NERC Inverter-Based Resource (IBR) Webinar Series:

Session 1: Introduction to Inverter-Based Resources

June 6, 2023

RELIABILITY | RESILIENCE | SECURITY




High-Level Overview of Inverter-Based Resources (IBRs) – IBRs 101

Andy Hoke, Principal Engineer, NREL

Presented to NERC Webinar Series: Inverter-Based Resources

June 6, 2023

In this presentation

- Introduction: What is an inverter-based resource, and why do we care?
  - Basic definitions
  - IBRs in the present and future power system
- Differences between synchronous machines and IBRs, and resulting challenges
- Some potential solutions for high IBR power systems

What is an IBR?

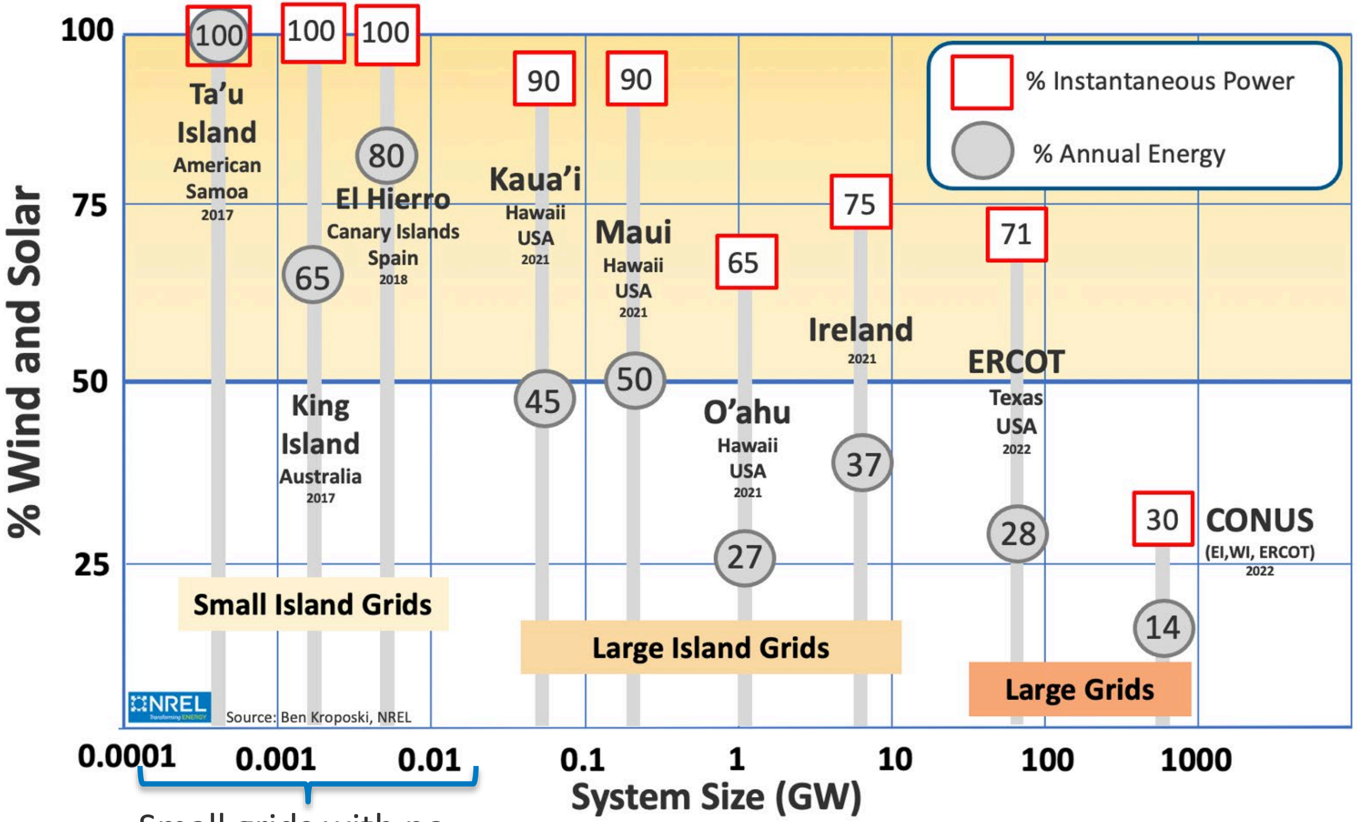
- The term inverter-based resource (IBR) refers to **power electronic converter-interfaced generation and storage resources**.
  - Most common IBRs are solar PV, type 3 and type 4 wind, battery energy storage etc.
- STATCOMs and HVDC stations are also converter-interfaced, so share many qualities with IBRs

IEEE 2800 definition*:

inverter-based resource (IBR): Any source of electric power that is connected to the *transmission system (TS)* via power electronic interface, and that consists of one or more *IBR unit*(s) capable of exporting active power from a *primary energy source* or *energy storage system* to a TS. A *collector system* or a *supplemental IBR device* that is necessary for compliance with this standard is part of an IBR. *See also:* **IBR plant; IBR unit**.

