefly described in IEEE P2800.2 and does not go into any explicit requirements on this topic. Periodic testing is included in IEEE P2800.2 but how this is enforced depends on how the standard is adopted and implemented by the AGIR (e.g., regulator, ISO/RTO, etc.).

[45] Note that, as of writing this summary, the current versions of NERC MOD-026 and MOD-027 are being combined into a single updated MOD-026 standard that encompasses both types of model validation.

- **Availability of IEEE P2800.2 Draft to the Public:** Members of IEEE Standards Association can sign up for the balloting pool for the standard when it is formed,[46] and then will have access to the draft standard when it is put to ballot. IEEE P2800.2 Working Group members (that attended at least two working group meetings) can access the latest developed draft online. During the IEEE SA Initial Ballot, the P2800.2 Draft will also become available (for purchase or via subscription) to the public.[47]
- **OEM-Provided Parameters Across Multiple Events:** It was emphasized that OEM-supplied information regarding model parameterization for the IBR unit and PPC should be used for model validations and that these validations should occur across multiple grid events and conditions. A discrepancy in one validation does not necessarily mean the parameterization of the model is incorrect. Validations across many events is most effective to determine whether model parameterization needs to be changed. This is most effective using disturbance monitoring data, capturing event records, and using those measurements to conduct automated model validations. An engineer can the evaluate whether the model is valid across the events or whether adjustments are needed.
- **Assurance that Ride-Through and Protection Settings are Validated Post-Commissioning:** Continuous assurance that the parameterization of models matching actual equipment post-commissioning may require occasionally reconducting design evaluations and possibly some commissioning tests over the course of the IBR plant lifecycle. Determining if a firmware upgrade affects the electrical behavior of the facility requires input from the OEM and continuous monitoring and alerting of the plant performance during normal operating conditions and in response to grid events.
- **Harmonization of IEEE 2800-2022 Protection and Ride-Through Requirements with NERC Requirements:** Manish highlighted that there may be one bullet in the list of explanations in NERC PRC-029 that could be interpreted as more stringent than IEEE 2800-2022. This is related to a clarification that "instantaneous trip settings based on instantaneously calculated voltage measurements with less than filtering lengths of one cycle (16.66 millisecond) are not permissible." However, overall they are aligned, particularly on the key point that IBR plant protections should not interfere with or limit the IBR plant's overall ride-through capability.

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[46] **Instructions to join ballot pool:** Log on to myProject (https://development.standards.ieee.org/) and access the menu bar on the top right. Select Invitations/Ballots > Open Invitations. The default view is My Invitations, which displays only invitations which are based on your interest designation and to which you have been invited. The All Invitations view shows all current open invitations. Under Ballot Invitations, click the Join Ballot Group icon. identify the project or standard you are interested in, then click Join Ballot. For step by step instructions including print screens, please see the IEEE SA Support Portal: https://standards-support.ieee.org/hc/en-us/articles/4405153859988-Join-SA-Ballot-Group-Individual-and-Entity-Balloting

[47] https://publicreview.standards.ieee.org/public-review-web/public-app

Key Themes

- **Post-Commissioning Conformity Assessment Activities:** These activities involve post-commissioning model validation, post-commissioning monitoring, and periodic tests. Using measured data captured from commissioning tests or real-world events can help evaluate the validity of the IBR plant models and provide feedback as to whether the IBR plant is meeting the IEEE 2800-2022 requirements or if changes are needed to either the models or the facility.
- **Alignment with Regulatory Changes:** The post-commissioning conformity assessment activities will be important to align with the changes occurring to NERC Standards related to IBRs. This relates to the NERC Milestone 3 standards revisions regarding model validation and also leverage the requirements regarding PRC-028 disturbance monitoring (which IEEE covers more extensively). Misalignment between IEEE 2800-2022 and NERC standards will create obstacles that could cause reliability and compliance issues in the long-term. Engagement in NERC standards development activities will be key to keep these aligned moving forward.

