GE Energy Consulting

NYISO IBR Roadmap Project

Presentation to New York State Reliability Council

30 November 2022
GEEnergyConsulting.com

Block Island, Rhode Island USA

NYISO's inverter-based resource (IBR) roadmap addresses transmission security needs for 2040

1 Technical

What risks should NYISO assess & mitigate in anticipation of 2040 IBRs?

GAP?

2 Regulatory

Emerging regulatory requirements addressing IBR risks

Please note that a review of NYISO's current planning practices was not part of the scope of this IBR Roadmap.
As a result, GE recommendations may overlap with existing NYISO processes and do not imply a gap in NYISO evaluations or criteria.

Anticipated 2040 reliability risks form core of NYISO IBR roadmap

Emerging regulations likely to overlap recommendations

1. WEAK GRID RISKS

- Synchronous machines (SMs) *form* today's voltage reference
- Today's IBRs *follow* the voltage reference ("grid following")
- As IBRs displace SMs, weakens voltage -> reliability risks:
  Steady state and dynamic voltage stability, controls stability, angular stability risks

2. SMALL SIGNAL STABILITY RISKS

- Unwanted non-fundamental resonances due to interactions between electrical elements
- E.g. Series compensation, IBR controls, high speed exciters

3. FREQUENCY STABILITY RISKS

New risks as IBRs displace SMs:

- Frequency response obligation can't be met w/o IBRs providing response
- IBR frequency response behavior/coordination may result in unreliable outcomes

NYISO IBR ROADMAP

Top recommendations

1. Adopt new screening methods

1. Use production cost modeling to screen for new IBR risk conditions
2. Weak grid screening using SCR analysis
3. Small signal screening using frequency scan analysis

2. Develop EMT modeling capabilities

to utilize after screening methods suggest high IBR risks

3. Develop interregional evaluation approaches given high IBR levels

1. EI-wide frequency stability evaluation
2. Regional weak grid and small signal risks

Prominent IBR-related disruptions were not due to technical risks

NYISO roadmap assumes post-event NERC guidelines are followed

WHEN	WHERE	% INVERTER	DISTURBANCE	LOST GENERATION	AFFECTED TECHNOLOGIES
March 2022	**Texas**	60%	Severe weather	**1000MW**	Wind
August 2021	**California**	40%	Wildfires	**800MW**	PV, Gas, DER
July 2021	**California**	50%	Wildfires	**800MW**	PV, Gas, DER
July 2021	**California**	35%	Fault	**550MW**	PV, DER
June 2021	**California**	45%	Fault	**1000MW**	PV, DER
June 2021	**Texas**	30%	Failed power line	**700MW**	PV
May 2021	**Texas**	45%	Failed electrical equipment	**1300MW**	Gas, PV
July 2020	**California**	50%	Failed power line	**1200MW**	PV
May 2019	**California**		Birds nest on power line	**1000MW**	PV, DER
April 2018	**California**	30%	Failed power line	**1200MW**	PV, Gas, DER
Oct 2017	**California**		Wildfires	**1600MW**	PV
Sept 2016	**S. Australia**	50%	Lightning	**State-blackout**	Wind, Coal, Gas

Events could have been avoided if pre-existing NERC guidelines were followed

- **IBRs w/ outdated unreliable performance attributes**
  NERC 2019 reliability guideline outlines required performance attributes (e.g. momentary cessation, phase jump immunity) that weren't followed
- **Poor IBR modeling practices**
  NERC 2019 reliability guideline outlines modeling improvements such as use of EMT models & validation that weren't followed

https://www.nerc.com/pa/rrm/ea/Pages/Major-Event-Reports.aspx
https://www.nerc.com/pa/Documents/IBR_Quick%20Reference%20Guide.pdf
https://www.aer.gov.au/wholesale-markets/compliance-reporting/investigation-report-into-south-australias-2016-state-wide-blackout
https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf

Weak grid risks

The displacement of grid-forming synchronous machines with grid-following IBRs weakens grid reference

Weakening voltage reference increases four related risks

1

Steady state voltage stability

Voltage can collapse in weak grids w/ higher power injection + high IBRs

2

Dynamic voltage stability

Voltage can collapse in weak grids after a disturbance

3

Controls stability

IBRs have multiple control layers/modes … weak grid -> control confusion

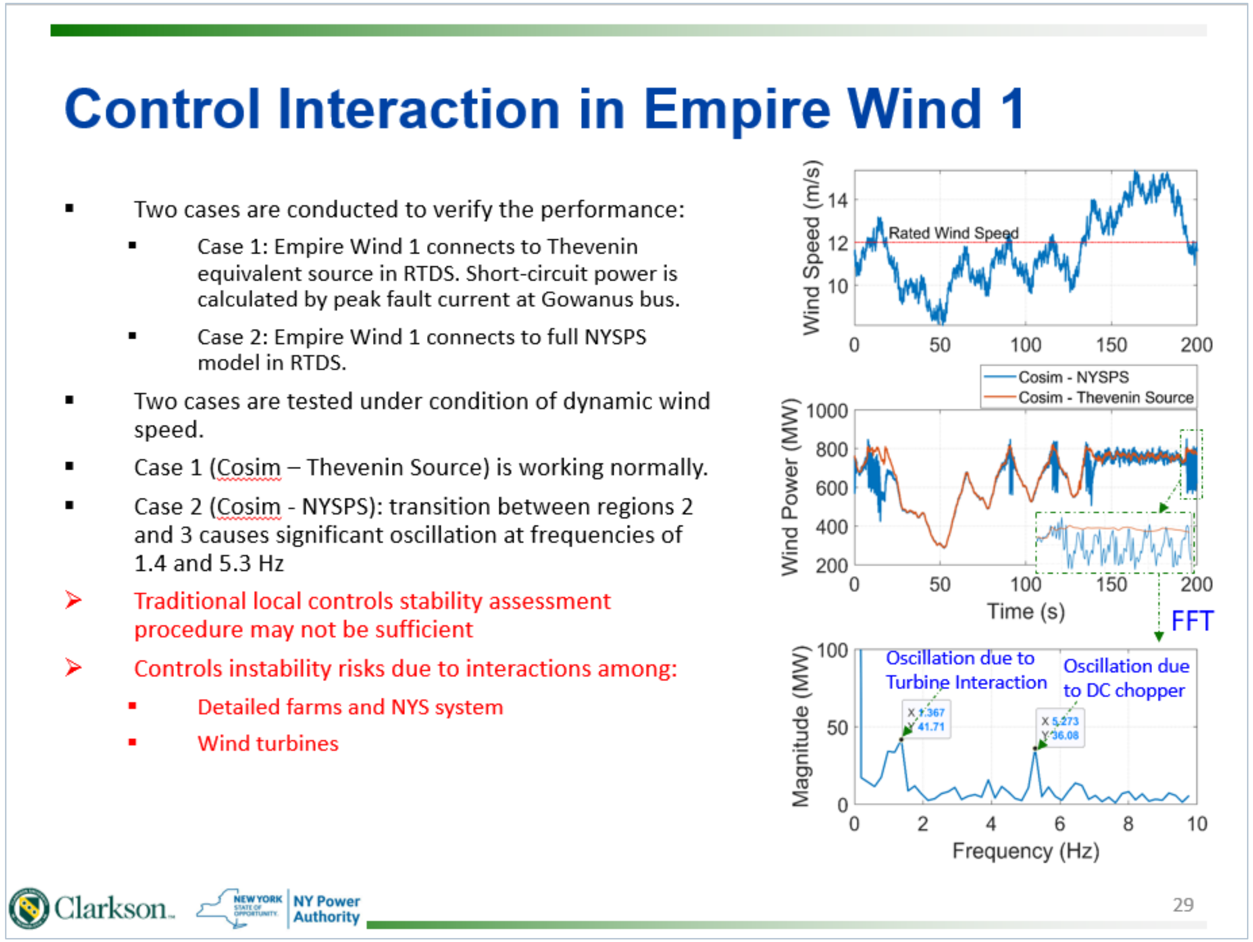
4

Angular stability

Weak grids increase risk of SMs losing synchronism after faults

Clarkson and NYPA observing controls stability risks w/NY offshore

Turbine-to-turbine interactions



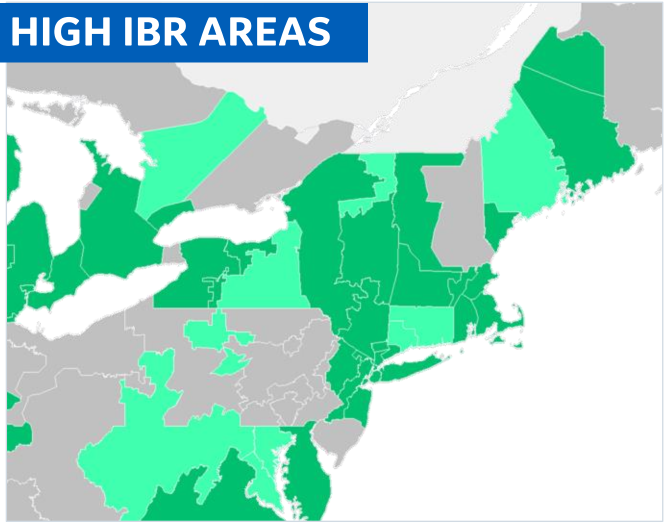
CLARKSON + NYPA AGILE LAB CONTROLS STABILITY MODEL

- 9GW offshore wind via Opal-RT simulator
- Onshore NY system via RTDS based on NYISO 2018 PSSE & Aspen models

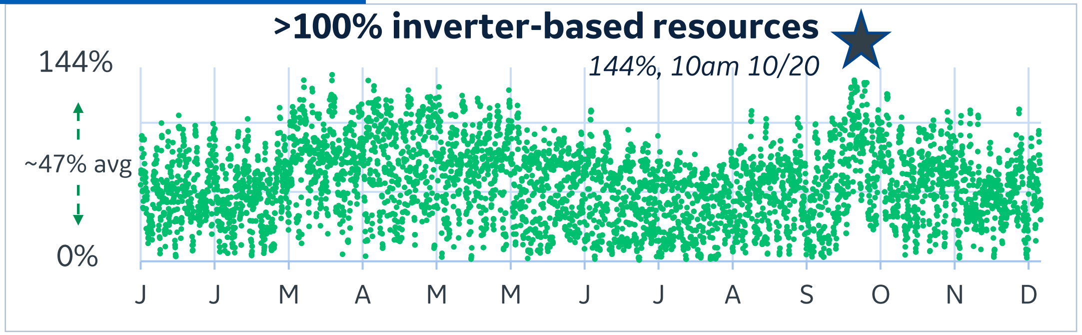
Possible **weak grid** risk conditions in 2040 New York?

High risk scenarios conditions to study

HIGH IBR AREAS



HIGH IBR HOURS



* % IBR = Nameplate IBR / (IBR + Hydro + Nuc + Gas & Coal) … >20MW units, SMs>75% online

Ref: GE Energy Consulting's non-proprietary forecast, ABB Hitachi

1 - https://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf

High risk geographic/operating conditions

1. **High IBR penetration**/low synchronous commitment … likely *regionally* weak grid condition
2. **High IBRs/multiple IBRs on same AC bus:** Likely a *locally* weak grid
3. **HVDC connections** (e.g. offshore wind)
4. **Neighboring jurisdictions w/high IBRs**

Regulatory note:

Generally silent on geographic guidance:

1. **NERC** guidance is generally silent on how to define the geographic coverage for weak grid screening & assessment.
2. **FERC's** upcoming interregional NOPR recognizes need for coordinated interregional planning but has yet to provide guidance regarding the need for coordinated weak grid screening. NOPR comments are highlighting the need for more.