*IEEE 2800 includes in its scope HVDC stations dedicated to interconnecting IBRs

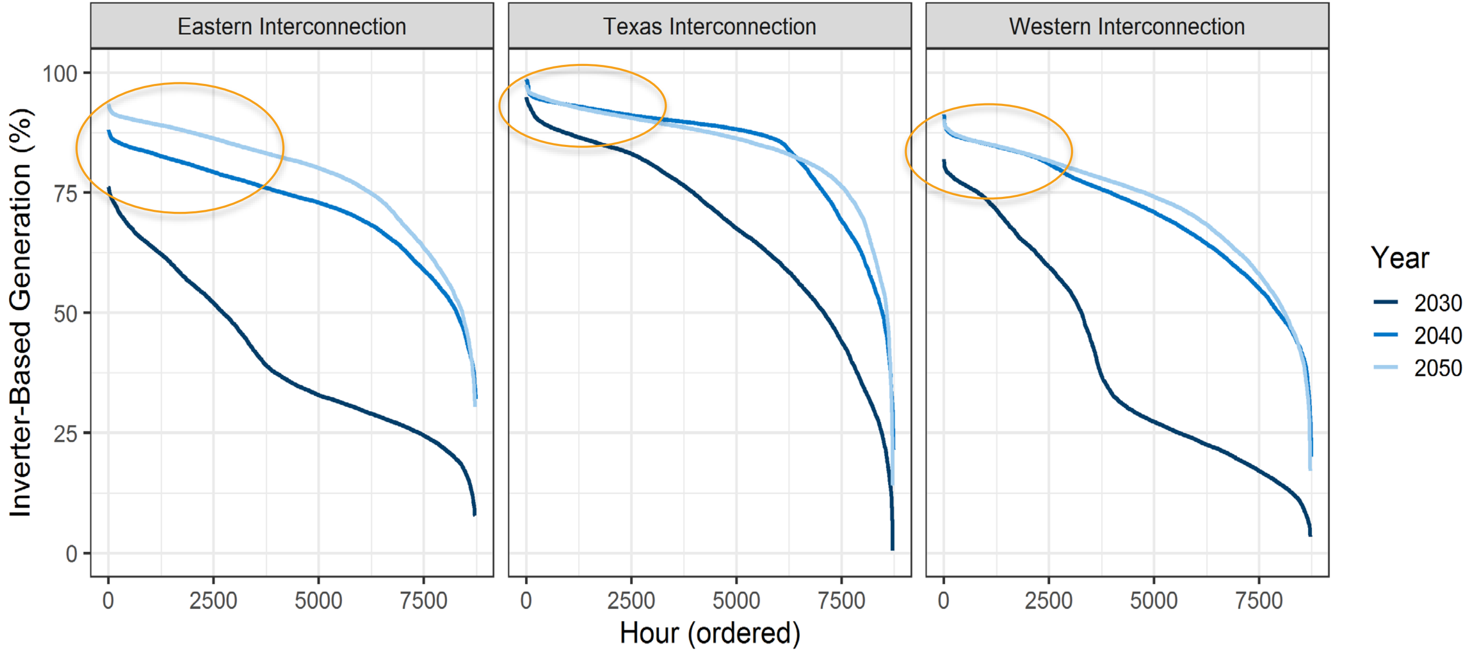
IBRs in the power system today



Small grids with no transmission system

IBRs in the power system tomorrow

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

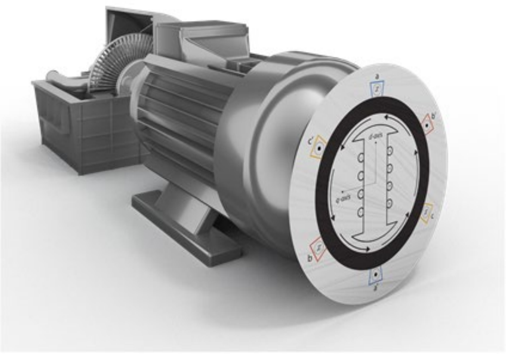


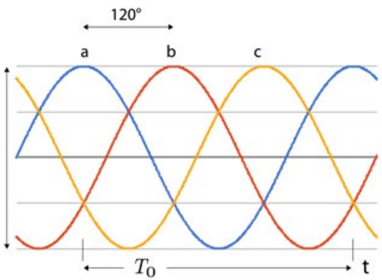
Data from 2021 DOE/NREL Solar Futures Study: https://www.nrel.gov/analysis/solar-futures.html