April 29, 2025 Virtual Meeting

Reactive Power – Voltage Control Requirements Continued (~190 simultaneous attendees)

Figure 53 shows the makeup of the meeting attendees by industry sector:

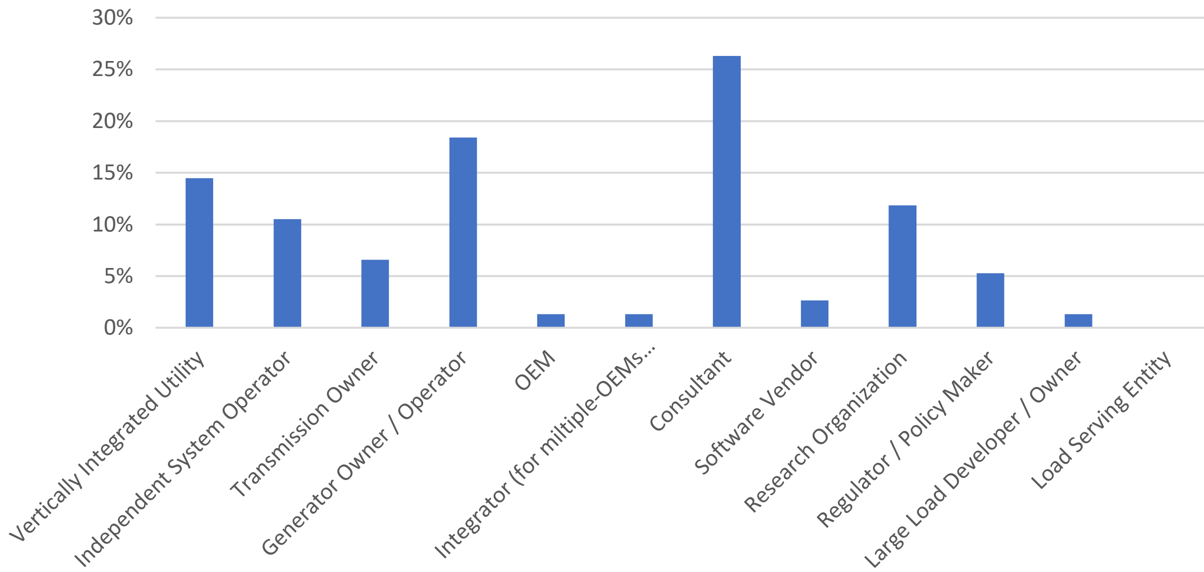

Figure 53: Meeting attendees by industry sector

This was the eleventh meeting of the DOE i2X FIRST initiative, focused on IEEE 2800-2022 *Clause 5: Reactive Power–Voltage Control Requirements within the Continuous Operation Region* with a specific focus on reactive power contribution during zero active power output. Presentations included:

- **Aminul Huque, EPRI:** Aminul presented on research exploring whether solar PV inverters can absorb/inject reactive power during nighttime when they are not generating active power, whether they can provide seamless voltage regulation during the transition from day to night, and how much active power a solar PV inverter or solar PV plant needs to consume to stay in operation and absorb/inject reactive power during nighttime. EPRI first tested a 33 kW three-phase inverter (used in distribution system-connected applications) in a laboratory environment. The inverter included a "reactive power output at night" settings that enabled (set as disabled by default) to keep the inverter in operation during nighttime. A clear sunny day solar profile was condensed into a 60-minute test and the inverter was set to absorb 20 kVAR. Test results showed the inverter was able to maintain reactive power absorption continuously during the daytime and nighttime transitions. Figure 54 shows the results of the tests. The inverters (33 kW rating) consumed 35 W baseline (0.1%) plus 14 W per kVAR exchanged. Thus the maximum active power consumed was around 350 W (1%).