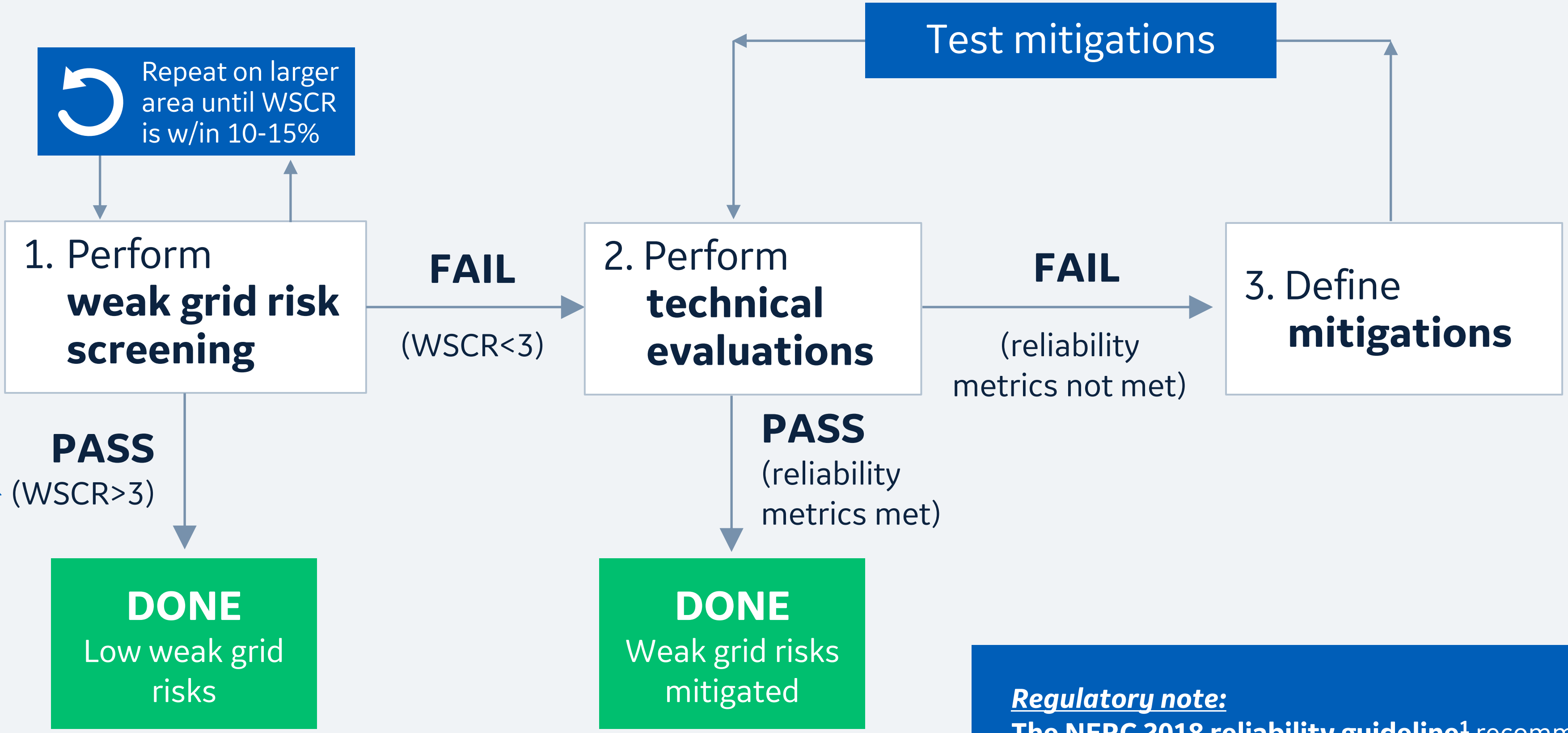
Operating conditions:

1. **NERC:** *NERC TPL-001[1] specifies peak load, off-peak but not other conditions. SAR has been opened & industry experts may weigh in.*
2. **FERC:** *Standards not covering system conditions … yet. Comments to the FERC Interconnection NOPR are highlighting need tor more guidance here.*

Recommended weak grid planning approach

WSCR used as a screening metric for further EMT evaluations

SCR is not a reliability metric
…it's a screening metric to know when positive sequence fundamental frequency models will not predict certain instabilities. Further evaluations (e.g. EMT studies) must be used to properly assess risks.



Regulatory note:
The NERC 2018 reliability guideline[1] recommends SCR as a good screening metric to use. For an SCR<3, more advanced modeling is required to assess and mitigate risks.

1 - https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Inverter-Based_Resource_Performance_Guideline.pdf

Weak grid risks technical evaluation approach

RISKS	STUDIES					METRICS		MITIGATION
	CONDITIONS	SCREEN	LF	DYN	EMT	COMPLIANCE METRICS	GE RECOMMENDED METRICS	
WEAK GRID RISK		WSCR					WSCR >3	Additional studies below
Steady state voltage stability	• High IBRs same AC line • Multiple IBRs same AC line • HVDC connection • High IBR neighbors • N-X w/ high IBR • Faults, trips		✓			Normal: $-5\%<V_{rating}<+5\%$	$\Delta V/\Delta P$ > 0.95 p.u.	• IBR tuning • Synchronous condensers • Interregional transmission • *Future:* Grid forming IBRs
Dynamic voltage stability				✓	✓	1. Normal: $-5\%<V_{rating}<+5\%$ 2. Fault ride through: No trip within voltage envelope	No voltage collapse post-fault/trip	
Controls stability				✓	✓	Avoid unwanted interactions	**Enter/exit control modes “cleanly”** • No observed hysteresis on limits • During/post VRT behavior well mannered	
Transient stability				✓	✓	**PRC 024:** Exemption you must not trip unless you are going to damage unit	1. Angle: 1st swing system angle “clean” recovery 2. Trips: Ok if limited system impact 3. Voltage swing: post-clearing voltage dips moderate	

Regulatory note:
NERC SARs will likely require EMT studies[1]
1. **TPL-001:** EMT studies must be performed for planning
2. **FAC-002:** EMT studies must be performed for interconnection

1 - https://www.nerc.com/pa/Stand/Pages/Project2022-04EMTModeling.aspx

Weak grid risk technical evaluation **model recommendations**

LOAD FLOW MODELS:

1. **Plant-level IBR voltage control models** including real and reactive power flow models. Inverter-level behavior will be captured in EMT models.
2. **Aggregated representation of each IBR plant** using one equivalent machine model is sufficient

DYNAMICS MODELS (*i.e.* positive sequence):

1. **Aggregated IBR plant models sufficient** for planning and interconnection studies
2. **Protection dynamics models** to be included
3. **Model acceptance criteria to allow user-written models** with sufficient detail
   - Functional-level representation of all control loops at inverter & plant. Generic models typically do not allow full representation.
   - Acceptable model validation criteria for model to match field equipment performance.
   - Generator & plant protection … and limiters need to be included.
   - New technologies (e.g. grid forming) should be represented. Such technologies rarely represented sufficiently in generic models.

EMT/TRANSIENTS MODELS

1. **Similar recommendations as dynamics**
2. **Developer EMT models** should be required
3. **Benchmarking between EMT & dynamics** models

Regulatory note:

1) Use of transients/EMT models will likely be required:

- **IEEE 2800 & 2800.2[1]**: Recommends EMT models used to assess IBR risks. Protection models should be included.
- **NERC MOD-032 (SAR)[2]:** EMT models must be used in planning

2) Acceptance criteria for user-written models: NERC MOD 26[3] update to require planners to develop model acceptance criteria for dynamics and EMT user-written models.

3) Benchmarking: MOD 26 (SAR) calls out need for benchmarking between dynamics and EMT models

1- https://standards.ieee.org/ieee/2800/10453/
2 - https://www.nerc.com/pa/Stand/Pages/Project2022-04EMTModeling.aspx
3 - https://www.nerc.com/pa/Stand/Pages/Project-2020_06-Verifications-of-Models-and-Data-for-Generators.aspx

Weak grid **risk mitigation recommendations**

BASELINE REQUIREMENTS

1. **Adopt IEEE 2800 requirements** to establish minimum capability to support grid stability.
2. **Require/incentivize IBR voltage regulation even with no wind or sun** … especially important during light load
3. **Follow NERC IBR event report recommendations[1]** … A prerequisite to this roadmap.

SYNCHRONOUS CONDENSERS:

1. **Retrofitting existing gas or oil generation**
2. **Building new condensers** (e.g. LIPA recommended $200M of new condensers to interconnect 3GW offshore[2])

IBR SOLUTIONS:

1. **Control tuning:** A number of pre-configured settings available suit varying grid conditions including weak grid (e.g. voltage regulator gains, current limits, ride through settings, etc.)
2. (*Future*) **Grid-forming controls:** Not commercial today on all IBR technologies but a piloting opportunity. Lower space requirement, cost and offshore deployment vs condensers.

INTERREGIONAL REINFORCEMENT

- **Connecting to stronger grids** can improve xSCR
- **DC connections** should be considered if connecting to weaker grids (e.g. offshore network).

Ref:
1 - https://www.nerc.com/pa/Documents/IBR_Quick%20Reference%20Guide.pdf
2 - https://www.lipower.org/wp-content/uploads/2021/02/13.-Briefing-on-Grid-Planning-Climate-Ladership-Community-Protection-Act.pdf

Small signal stability risks

High risk **small signal stability** conditions in 2040 New York?