In this presentation

- Introduction: What is an inverter-based resource, and why do we care?
  - Basic definitions
  - IBRs in the present and future power system
- **Differences between synchronous machines and IBRs, and resulting challenges**
- Some potential solutions for high IBR power systems

Synchronous Generators



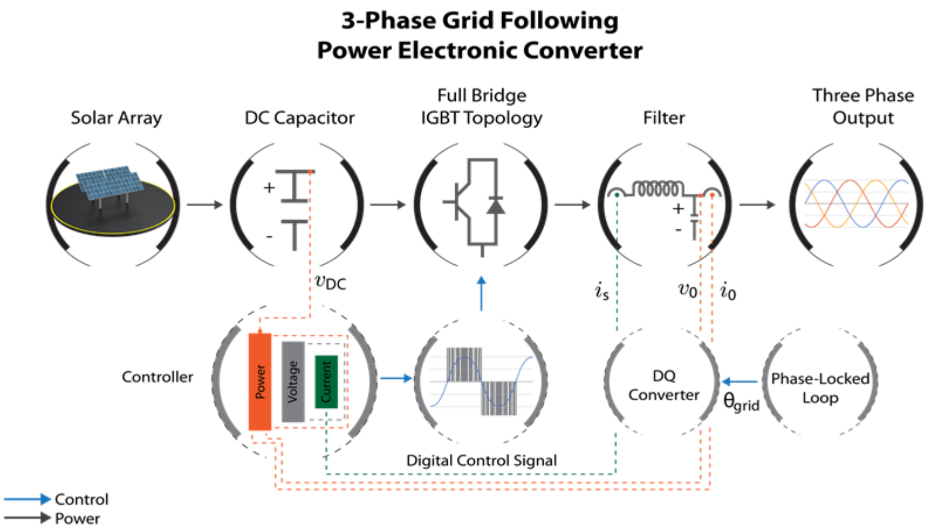


T_0 = one rotor revolution if single pole pair

- Synchronous generator (SGs) naturally generate a sinusoidal output **voltage** waveform; they are *grid-forming* devices
  - A de-facto voltage source on the power system
  - A large mass (the turbine/machine) is electromagnetically coupled to the AC power system
    - Embeds inertial characteristics
- Governors, which change mechanical power, are relatively slow (> 0.5 seconds)
  - Load perturbations initially met by inertial energy
- Large, transient overcurrents in faulted conditions (4 to 7 times rated)
  - Basis for many protection systems

[4] "Stability and control of power systems with high penetrations of inverter-based resources," R.W. Kenyon, et al., *Solar Energy*, 2020

Grid-Following (Conventional) IBRs

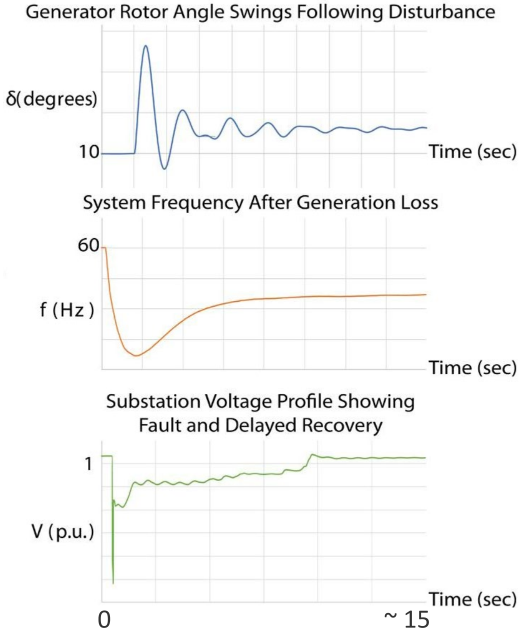


- Inverter tracks an existing, sinusoidal voltage waveform with a phase-locked loop and bases all control objectives on the assumed presence of this waveform
  - Hence, grid-following ("GFL")
  - Acts as a current source at fundamental frequency
- A collection of cascaded dynamic control systems
  - Phase-locked loop
    - To determine phase of the power system
  - Inner current loops
    - To regulate output current across filter inductor
  - Power loops
    - To regulate power output to setpoints
  - Auxiliary control
    - Grid support functionality, self-protection, fault behavior, etc.
- Not modelled in our studies is the pulse width modulation control and associated power electronic switching
  - This happens fast enough not to significantly affect grid stability