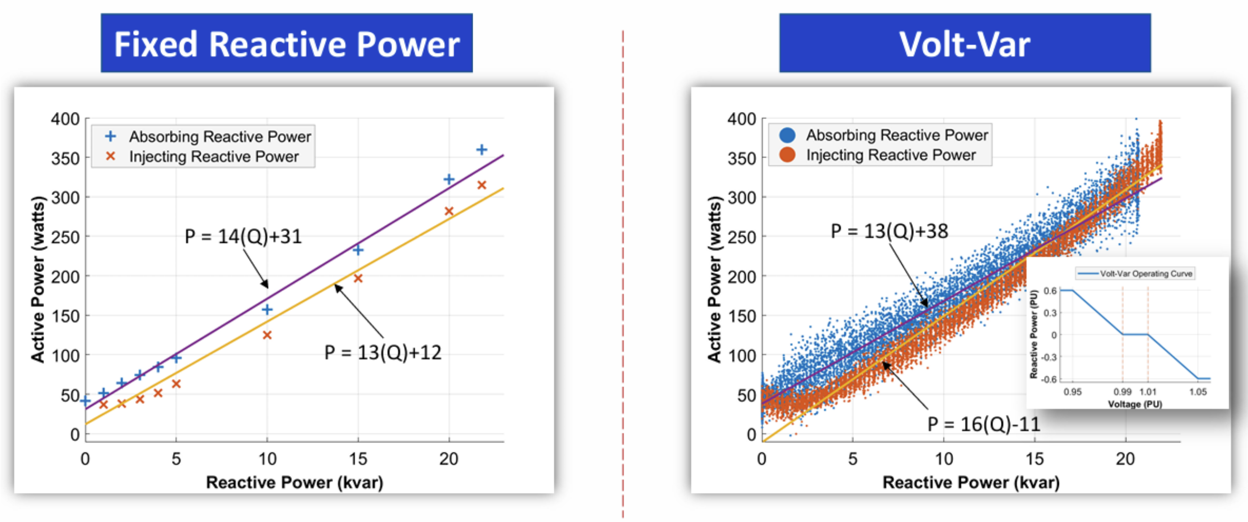

Figure 54: Results of Q at Night Test in Two Different Control Modes [Source: EPRI]

EPRI then tested another 50 kW three-phase string inverter that is IEEE 1547-2018/UL 1741SR certified. The inverter has a "reactive power for zero active power" setting that must be activated during feed-in (solar generation) operation. The setting can be specified to different types of reactive power control. The inverter was configured with Category B IEEE 1547-2018 voltage control settings. Again, the inverter successfully absorbed/injected reactive power following the configured volt-var curve without solar power available. Standby operation consumed 139 W (0.28%) of power when the function was enabled and approximately 14 W per kVAR exchanged, up to a maximum of 450 W (0.9%). For comparison, the inverter consumed 5 W of power when the setting was disabled during no solar availability.

Next, EPRI conducted a field demonstration on a 105 MWac (90 MW operating limit) solar power plant connected to 240 kV in California, in partnership with the utility and generator owner/operator. The generator was compensated for participation in this study for the incurred losses during testing. The site included 32 power block – 30 equipped with 3.2 MVA central PV inverters, one with 33 100 kVA string inverters, and one configured with dc-coupled PV plus energy storage for different research objectives. Tests showed that the site was able to respond and follow changes in reactive power command even during the nighttime, although the median settling time varied between 10 to 24 seconds between tests. Aminul highlighted that the site was not originally designed with some of these features in mind, and thus some of the response characteristics were likely anomalous because of these design limitations that were uncovered during testing.

Again, the results were very similar. Nighttime losses for the plant in "sleep mode" (no reactive power support at night) were around 317 kW while those losses were between 575 to 725 kW when the capability was enabled with Q at zero output. Figure 55 shows active power consumption again increased with reactive power exchange up to about 1.1 MW (about 1% again).