High risk scenarios conditions to study

E.g. Proposed T019 345kV path includes 50% series compensation

Town	Proposed Work	Miles	Change in No. of Structures
Schodack	New Knickerbocker 345kV Switching Station on utility-owned land	-	-
Schodack	Holds a new 345kV line and one existing 115kV line	2.6	+4
Stuyvesant		8.0	-4
Stockport		4.5	+3
Ghent		0.8	No Change
Claverack		6.3	+12
Claverack	Rebuild the existing Churchtown 115kV Switching Station on existing utility-owned land	-	-
Livingston		2.2	No Change
Claverack	Holds a new 345kV line and one existing 115kV line	1.0	-7
Livingston		8.3	-60
Gallatin		1.2	-9
Clermont		0.7	-4
Milan		8.0	-76
Clinton		8.0	-59
Pleasant Valley		5.1	-38
Pleasant Valley	New Van Wagner Capacitor Bank Station and upgrades to Pleasant Valley Substation	0.8	+5

*All mileage and structure change information is approximate

Commitment/dispatch/locational conditions

1. **IBRs near series compensation:** Can result in subsynchronous resonance (SSR) which can trigger subsynchronous controls interaction (SSCI) or subsynchronous torsional interaction (SSTI)
2. **IBRs w/high AC cable charging** (e.g. large Offshore plants w/AC cabling)
3. **Weak grid conditions:** Represents a low damping condition which can result in sustained oscillations
4. **SMs w/ high speed exciters:** Not specifically related to IBRs … NYISO may have processes in place if they have such SMs
5. **Torsional interaction conditions**: If there are series capacitors in NYISO & the power flows only through that path from IBR pockets or a single SM, then there is likely to be SSR or SSCI & a more comprehensive analysis needs to be commissioned by experts in torsional interaction.
6. **N-X grid conditions:** While the N-0 grid may be strong enough to damp out oscillations, the N-X grid may not be strong enough

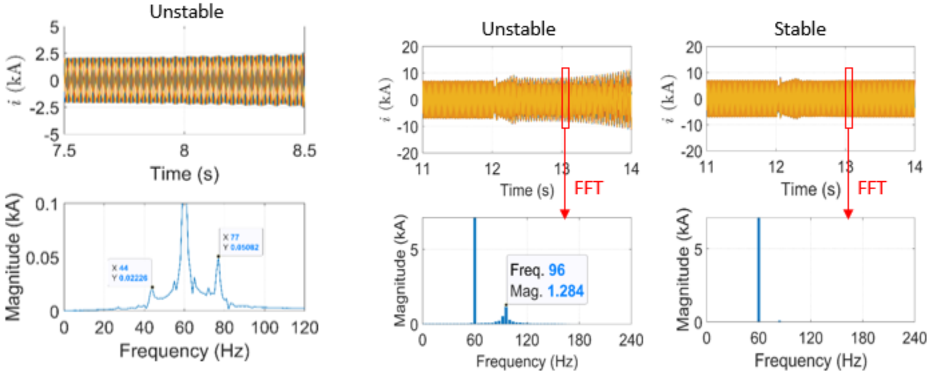
Clarkson & NYPA observing small signal stability risks w/NY offshore

EMT modeling enables risk assessment & mitigation of non-fundamental frequency oscillations

SUSTAINED PLANT-TO-PLANT OSCILLATIONS ACROSS EMPIRE 1 AND EMPIRE 2

FRT Performance of Empire Wind 2 – 1260 MW behind Equivalent source (Local)

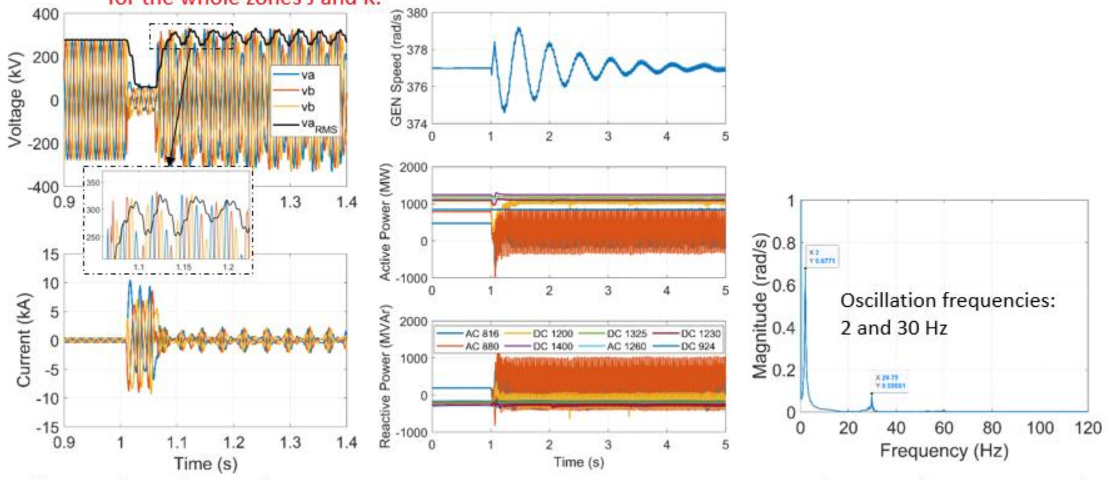
- Wind farm operates at the rated power.
- High impedance fault at offshore collector bus is applied at 12s and it is clear after 8 cycles.
- Voltage and current are measured at POI
- FFT analysis of POI current shows the resonance frequency of 44, 77, and 96 Hz in the unstable cases
- Harmonic and subsynchronous instabilities
- Optimal tuning the controller gains mitigates the resonance.



Clarkson. NEW YORK STATE OF OPPORTUNITY. NY Power Authority

SUSTAINED OSCILLATIONS ACROSS 9GW OFFSHORE FLEET

- Three-phase-to-ground fault at GOETHLS bus; fault impedance is 0.1Ω and fault duration is 3 cycles.
- Significant oscillation in three farms: AC816, AC880, and DC1200.
- Sustained voltage oscillation at 30Hz at Gowanus
- Sustained frequency oscillation at 2Hz and 30Hz
- The grid is weaker due to 9GW pumped to Zones J and K. The Short Circuit Power is being evaluated for the whole zones J and K.



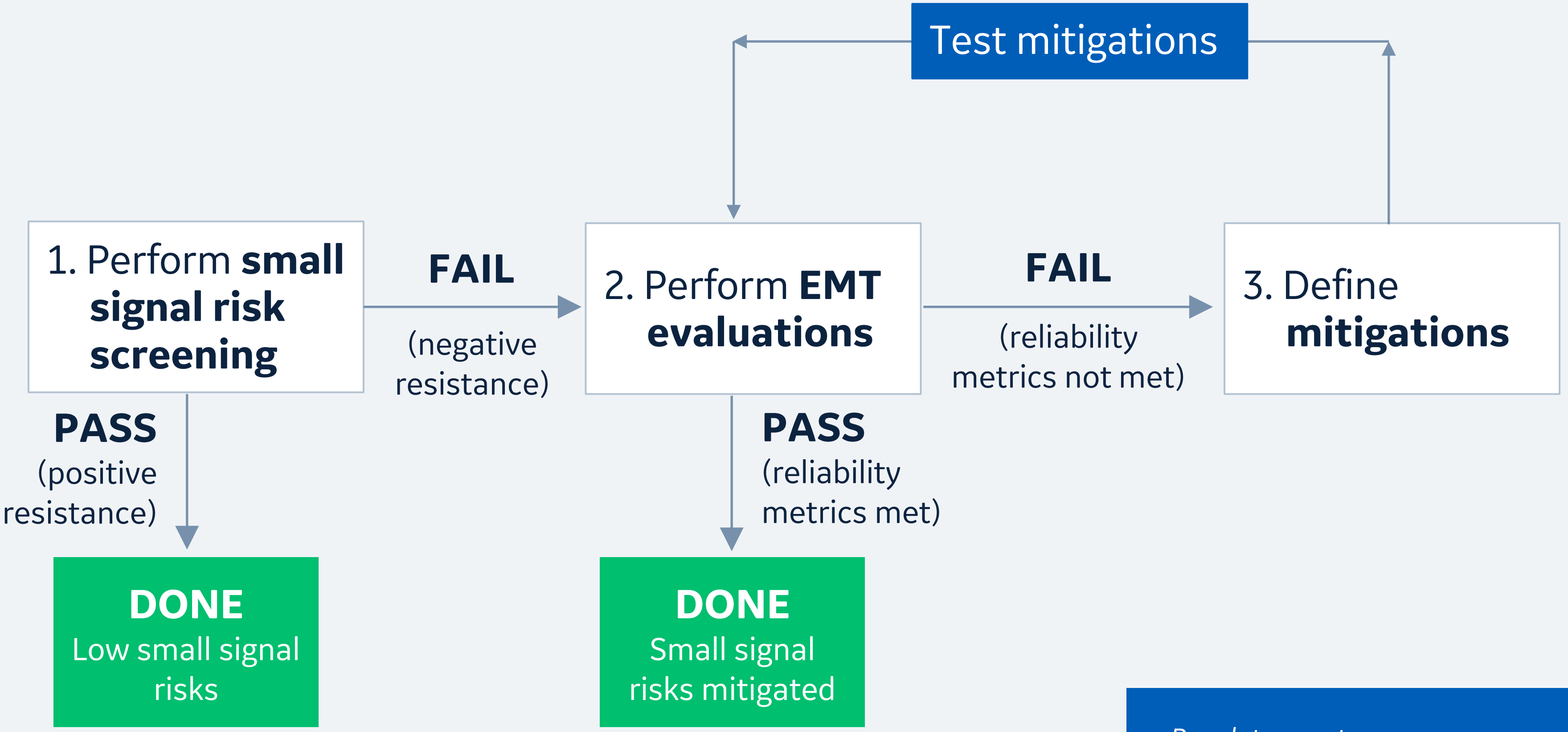
Gowanus bus voltage and current from GEOTHLS to GOWANUS

Output power of 8 farms

Spectrum of generator speed

Clarkson. NEW YORK STATE OF OPPORTUNITY. NY Power Authority

Recommended small signal stability planning approach



Regulatory note:
Small signal stability is currently not addressed by industry standards or regulations.

Small signal stability risks technical evaluation approach

RISKS	STUDIES					METRICS		MITIGATION
	CONDITIONS	SCREEN	LF	DYN	EMT	COMPLIANCE METRICS	GE RECOMMENDED METRICS	
SMALL SIGNAL STABILITY	• High IBRs same AC line • Multiple IBRs same AC line • HVDC connection • High IBR neighbors • N-X w/high IBR • Torsional condition • Faults, trips	Freq scan					Negative resistance	Additional studies below
SSR					✓		Damping factor (ζ) >>0.1 (Critically damped) Phase angle (δ) <90 °	SMs: torsional stress relays (TSRs) IBRs: IBR settings tuning, grid strengthening
Power swings				✓	✓			SMs: Power system stabilizers (PSS)
Super-synchronous oscillations					✓			• Tuning IBR gains • Passive filters

Model recommendations:

1. **IBR models**: specific EMT models that capture SSCI risk (e.g. low frequency behavior captured)
2. **Protection models** as it relates to SSCI risk (e.g. low frequency behavior)
3. **Interregional** given potential interregional interactions (e.g. if series comp in PJM on AC line to NY)

Small signal stability **risk mitigation recommendations**

Mitigations depend on the type of resonance

SSR MITIGATIONS

1. **Low Level of Series Compensation** to avoid SSR
2. **Topology/Power-Based Switching Schemes**
3. **Tuned IBR controls** to add damping and mitigate SSCI.
4. **Supplementary Excitation Damping Control** (SEDC)
5. Properly tuned **thyristor-controlled series capacitors**
6. **SVC-type SSR Damper**
7. **Passive SSR Bypass Filter** on series capacitor bank
8. **SSR Blocking Filters**