[4] "Stability and control of power systems with high penetrations of inverter-based resources," R.W. Kenyon, et al., *Solar Energy*, 2020

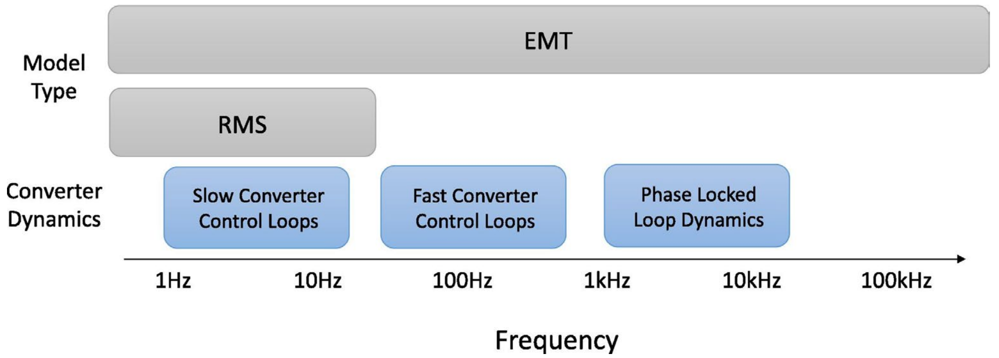
Challenges of operating power systems with very high levels of inverter-based generation

- Scheduling and dispatch, including reserves scheduling
  - Inertia scheduling?? % IBR constraints??
- Load-generation balance at various time scales
  - Sub-second (inertial time scale)
  - Seconds (primary frequency response time scale)
  - Minutes (secondary frequency regulation time scale)
  - Hourly and longer
- Voltage and frequency transient stability
  - Small-signal stability
  - Resilience to faults
  - Resilience to loss of generation/load
  - Resilience to loss of system strength
- Black start
- Protection
- Fault ride through
- Modeling
  - Higher detail needed to capture fast controls
  - Matching IBR models to device behavior



- Maybe replace this figure…

Electromagnetic Transient Simulations



- Both grid-forming and grid-following inverter controllers act on instantaneous AC voltage quantities (point-on-wave), and can react in well under a line cycle
- Traditional **positive sequence phasor domain simulation tools** ("RMS" tools like PSSE, PSLF, …) capture most conventional power system electromechanical modes well, but do not model waveforms and **can miss dynamics faster than a few Hz**
- Electromagnetic transient (EMT) simulation tools (PSCAD, EMTP, …) can simulate AC waveforms on arbitrarily small timesteps, so can capture full IBR dynamics
- Model runtimes are orders of magnitude slower
- New IBRs should provide validated EMT models. EMT studies needed in some cases