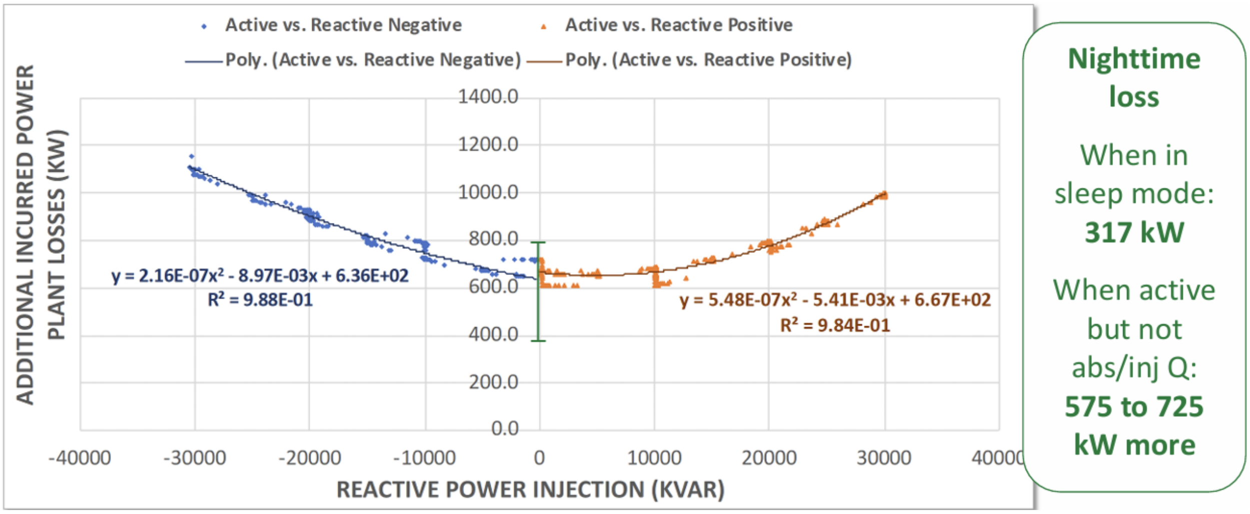

Figure 55: Results of Q at Night Field Demonstration for Bulk Power System Solar Plant [Source: EPRI]

When the volt-var function was enabled at nighttime, point of interconnection voltage control was notably tighter and more controlled (see Figure 56). An estimated 9.5 MWh of additional energy per day was consumed by the plant to provide the voltage regulation (on a 100 MWac plant). About 60% of the time, reactive power contribution from the plant was 5 MVAR or less, showing how tighter voltage control can be achieved with relatively minor contributions from the IBR plant more of the time.