LOCAL AND INTER-AREA OSCILLATIONS

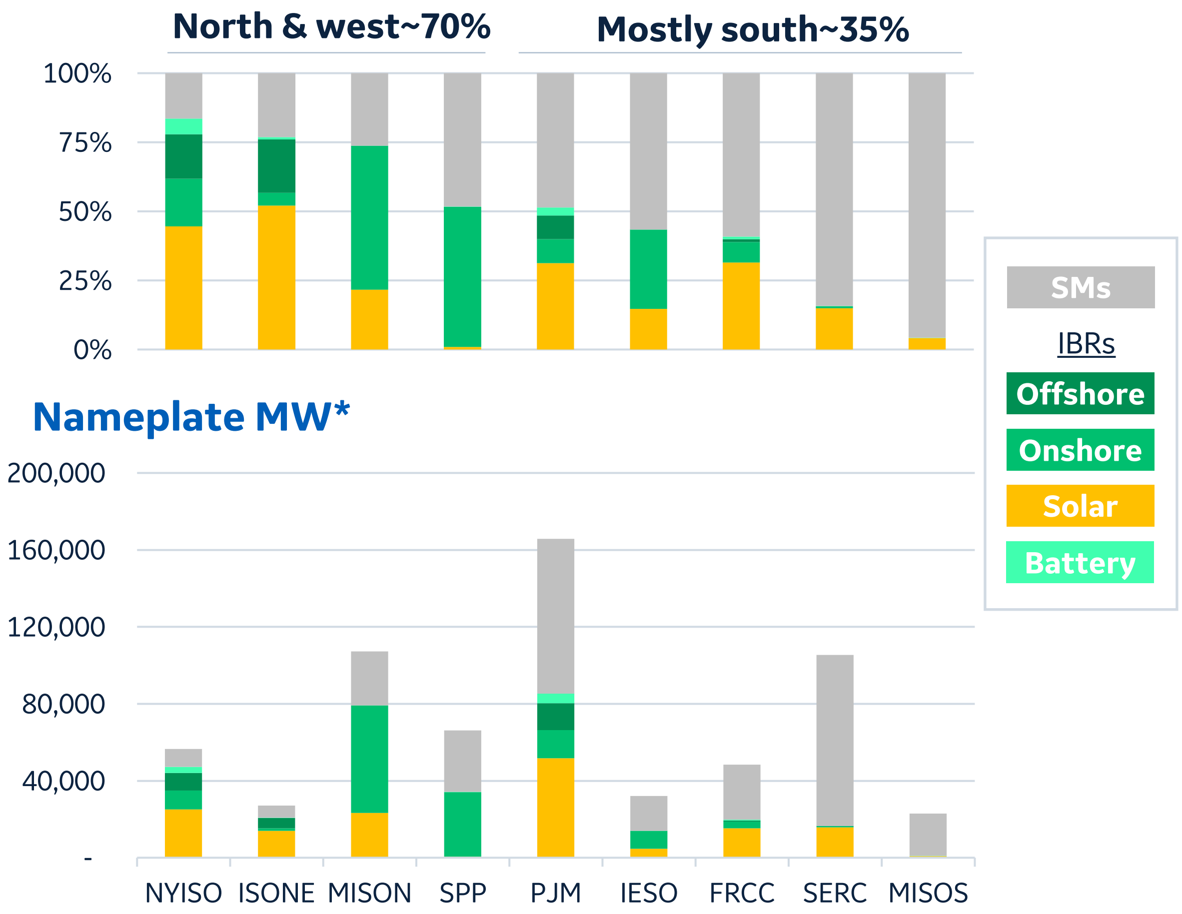
1. **Power system stabilizers (PSS):** Generally, an active filter on an SM … similar capability can be deployed with an SEDC
2. **Generation curtailment:** Avoid oscillations through reduced power flow

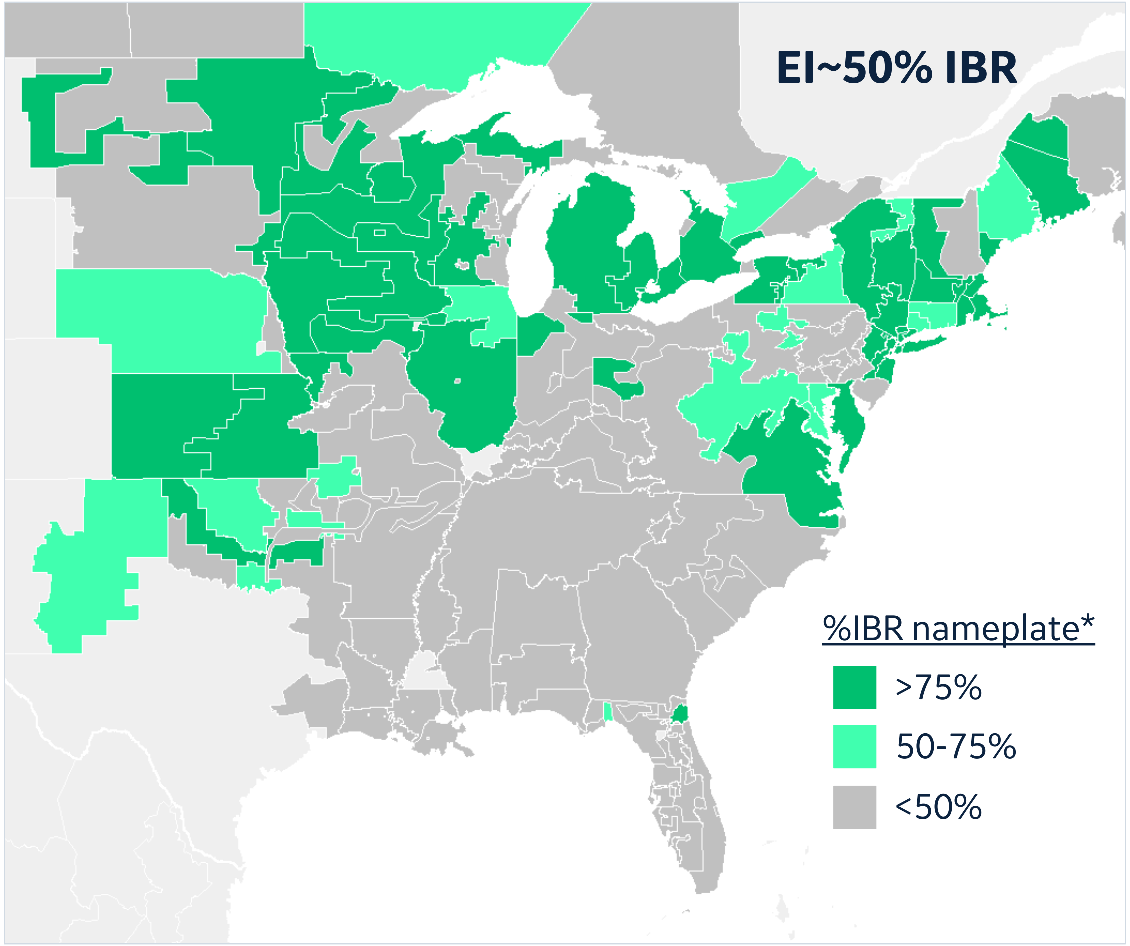
SUPER-SYNCHRONOUS OSCILLATIONS:

1. **Control tuning:** to increase damping
2. **Passive filters:** more expensive vs IBR tuning

Frequency stability risks

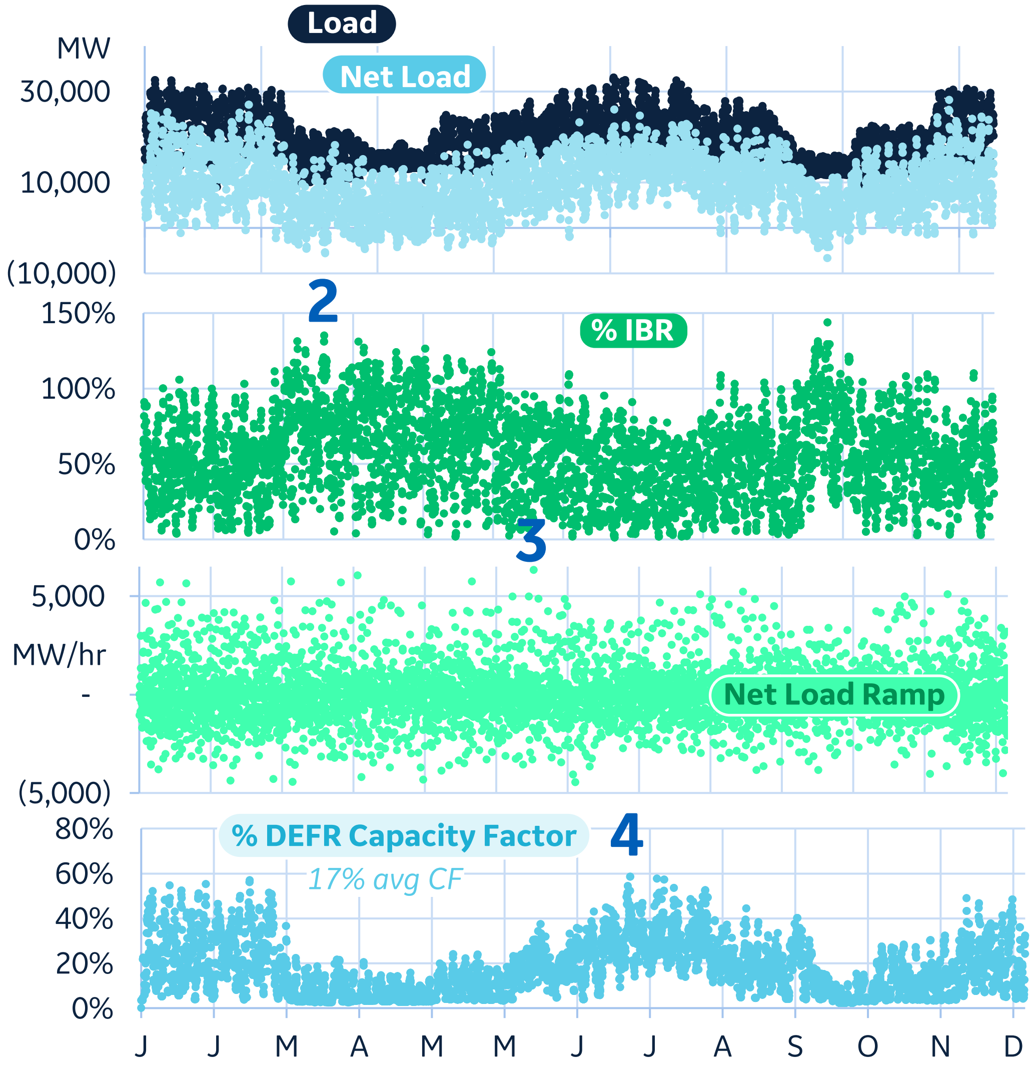
By 2040, the Northeast & Western parts of the Eastern Interconnect will depend on IBRs ... is frequency stability at risk?





* % IBR = Nameplate IBR / (IBR + Hydro + Nuc + Gas + Coal) ... units >20MW & SMs >75% online

High risk **frequency stability** conditions in 2040 New York?



Ref: GE Energy Consulting, non-proprietary database

1 - https://www.nerc.com/pa/Stand/Pages/Project201701ModificationstoBAL00311.aspx

2 - https://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf

Commitment/dispatch conditions

1. **Coordination across EI:** How to *reliably* meet NY's (likely higher) FRO w/IBRs?
2. **Low inertia:** High IBR/low synchronous commitment
3. **High ramping:** Can the remaining units ramp quickly enough? Is there enough headroom left in system?
4. **Low synchronous headroom:** Not enough ability to support underfrequency
5. **N-X conditions:** That may result in high IBR/low inertia

Regulatory note:

Interregional coordination:

1. **NERC** BAL-003-1.1 (SAR)[1] how to update IFRO but open question about IBR performance requirements
2. **FERC's** upcoming Interregional NOPR recognizes need for coordinated interregional planning but hasn't addressed frequency stability

Operating conditions:

1. **NERC:** NERC TPL-001[2] specifies peak load, off-peak but not other conditions. SAR has been opened & industry experts may weigh in.
2. **FERC:** Standards not covering system conditions … yet. Comments to the FERC Interconnection NOPR are highlighting need for more guidance here.