[x] Update references

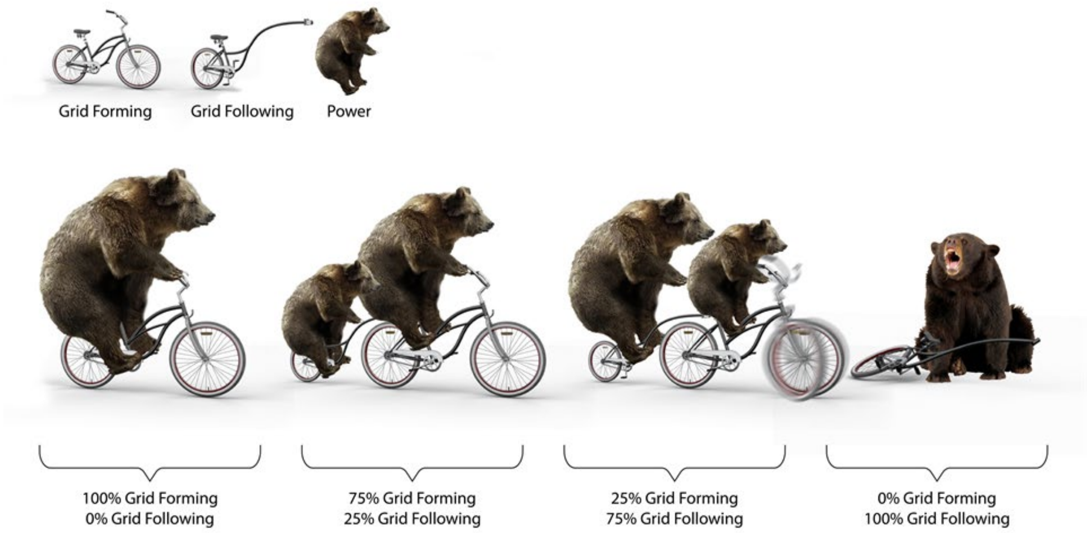
In this presentation

- Introduction: What is an inverter-based resource, and why do we care?
  - Basic definitions
  - IBRs in the present and future power system
- Differences between synchronous machines and IBRs, and resulting challenges
- **Some potential solutions for high IBR power systems**

Potential solutions for high-IBR power systems

- Grid-supportive IBRs that (among other things):
  - Reliably ride through transient events
  - Provide voltage support (steady-state and transient)
  - Provide frequency support on inertia timescale and longer timescales
- Models that accurately reflect IBR behavior
- Standards that can help:
  - Various NERC standards
    - 2020-02: Modifications to PRC-024 (Generator Ride-through)
    - 2022-04: EMT Modeling
    - IBR Registration activities related to the NERC submitted work plan as approved by FERC
  - IEEE 1547 for distribution-connected IBRs
  - IEEE 2800 for transmission-connected IBRs

What Happens with Fewer Grid-Forming Assets?

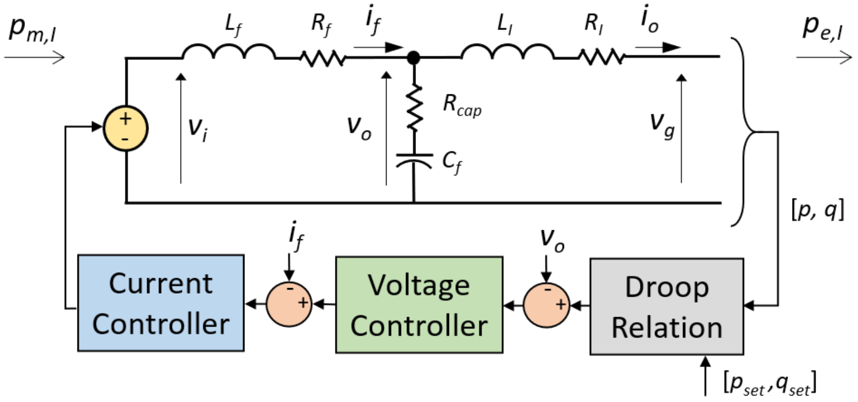


Here, *grid-forming* is a broad term including synchronous machines

- With fewer grid-forming assets online, the *stiffness* of the AC voltage is reduced
  - Metrics such as short circuit ratio/system strength attempt to capture this
- This impacts the stability of assets that require a voltage waveform to operate; i.e., grid-following inverters
- Not necessarily a low-inertia problem, although there is a relation if the only grid-forming assets involved are SGs

[4] "Stability and control of power systems with high penetrations of inverter-based resources," R.W. Kenyon, et al., *Solar Energy*, 2020

Grid-Forming (GFM) Inverters



- Whereas grid-following inverters track an existing AC voltage waveform, a *grid-forming* inverter **generates an AC voltage waveform** at its output terminals
  - Acts as a voltage source
  - Does not depend on external source for stability
  - Inherently resists changes in grid conditions
- Grid-forming inverters have been used for decades in off-grid/islanded applications.
- **Emerging application: grid-connected GFM inverters in parallel with the rest of the power system.**
  - Synchronize with other voltage sources via droop control (or similar)
- Control schemes are designed to accomplish objectives such as
  - Load sharing
  - Voltage control
- Some limitations compared to grid-forming synchronous machines, such as over-current capabilities
  - Control can be very fast. (Good? Bad?)

Insert additional references including NERC GFM docs here.