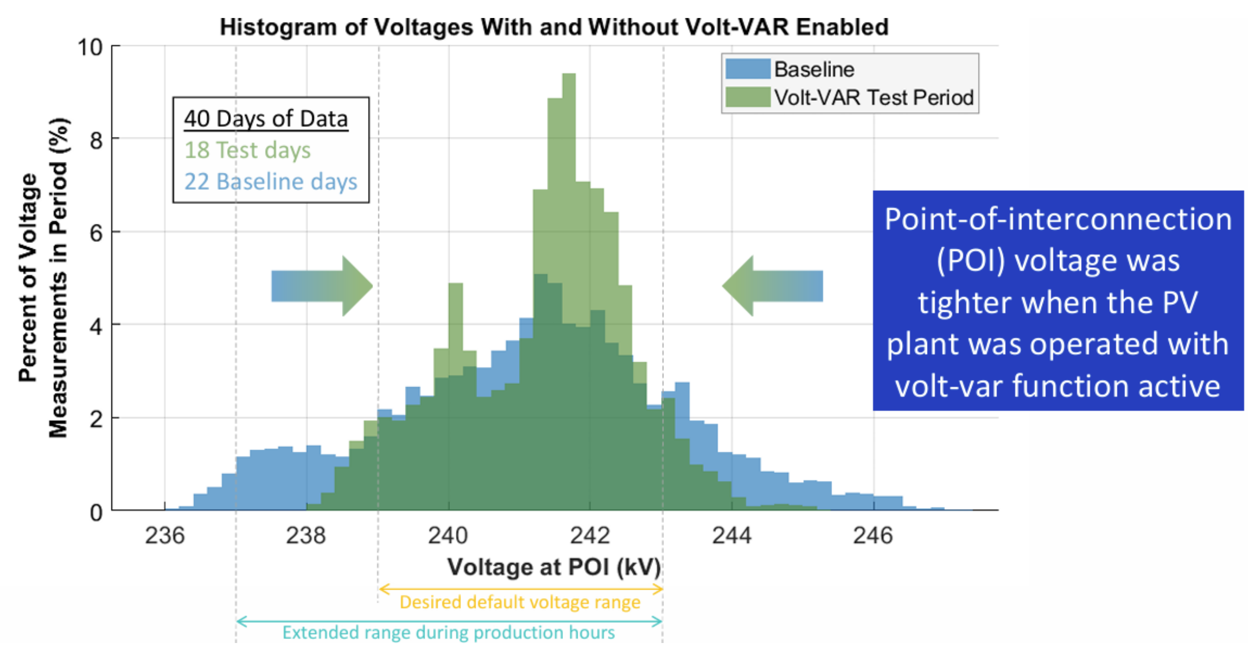

Figure 56: Tighter Voltage Control with Nighttime VARs Enabled [Source: EPRI]

The work showed that nighttime reactive power support from solar PV inverters and solar PV plants is possible and comes with a cost to keep the inverters/plant operational instead of going into "sleep mode" to reduce losses. Solar PV systems can provide 24/7 voltage regulation support if designed and configured accordingly. IBR plants would be required to reliably operate in this mode for system operators to build confidence on this reliance. Additionally, some form of compensation mechanism would be required to account for the increased costs to the generator owner for operating in this mode.

- **Alex Lee, ERCOT:** Alex presented on ERCOT experience regarding communication of capability and status of online IBRs at zero active power output. All ERCOT generating resources should provide voltage support service and regulate voltage at their point of interconnection. Some IBRs have experienced reactive power oscillations at very low active power output. ERCOT detected voltage oscillations in real-time and investigated the root causes as the problem started occurring in multiple areas (see example in Figure 57).

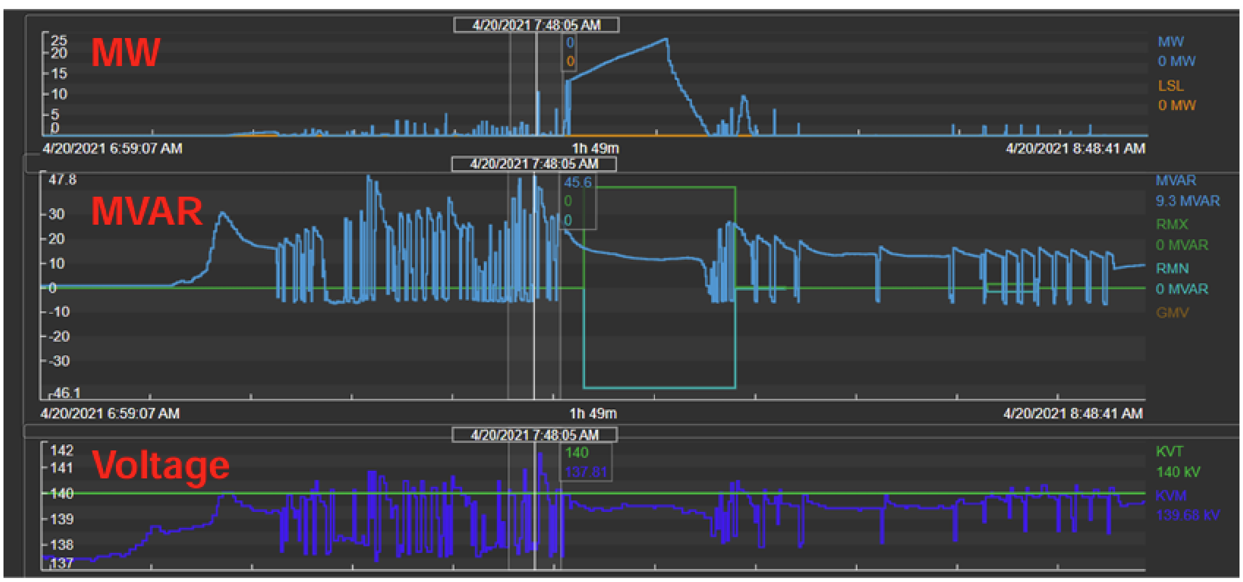

Figure 57: Example Observed Oscillation Event during Zero Active Power Output at IBR Plant in 2021 [Source: ERCOT]