Frequency stability risk technical evaluation approach

RISKS	STUDIES					METRICS		MITIGATION
	CONDITIONS	SCREEN	LF	DYN	EMT	COMPLIANCE METRICS	GE RECOMMENDED METRICS	
FREQUENCY STABILITY	• 2040 EI-wide • Low inertia • High net load ramping • Low SM headroom • N-X resulting in low inertia		✓	✓		1. FR > NY FRO in 2040 2. MDF < 420 mHz 3. Nadir > 59.5Hz	1. Recovery well mannered>critical damped 2. Settling time<15sec	• New IBRs provide: FFR, PFR, FRT, Reg • Tune IBR response • Tune SM performance • New operating/ resource limits • Network reinforcements

Model recommendations:

1. **EI-wide models** to assess reliable IBR FR participation.
2. **IBR frequency response control models** for dynamics simulations
   a) **Fast frequency response (FFR)** control models. User-written or updated 3rd generation generic models should be used to evaluate FFR.
   b) **Primary frequency response (PFR)** control models
3. **Non-IBR protection models** to assess unwanted tripping during grid frequency events

Frequency stability **risk mitigation recommendations**

IBR CONTROLS

1. Require new IBRs to provide:
   a) **Fast frequency response** (FFR)
   b) **Primary frequency response** (PFR)
   c) **Fault ride-through** capability
2. **Tune frequency response** settings

OPERATING/RESOURCE LIMITS

1. Real time **inertia monitoring** + operating protocols to remain above floor
2. **Geographic limits** for FR participation (e.g. by zone)
3. **Technology limits** for FR participation (e.g. SMs vs IBRs)

NETWORK UPGRADES

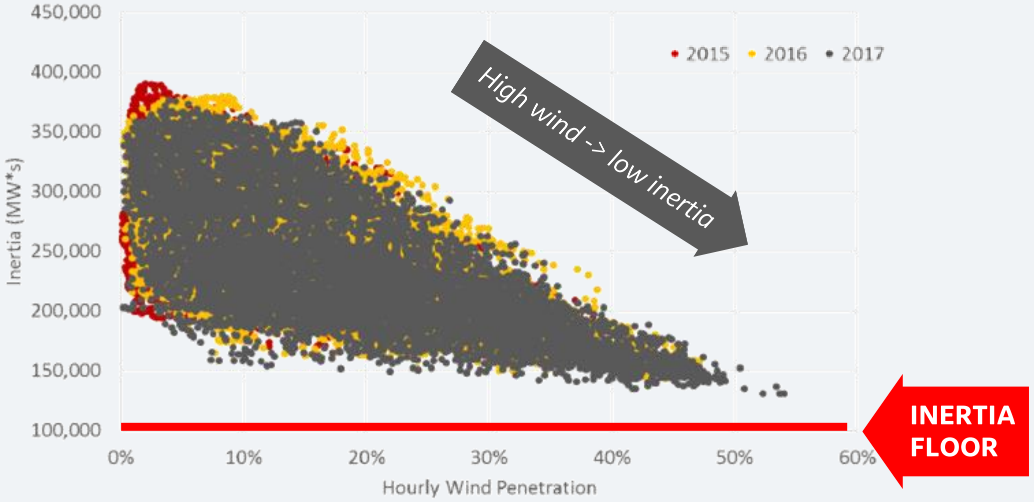
Flywheel addition to synchronous condensers

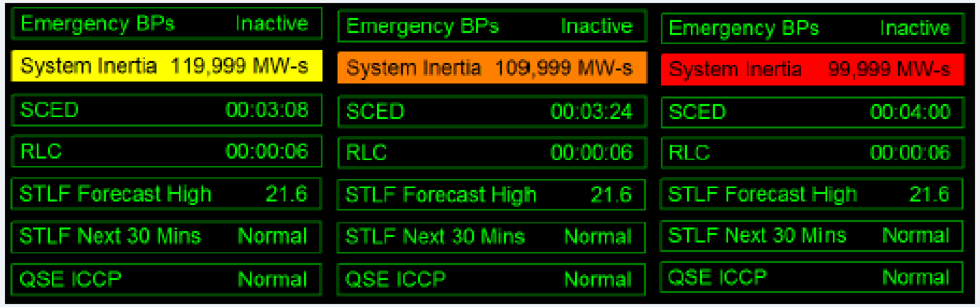
Regulatory note:

- *IEEE 2800[1]:* Minimum PFR & FFR performance standards
- *NERC & FERC, most Balancing Authorities:* yet to adopt minimum performance standards for IBR frequency response. Texas, New England & MISO assessing piecemeal adoption of 2800.
- *FERC 842[2]:* Requires IBR capability to provide FR, but does not define how to implement in practice to meet FRO and reliability needs.

EXAMPLE: ERCOT TRACKS REAL TIME INERTIA

Synchronous inertia vs. hourly wind penetration





OPERATOR DISPLAY: REAL TIME INERTIA

Source: Inertia: Basic concepts & impact on the ERCOT Grid, courtesy Julia Matevosyan, 2018

1- https://standards.ieee.org/ieee/2800/10453/
2- https://www.ferc.gov/sites/default/files/2020-06/Order-842.pdf

NYISO IBR roadmap: anticipated 2040 reliability risks inform next steps

1. WEAK GRID RISKS

As IBRs displace SMs, weakens voltage -> new reliability risks:
Steady state and dynamic voltage stability, controls stability, angular stability risks

2. SMALL SIGNAL STABILITY RISKS

Unwanted non-fundamental resonances due to interactions between electrical elements
E.g. Series compensation, IBR controls, high speed exciters

3. FREQUENCY STABILITY RISKS

New risks as IBRs displace SMs:

- Frequency response obligation can't be met w/o IBRs providing response
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NYISO IBR ROADMAP

Top recommendations

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2. Weak grid screening using SCR analysis
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2. Develop EMT modeling capabilities

to utilize after screening methods suggest high IBR risks

3. Develop interregional evaluation approaches given high IBR levels

1. EI-wide frequency stability evaluation
2. Regional weak grid & small signal risks

ERCOT

Generator Interconnection Study Queue (OCT'22)

Fuel type	IA signed & FIS done or underway	Total in Queue (SS complete)
CCCT + CT Gas	6,269 MW	9,606 MW
Wind	16,726 MW	**23,025 MW**
Solar	98,898 MW	**122,585 MW**
Battery	59,357 MW	**75,630 MW**

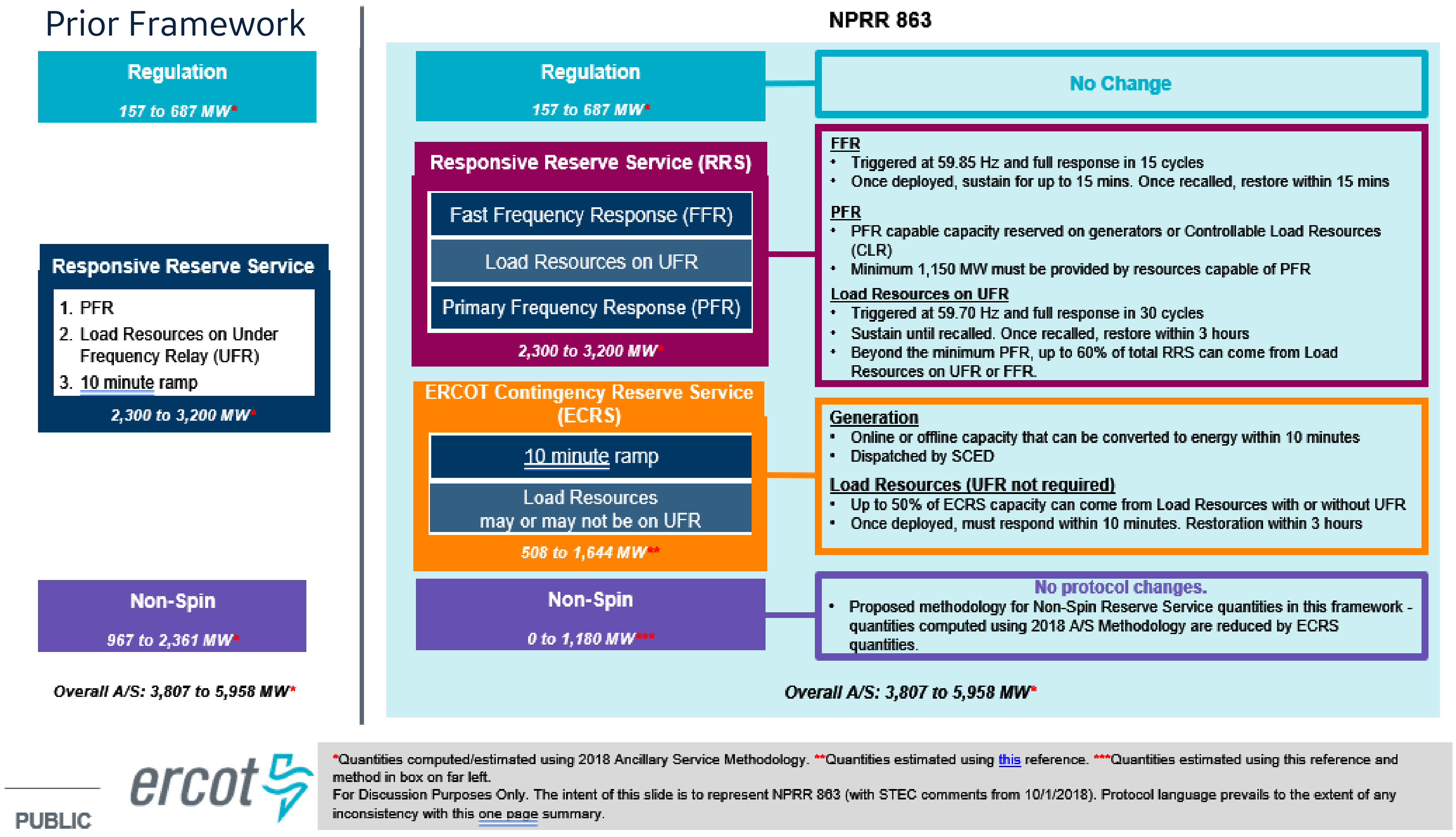
http://www.ercot.com/gridinfo/resource

- New RRS A/S co-optimized with Energy
- Must meet min. performance specified in NP
- Procure min amount to sustain nadir > UFLS

New Ancillary Service Products - NPRR 863:

New Responsive Reserve included as of March 2020

RRS is a market-based approach for procuring frequency services.