[5] "Research Roadmap on Grid-Forming Inverters", Y. Lin et al., NREL/TP-5D00-73476, Nov 2020

Grid-Forming (GFM) Inverters – State of the Art

IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 8, NO. 2, JUNE 2020

Grid-Forming Inverters: A Critical Asset for the Power Grid

Robert H. Lasseter, *Life Fellow, IEEE*, Zhe Chen, *Student Member, IEEE*, and Dinesh Pattabiraman, *Student Member, IEEE*

I. Introduction

- Potentially key to operation of power systems at/near 100% instantaneous inverter-based resources
- GFM battery inverters for use in parallel with large power systems are now available from several manufacturers
  - Field experience is limited but promising
- The term “grid-forming” is becoming a buzzword
  - Often used in conflicting/misleading ways, even by experts
- NERC Inverter-based Resource Performance Working Group (IRPWG) proposed a unified definition:
  - ~ “An inverter that maintains a constant voltage phasor in the transient and sub-transient time frames”
- Performance is not standardized
- Required in some recent utility RFPs
- Helpful, but not a panacea

[1] “Massive Integration of Power Electronic Devices (MIGRATE),” 2017-2020, https://www.h2020-migrate.eu/
[5] “Research Roadmap on Grid-Forming Inverters”, Y. Lin et al., NREL/TP-5D00-73476, Nov 2020
[7] R.H. Lasseter, Z. Chen, D. Pattabiraman, “Grid-Forming Inverters: A Critical Asset for the Power Grid,” *IEEE Journal on Selected and Emerging Topics in Power Electronics*, 2020

Conclusions

- IBRs (solar, wind, batteries) are becoming dominant power sources
- Operating high-IBR power systems brings challenges that are not present with lower levels of IBRs
  - Not insurmountable, but needs to be planned for
- EMT models may be needed to capture faster IBR dynamics
- Because it is typically challenging to retrofit IBRs with new capabilities, it is important that IBRs being installed today have the functionalities needed for high-IBR conditions
  - Ride through, voltage and frequency support, accurate models
  - Applying latest standards (IEEE 2800 and 1547)
- For very high IBR conditions, some IBRs will need to be grid-forming
  - Grid-forming BESS inverters are available and add little cost relative to conventional BESS inverters

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

NERC IBR Webinar Series Overview:

NERC IBR Strategy and Webinar Series Details

June 6, 2023

RELIABILITY | RESILIENCE | SECURITY




NERC IBR Strategy

Risk Analysis

- Event Analysis
- Disturbance Reports
- Alerts
- Lessons Learned

Interconnection Process Improvements

- Improvements to GIAs and GIP
- Enhanced Interconnection Requirements
- Modeling and Study Improvements
- IEEE 2800-2022

Best Practices and Education

- Reliability Guidelines
- Webinars and Workshops
- Outreach and Engagement
- Emerging Reliability Risk Issues

Regulatory Enhancements

- NERC Standards Projects
- BES Definition Review
- Inverter-Specific Requirements and Standards
- Risk-Based Compliance

NERC IBR Strategy

NERC Disturbance Reports

Planned Upcoming Reports:

- BESS-Related Events in California in 2022
- Texas Wind Event in Texas in 2022
- Solar PV Related Event in Utah in 2023

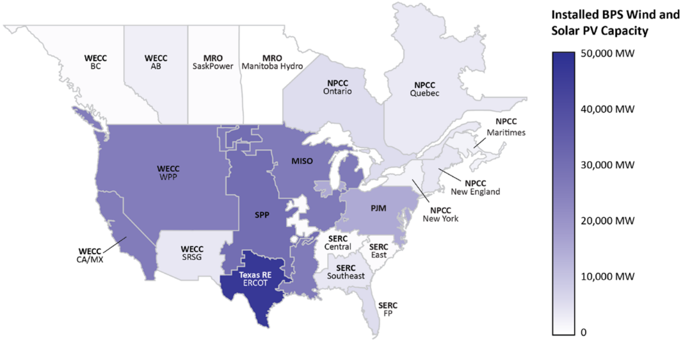
https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx

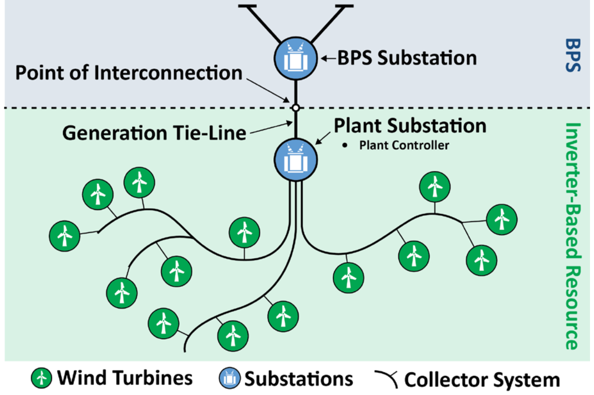
Disturbance Driven Activities

- Elevating the inverter risk issues within the ERO risk framework
- Immediate action by industry stakeholders to enhance local interconnection requirements
- Agile NERC Standards development activities
  - Comprehensive ride-through standard
  - New performance validation standard
  - Disturbance monitoring, EMT, planning assessments, etc.
- Level 2 NERC Alert(s) to understand extent of condition
  - Performance issues and modeling issues
- Enhancements to the FERC *pro forma* GIAs
- Improvements to plant commissioning practices
- FERC NOPR on inverter-based resources (performance and registration)
- NERC IBR Webinar Series