ERCOT issued a request for information (RFI) in 2019 to gather information on this topic. ERCOT found that many Intermittent Renewable Resources (IRRs) – wind and solar PV resources – are not capable of providing reactive power at zero active power output. Even IRRs that responded "yes" to the RFI require additional cost and/or setup from the OEM. Many facilities are already consuming active power from the grid when at 0 MW power production.

This led to ERCOT NPRR1138[48] to clarify responsibilities based on the capability, which ultimately modified how capability curves are reported (see Figure 58).

[48] https://www.ercot.com/mktrules/issues/NPRR1138

- If the IRR cannot provide reactive power at zero active power output, then…
  - The Low Sustained Limit (LSL) should be set to a non-zero value, not to exceed 1 MW.
  - Reactive power capabilities curves must be submitted to reflect this limitation.
  - In real-time, automatic voltage regulator (AVR) status of "off" should be used when synchronized but not producing reactive power.
- If the IRR can provide reactive power at zero active power output, then…
  - The LSL may be 0 MW.
  - AVR status should be "on".
- IRRs may physically desynchronize inverters from the ERCOT system when not producing active power.

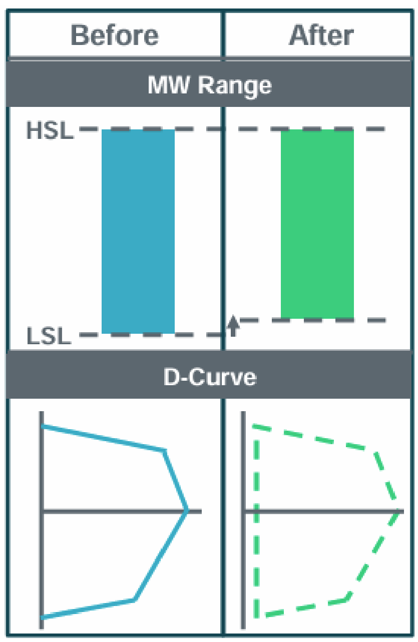

Figure 58: Capability Curve Example with HSL and LSL Before and After NPRR 1138 [Source: ERCOT]

The NPRR 1138 rule minimizes reactive power and voltage oscillations caused by current equipment limitations. More accurate and consistent capability curve information is also provided by the generator owners, improving operator situational awareness and reliability studies.

ERCOT has also leveraged its extensive network of 270 PMUs streamed at 30 samples per second for improved situational awareness of oscillations. There are multiple ongoing efforts to investigate and identify root causes of oscillations on the ERCOT system including active power oscillations, reactive power oscillations at non-zero active power outputs, simultaneous active and reactive power oscillations, and subsychronous resonance (SSR) issues. Figure 59 shows an example of reactive power oscillations at a solar PV interconnection substation.