New York is aiming for +40GW IBRs by 2040

Significantly higher in-state generation may increase frequency response obligation

Requirements

- 70% RE x 30
- 6GW PV x 25
- 3GW storage x 30
- 9GW offshore x 35

Assumptions

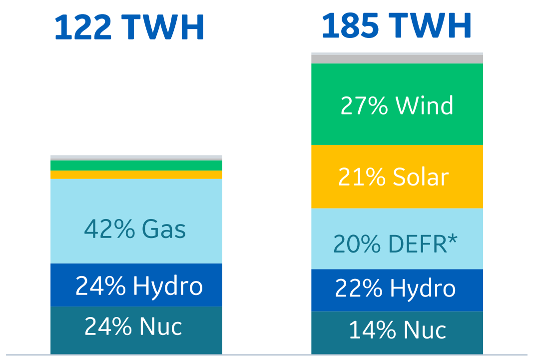
- Load: NYISO baseline view
- Gas: Converts to "Dispatchable Emission-Free Resource" (DEFR) by '40
- Imports/Exports: flexible
- REN: NYISO 70x30 scenario
- Electrification: NYISO … picks up post '40

Nameplate (GW)

Type	'21 (GW)	'40 (GW)	Δ
Gas	23	23	-
Hydro	5	5	-
Nuclear	4	3	-1
Solar	5	26	+21
Onshore	3	10	+7
Offshore	0	9	+9
Storage	2	5	+3
Other (Oil)	4	4	-
Total	**47**	**84**	**+37**

+40GW IBR

In-state generation (TWH)

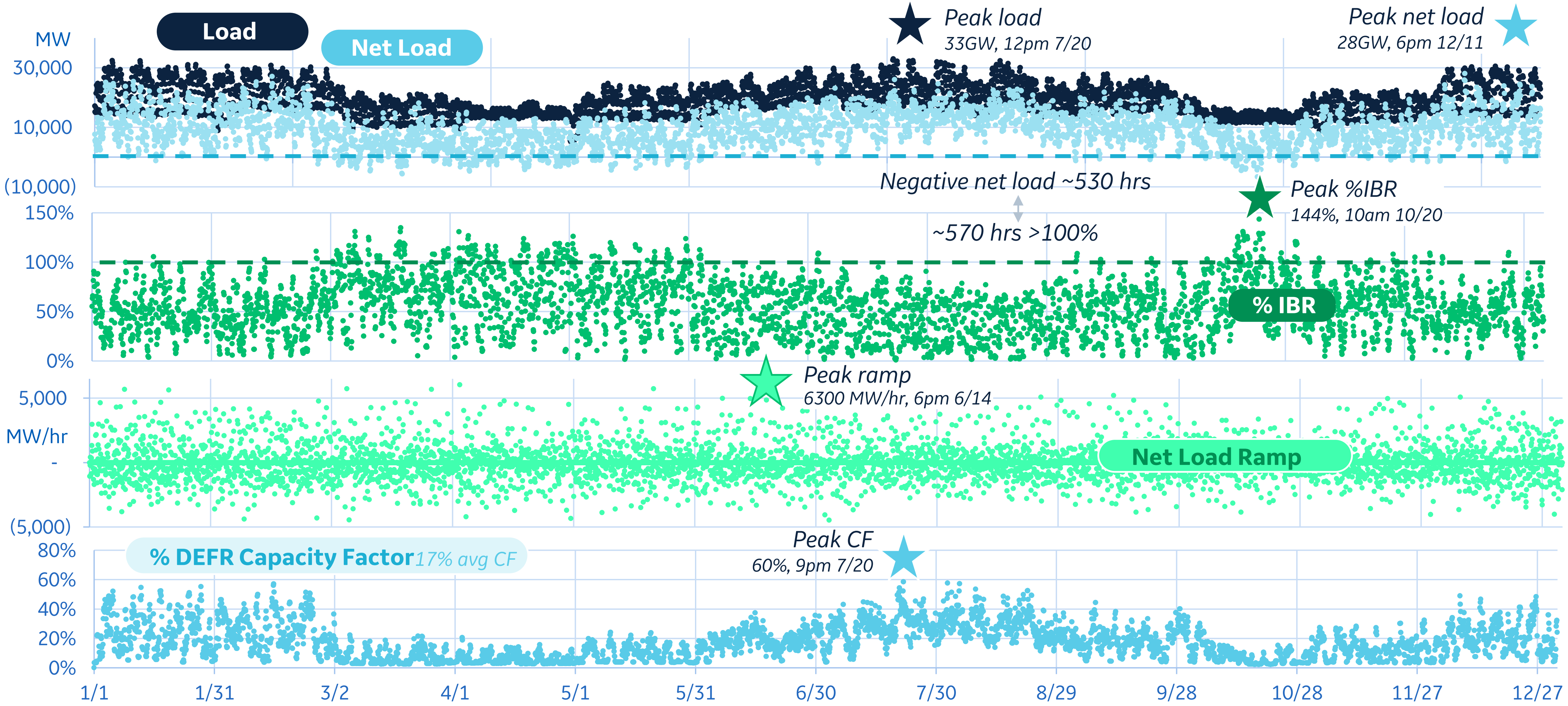


	2021	2040
Load (TWH)	151	184
CO_2-free	56%	100%
% IBR	9%	47%

*DEFR = Dispatchable Emission-Free Resource

New York 2040: New off-peak conditions to plan around

NYISO production cost modeling can help identify new hours of IBR risk

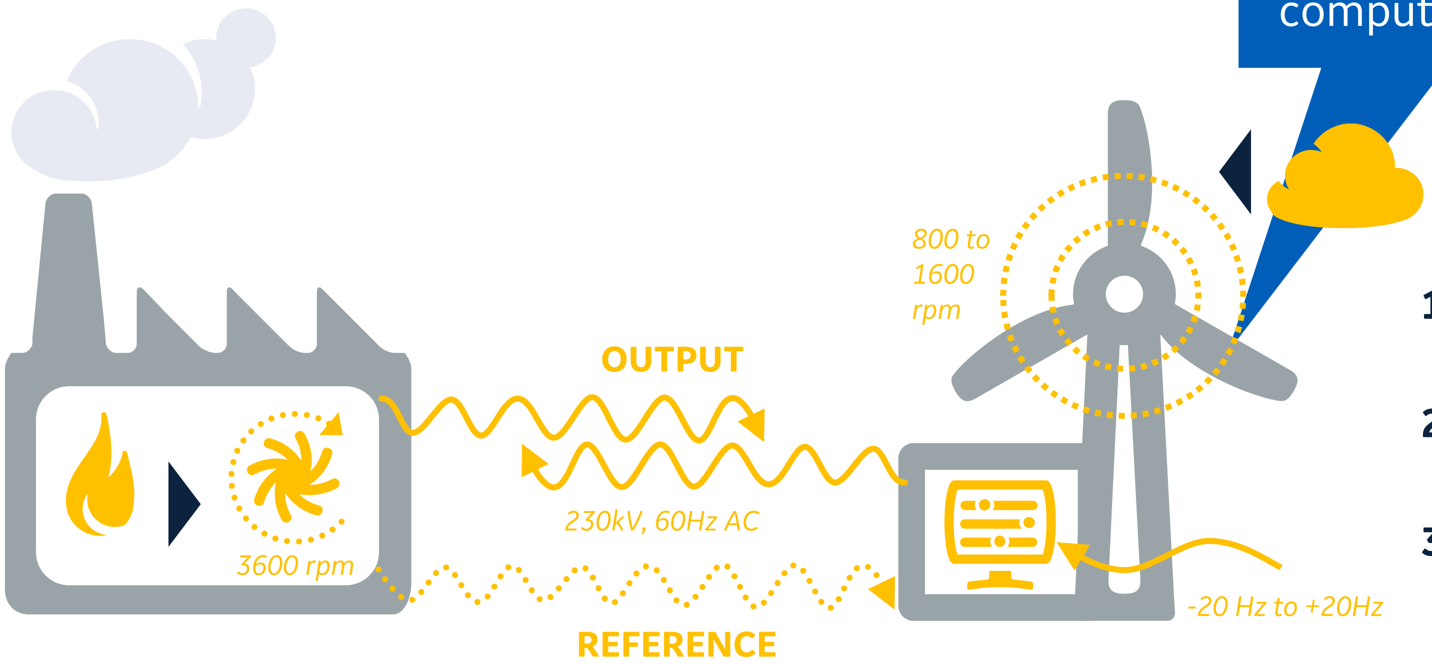


Ref: GE Energy Consulting, non-proprietary database

NYISO roadmap challenge: IBRs form voltage and frequency differently from synchronous machines

MECHANICAL:
voltage & frequency are created by mechanical rotation

1. **CREATES VOLTAGE** reference
2. **SLOW**: Changes in ~seconds
3. **FIXED**: Less configurable



SYNCHRONOUS MACHINES (SMs)
Gas, nuclear, hydro, coal

INVERTER-BASED RESOURCES (IBR)
Wind, solar, batteries, HVDC

ELECTRONIC:
voltage & frequency are engineered by computer algorithms

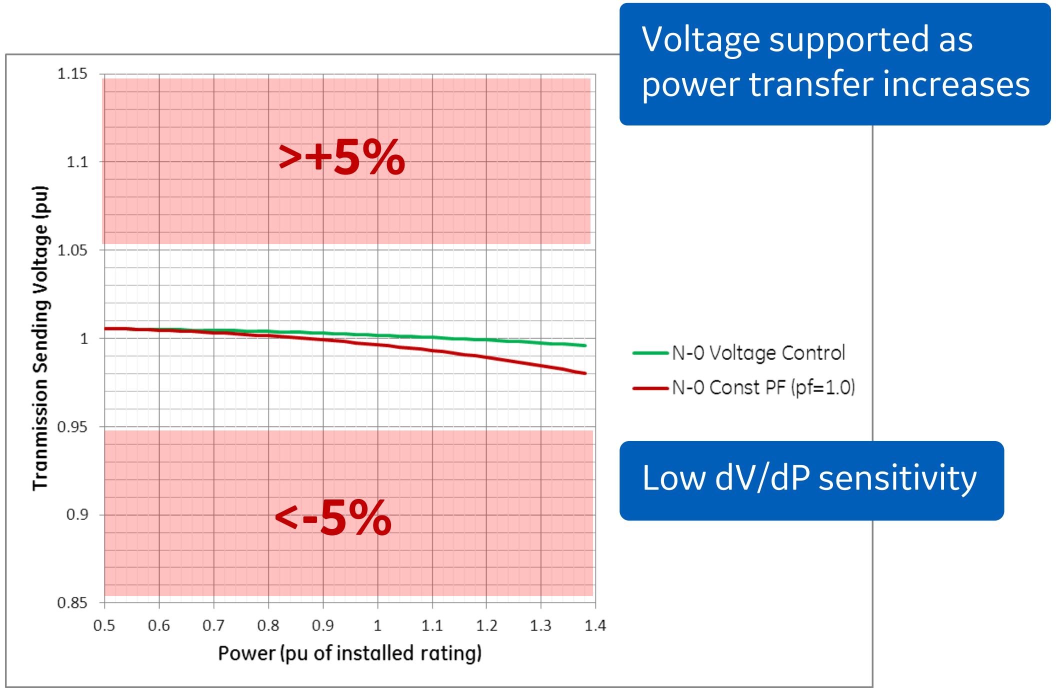
1. **NEEDS VOLTAGE** reference (today)
2. **FAST**: Changes in ~microseconds
3. **CUSTOMIZABLE**: Extremely configurable

Steady state voltage stability: Voltage can collapse in weak grids w/ higher power injection + high IBRs