NERC IBR Basics Document

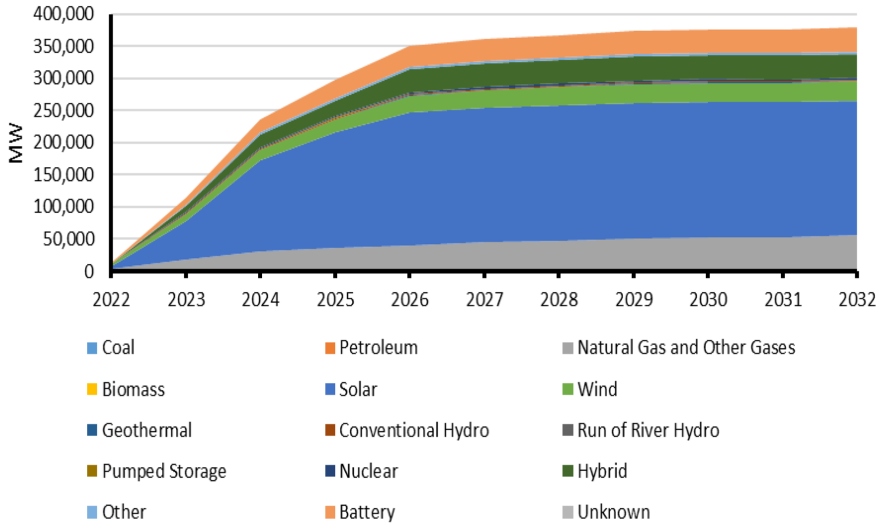
- Addresses a number of the "frequently asked questions" NERC receives from industry
- Defines many commonly used terms and provides high level descriptions of IBR plants
- Provides information on the differences between synchronous and inverter-based resources
- Briefly discusses how to ensure bulk power system (BPS) reliability under the current rapid grid transformation





NERC IBR Primer Document

- Much more detailed than the basics document
- Detailed information on the grid transformation
- Expands upon inverter and synchronous machine differences
- Discussion on the nuance between IBR and distributed energy resources (DER)
- Discussion on BPS reliability risks posed by IBR at high penetrations



IBR Webinar Series

- Intended to be a "one stop shop" for IBR- and Industry-related information
- Will start with IBR basics today and move through numerous topics related to the current state of the industry at a digestible level
- 24 non-NERC presenters from 20 organizations

4-5 PM ET, Thursday, 6/8/2023	**Webinar 2 - NERC Disturbance Reports and Lessons Learned** Overview of the NERC event analysis process and lessons learned from event analysis investigations
4-5 PM ET, Tuesday, 6/13/2023	**Webinar 3 - IBR Performance Issues** Industry experience with managing high penetrations of IBR and discussion on current IBR performance issues
4-5 PM ET, Thursday, 6/15/2023	**Webinar 4 - Establishing and Enhancing Interconnection Requirements** Industry approaches to establishing and enhancing interconncetion requirements and lessons learned
4-5 PM ET, Tuesday, 6/20/2023	**Webinar 5 - Modeling Part 1 - Modeling Requirements, Model Creation, Model Useability** Industry perspectives on using requirements to drive model improvements, creating facility models, and regional experience in establishing and enforcing modeling requirements
4-5 PM ET, Thursday, 6/22/2023	**Webinar 6 - Modeling Part 2 - Model Quality, Model Benchmarking** Regional experience with model quality and benchmarking and equipment manufacturer perspectives on model creation, benchmarking, and model support
4-5 PM ET, Tuesday, 6/27/2023	**Webinar 7 - Studies - EMT, Special Studies, Interconnection Studies** Guidance on best practice for interconnection studies and ensuring accurate data, special studies, and EMT modeling and and studies
4-5 PM ET, Thursday, 6/29/2023	**Webinar 8 - Interconnection Process** Industry experience regarding the challenges of managing and enforcing the Interconnection Process
4-5 PM ET, Tuesday, 7/11/2023	**Webinar 9 - Commissioning** Industry experience regarding commissioning testing proceses, lessons learned while navigating the commissioning process, and manufacturer perspectives on commissioning
4-5 PM ET, Wednesday 7/12/2023	**Webinar 10 - IBR Registration and Reliability Standards Enhancements** Current NERC activity regarding IBR registration and Standards improvements
4-5 PM ET, Tuesday, 7/13/2023	**Webinar 11 - Overview of IBR Risk Mitigations and Next Steps** High level recap of the webinar series key takeaways and presentation of the ERO Risk Mitigation activities moving forward