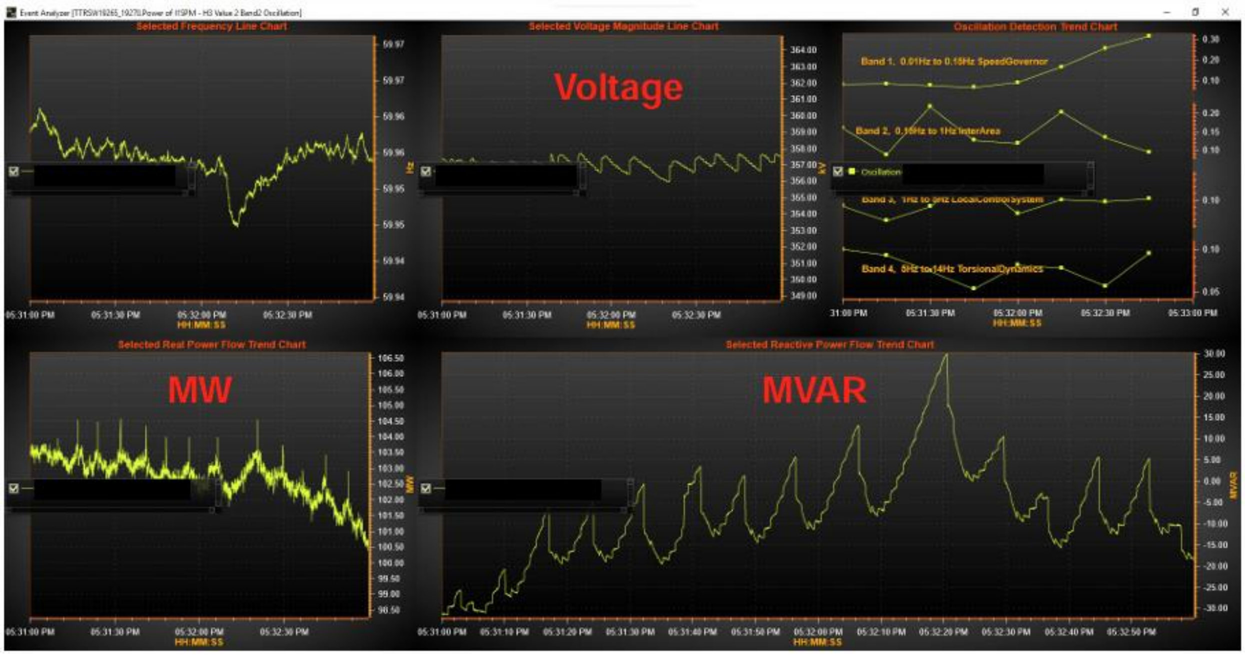

Figure 59: Reactive Power Oscillations at a Solar PV Interconnection Substation Observed with PMUs [Source: ERCOT]

Some oscillations have been fully resolved through tuning and equipment adjustments. ERCOT's short-term focus is to reduce the number of oscillations that occur on the system due to equipment limitations. ERCOT recommends that IBR owners work with their OEMs to achieve an LSL of 0 MW or as close to 0 MW as possible, requiring possible controller and inverter tuning and tighter operational margins. ERCOT's long-term goal is to achieve stable voltage control at all MW outputs for IBRs.

- **Divya Kurthakoti Chandrashekhara, Orsted:** Divya shared perspectives from a renewable developer and owner/operator. Firstly, Divya stressed that many of these features such as reactive power control at zero active power output are much easier to operate to when they are designed into the site up front. The plant must be designed with necessary equipment and controls to be capable of providing these features and services.

  Divya shared experience with the cost of reactive power for offshore wind capability and utilization. For offshore wind, experience shows that it is likely to be more cost effective to have onshore reactive power devices operate as a STATCOM and provide voltage control rather than have the offshore equipment provide that performance. For example, a 1 GW plant with STATCOM or VSC HVDC as a reactive power source would have the VSC HVDC with about 10-20 MW of losses whereas the STATCOM would be about 4 MW of losses. Therefore costs for losses are expected to be up to 5x more to use the HVDC facility.

Divya also highlighted that reactive power flow and voltage control is a somewhat localized issue. Thus it is important to understand how each plant contributes to possible voltage issues, account for the cost of keeping generators online (i.e., covering losses and any degradation of lifespan), understanding IBR control interactions at different output levels, and ensuring that societally the grid is operated as optimally as possible.

Lastly, Divya highlighted that systems planning is an important factor in this area, determining what is best for the overall system and for ratepayers. This includes determining the optimal type and location of reactive power support. She emphasized that it may not be economical to impose prescriptive requirements on each project.