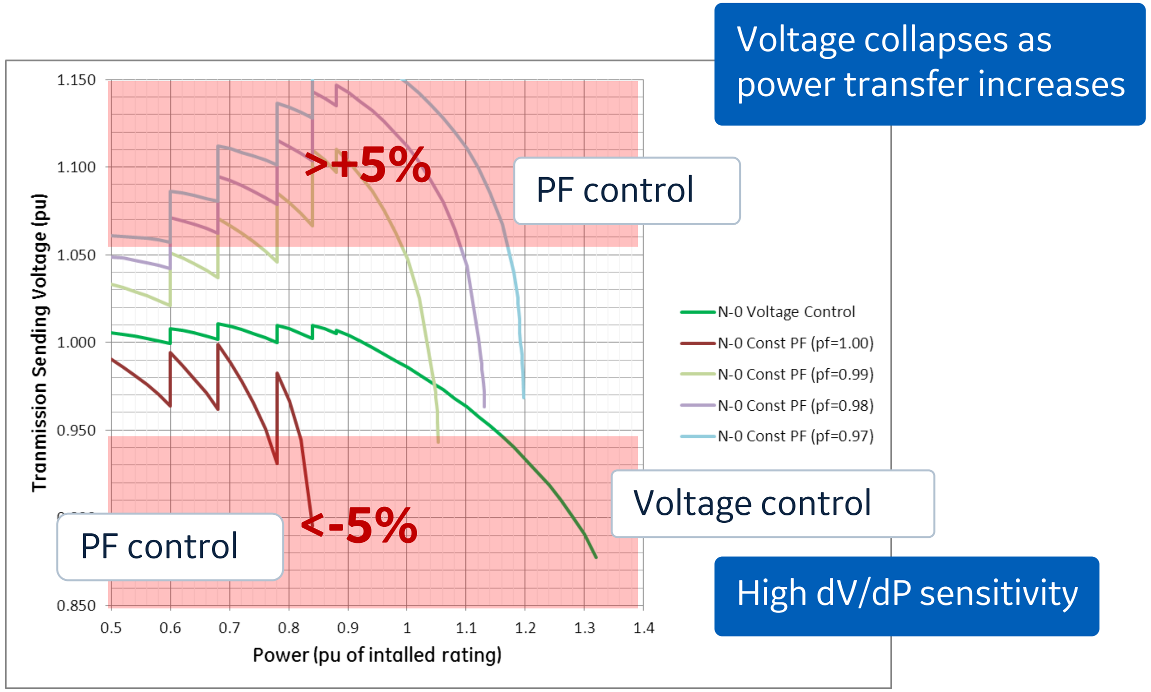
E.g. WECC Western Wind & Solar Integration Study

Regulatory note:
NERC VAR -002[1] closed loop voltage regulation is required.

STRONG GRID (e.g. low %IBR)
Voltage is insensitive to power injection



WEAK GRID (e.g. high %IBR)
Voltage collapses w/higher power injection

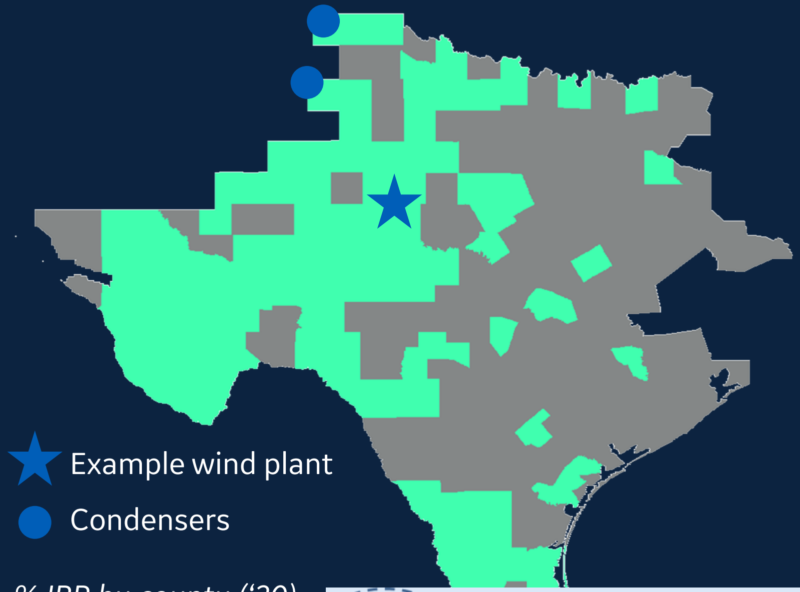


1 - https://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf

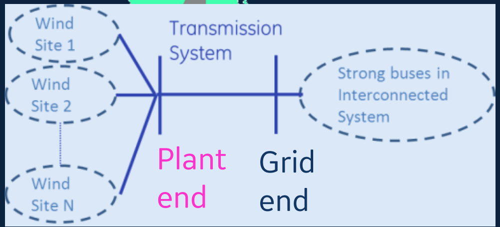
Dynamic voltage stability: voltage can collapse after a weak grid disturbance

e.g. Onshore wind plant in West Texas

e.g. ERCOT: LOW %SM IN PANHANDLE WEAKENS VOLTAGE REFERENCE

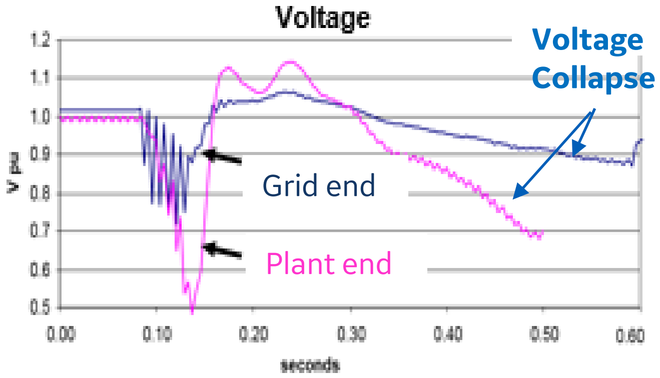


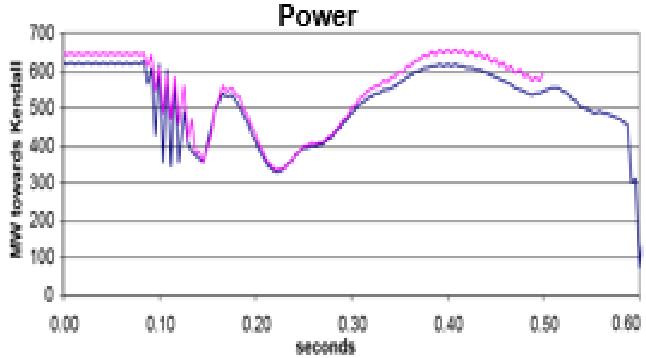
% IBR by county ('20)
- <30%
- 30-60%
- >60%



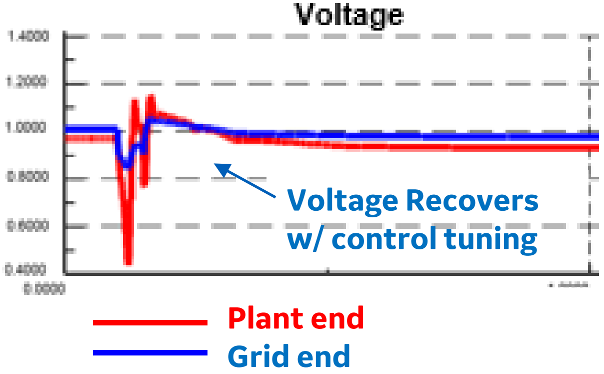
Ref: ABB, ERCOT

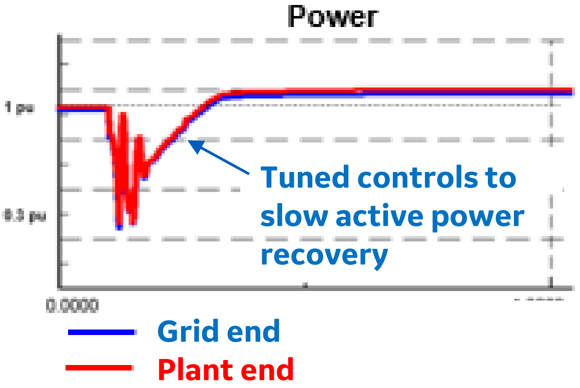
Field measurements: Voltage collapse due to weak grid





Simulated mitigation: Tuning controls to avoid voltage collapse





- Extremely weak application cause risk of voltage collapse
- Stable at fault clearing, collapse during power pickup before improvements
- Time frame of collapse is dictated by active power recovery

Controls stability: IBRs have multiple control layers & control modes that depend on voltage reference … weak reference -> confusion

	RESPONSE TIME	LOAD FLOW	DYNAMICS	TRANSIENTS
LAYERS OF WIND PLANT CONTROL				
1. Turbine level	1-10 sec	Only models a static output vs. a change in output	✓	✓
2. Converter level Inner loop	200 ms		Simplified	✓
Outer loop	1 sec		✓	✓
3. Plant level	10-20 sec		✓	✓
4. Plant to plant level	10-20 sec		✓	✓
CONTROL MODES OF OPERATION				
1. Turbine level 1) Normal 2) Ride-thru torque control 3) Ride-thru energy management	200 ms	Only models a static output vs a change in output		✓
2. Converter level 1) Normal 2) Under/over freq ride-thru 3) Under/over voltage ride-thru 4) SSCI damping	200 ms			✓

Different modes ensure turbine safety

Different modes provide grid reliability services

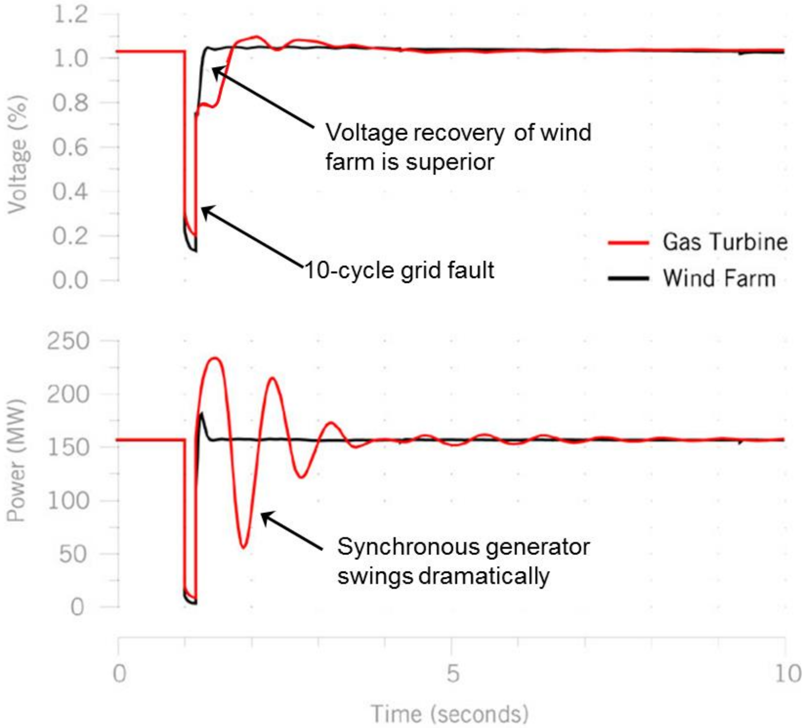
- Turbines and converters switch control modes based on grid voltage and frequency
- In weak grids, large voltage fluctuations may lead to confusion across plants, control layers and/or control modes