IBR Webinar Series

Date	Topic	Presenter	Organization
	Webinar 2 - NERC Disturbance Reports and Lessons Learned		
4 PM ET, Thursday, 6/8/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	NERC Event Analysis Process and Disturbance Reports	Rich Bauer	NERC
	What Goes Into Analyzing These Events	Patrick Gravois	ERCOT
	OEM Involvement to Mitigate IBR Risks (Blue Cut Fire)	Allan Alves Montanari	SMA
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 3 - IBR Performance Issues		
4 PM ET, Tuesday, 6/13/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	Experience with High Penetrations of IBRs	Dede Subakti	California ISO
	ERCOT Experience with IBR Performance Issues	Jeff Bilo	ERCOT
	IBR Performance Issues	Josh Shultz	Tenesee Valley Association
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 4 - Establishing and Enhancing Interconnection Requirements		
4 PM ET, Thursday, 6/15/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	ISO-NE Approach and Lessons Learned	Jim Helton	New England ISO
	Adopting and Implementing IEEE 2800	Julia Matevosyan	ESIG
	BPA Experience and Lessons Learned	Dmitry Kosterev	Bonneville Power Administration
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 5 - Modeling Part 1 - Modeling Requirements, Model Creation, Model Useability		
4 PM ET, Tuesday, 6/20/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	Using Modeling Requirements to Drive Model Improvements	Steve Giguere	Power Electronics
	Facility Model Creation and Useability Roadblocks	Billy Yancey	Electric Power Engineers
	MISO Experience with Establishing Modeling Requirements	Tom Dagenais	American Transmission Company
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 6 - Modeling Part 2 - Model Quality, Model Benchmarking		
4 PM ET, Thursday, 6/22/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	ERCOT Experience with Model Quality and Benchmarking	Jonathan Rose	ERCOT
	Model Benchmarking Process and Capabilities	Thomas Schmidt Grau	Vestas
	OEM Experience Around the World	Prashant Kansal	Tesla
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC

Date	Topic	Presenter	Organization
	Webinar 7 - Studies, EMT, Special Studies, Interconnection Studies		
4 PM ET, Tuesday, 6/27/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	Interconnection Studies, Best Practices for Ensuring Accurate Data	Andrew Isaacs	Electranix
	Typical Special Studies and Why They Are Needed	Andrew Arana	Florida Power & Light
	EMT Modeling and Studies (Guideline)	Aung Thant	NERC
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 8 - Interconnection Process		
4 PM ET, Thursday, 6/29/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	Current Interconnection Process Challenges	XXXXX	XXXX
	Roadblocks to Process Enforcement	Evan Wilcox	American Electric Power
	Challenges Managing the Queue	Jay Teixeira	ERCOT
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 9 - Commissioning		
4 PM ET, Tuesday, 7/11/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	Commissioning Testing Process	Jim Helton	New England ISO
	Traversing the Comissioning Process	Katie Iversen	AES
	OEM Perspectives	Chris Chuah	GE
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 10 - IBR Registration and Reliability Standards Enhancements		
4 PM ET, Wednesday 7/12/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	NERC Team	NERC
	NERC IBR Registration Activities	Pete Heidrich	SERC
	NERC IBR-Related Standards Projects Underway	Alex Shattuck	NERC
	Panel Q/A	All Presenters	-
	Recap of Key Takeaways and Closing Remarks	NERC Team	NERC
	Webinar 11 - Overview of IBR Risk Mitigations and Next Steps		
4 PM ET, Tuesday, 7/13/2023	**Topic**	**Presenter**	**Organization**
	Welcome and Introduction	Ryan Quint	NERC
	Recap of Key Takeaways from All Webinars Thus Far	Alex Shattuck	NERC
	ERO Risk Mitigation Activities Moving Forward	Aung Thant	NERC
	Webinar Series Close-Out	Ryan Quint	NERC

Questions and Answers

Feel free to reach out to us if interested in participating in the NERC IRPS or EMTTF!