Presentation recording and slides are available to download here.

Q&A for Presenters in Slido

- **Impact of Providing Reactive Power at Zero Active Power Output to Lifespan of Inverters:** This needs further quantitative research and exploration; however, some presenters recognized that operation in this mode may actually help improve the life expectancy of the devices and it does not appear this would cause severe degradation of equipment. Concerns were also raised about any possible generator step-up transformer lifespan impacts; however, this needs further research as it was also highlighted that keeping moderate load at night could help reliability of devices like transformers.
- **Forms of Compensation for the Reactive Power at Zero Active Power Service:** ERCOT described that they are taking a holistic approach, including market or financial compensation approaches. If an entity is providing a stability service or other service that strengthens the resilience of the grid, then they are analyzing where that compensation should come from. This applies to more than voltage control and also includes frequency, dynamic response, inertia, etc. This is a challenging problem that has been a focal point of stakeholder discussions for years and may warrant more rigorous research and evaluation.
- **Performance of Solar PV Reactive Power at Night After Tripping:** Aminul described that for the laboratory tests conducted, the data sheet stated that if there was a disconnection of the inverter from the grid unexpected (i.e., tripping) then it would not restart with reactive power support at nighttime and that it would need to be reactivated post-trip. This performance was not tested, but was noted when reviewing manuals.
- **Inclusion of Reactive Power at Zero Active Power Commissioning Tests:** These tests have not been integrated into any ERCOT requirements for commissioning testing, and this has mainly simply been a factor of prioritizing risks. While these issues are known to ERCOT, they have fallen relatively lower on the rank order of risk mitigations. However, this is a known area where enhancements could be made. These concepts apply to all other transmission providers and market operators across the US as well.

- **Leveraging Full IBR Reactive Capability Versus Other Solution Options:** Industry has struggled to quantitatively justify the use of reactive power at zero active power output as compared with other solutions options, mainly due to the way that transmission planning and interconnection studies are conducted. This comparison requires a deeper look at utilization and costs, which are often not readily available in these domains.

Key Themes

- **Reactive Power at Zero Active Power Output Is Feasible but Comes with a Cost:** Lab and field demonstrations confirmed that modern solar PV inverters can inject or absorb reactive power even during nighttime or periods of zero active power output. Doing so requires the inverter to remain powered, consuming a small but measurable amount of energy (~0.3%–1% of inverter rating), resulting in energy losses that must be considered. Standby and reactive power losses scale at utility scale, such as ~9.5 MWh/day for a 100 MWac plant. These non-trivial operating losses and potential equipment degradation need further analysis and better understanding, and stakeholders broadly acknowledge that issues of compensation (e.g., market-based, contract-based) veresus interconnection requirements must be broadly resolved before IBR plants universally provide reactive power service around the clock. Such resolution should improve acceptance of IEEE 2800's continuous operation expectations.
- **IEEE 2800-2022 Clause 5 Requirements Demand Design-Phase Considerations:** Enabling and meeting IEEE 2800-2022 Clause 5 requirements, especially under zero active power conditions, requires these capabilities to be designed into the IBR plant from the beginning. Retrofits are difficult, costly, and can introduce anomalous behaviors. Plant-level equipment, controls, and OEM support is needed in the design phase of an IBR plant.
- **Grid Stability Depends on Accurate Capability Reporting and Operator Visibility:** Experience from ERCOT showed that misalignment between reported and actual IBR reactive power capabilities can cause voltage and reactive power oscillations, especially when real-time data and settings do not reflect physical limits. ERCOT's NPRR1138 clarified requirements to address these issues.
- **Standardization and OEM Tuning Are Critical to Mitigate Oscillations:** Reactive power oscillations, whether at zero or non-zero MW outputs, have been observed across multiple IBR sites. These stem from controller tuning issues, lack of coordination, or inappropriate settings. Grid operators are actively addressing these types of issues but emphasize the need for close collaboration with OEMs to tune controls and reduce systemic oscillatory behavior.

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