Angular stability: Weak grids can increase angular stability risk … SMs may lose synchronism after faults

e.g. GE simulation from New York 2004

RESPONSE TO 10 CYCLE FAULT

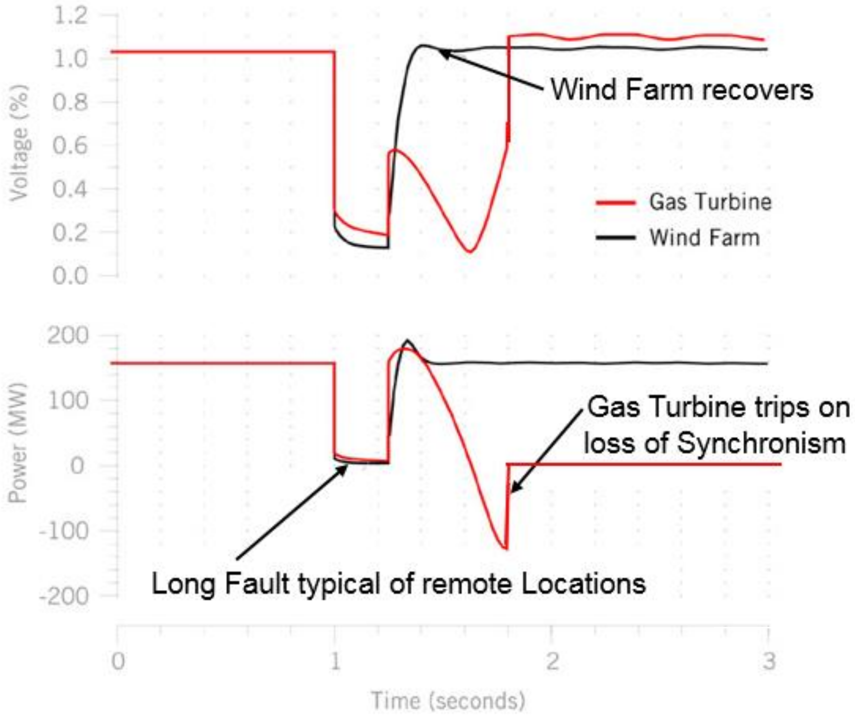
IBR & GT voltage recovers



Inverter-based resources can be more stable than conventional synchronous generators regarding transient stability, but can eventually cause a high-stress grid to fail faster and with less warning

RESPONSE TO 20 CYCLE FAULT

IBR voltage recovers but GT doesn't

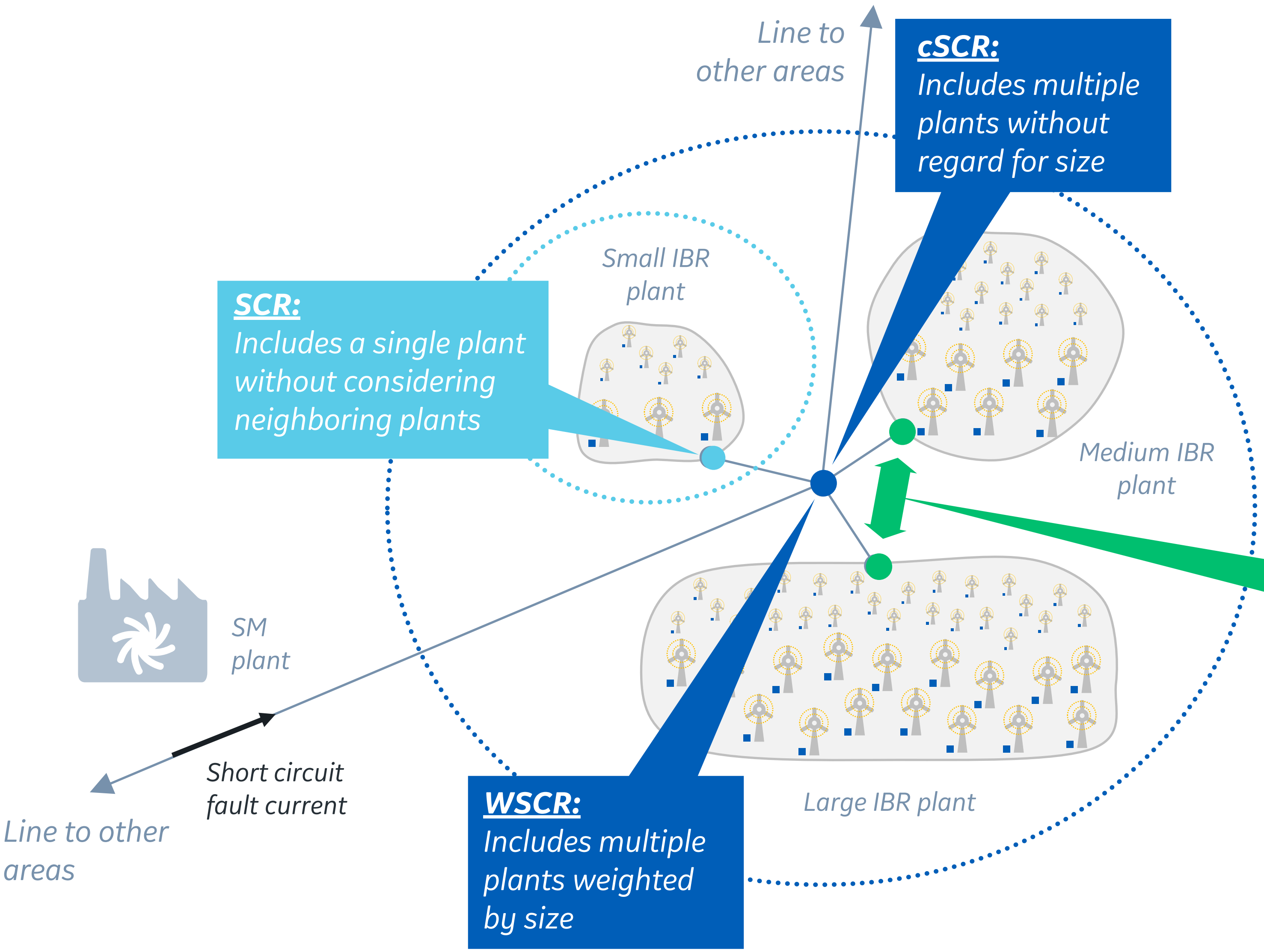


Long duration disturbances can trip conventional synchronous generators due to physical properties of the machine (critical clearing time, pole slips, loss of synchronism)

Loss of synchronism can be local or regional

Short Circuit Ratio (SCR) screening:

GE recommends using weighted SCR in NY since it accounts for plant size



MULTIPLE SCR METRICS TO CONSIDER

1. **SCR**: used for a single IBR plant
2. **cSCR (compound SCR)**: used for multiple IBRs at a common bus
3. **WSCR (weighted SCR)**: used for multiple IBRs weighted by each plant's contribution
4. **SCRIF (SCR Interaction Factor)**: used to test the interaction between two IBRs

Regulatory note:
The 2018 NERC Reliability Guideline[1], co-authored by GE, has suggested when to use each of the different Short Circuit Ratio Metrics.

1 - https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Inverter-Based_Resource_Performance_Guideline.pdf

Example: How to calculate SCR & WSCR?

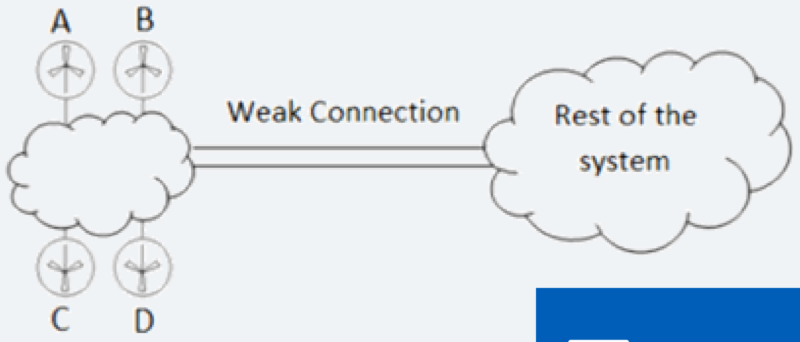
MW_{VER} $SCMVA_{POI}$

Table E.1: Wind Capacity and SCR Values Assuming No Interaction

Wind plant	Wind Capacity (MW)	Short Circuit Capacity (SCMVA)	SCR
A	1,200	6,500	5.42
B	1,000	8,000	8.00
C	800	8,500	10.63
D	2,000	7,000	3.5

SCR: FOR INDIVIDUAL PLANTS

$$SCR_{POI} = \frac{SCMVA_{POI}}{MW_{VER}}$$



WSCR: FOR GROUPINGS OF PLANTS

$$WSCR = \frac{\sum_i^N SCMVA_i * MW_{VERi}}{\left(\sum_i^N MW_{VERi}\right)^2}$$

$$WSCR = \frac{1{,}200*6{,}500+1{,}000*8{,}000+800*8{,}500+2{,}000*7{,}000}{(1{,}200+1{,}000+800+2{,}000)^2} = 1.46$$

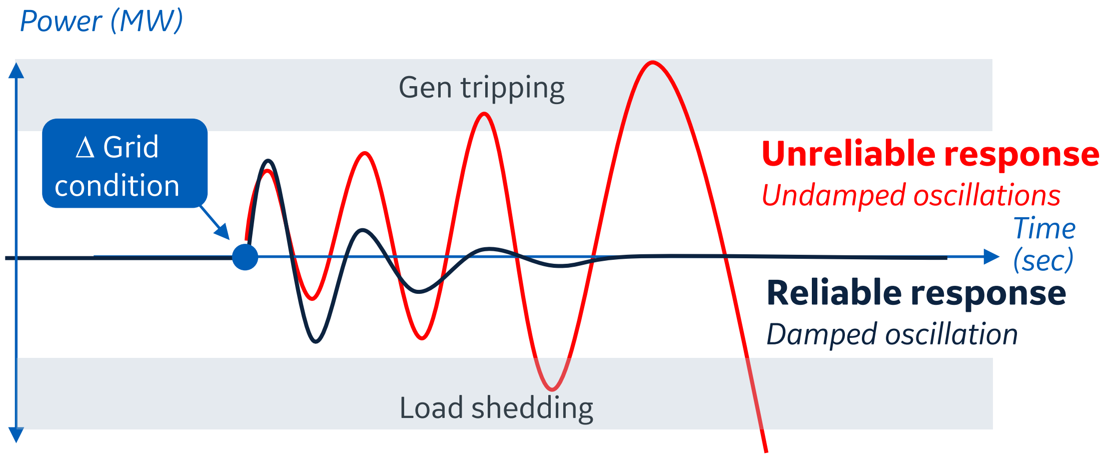
WSCR is weaker than individual SCRs due to plant-to-plant interaction

Ref: https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf

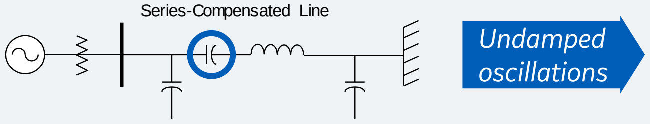
“Small signal stability”: Change in grid condition can trigger power oscillations

Grid operators often overlook this risk .... can result in equipment damage if undetected

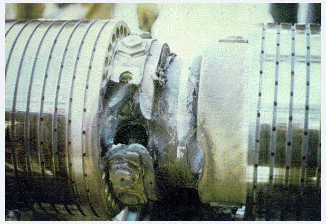
Power oscillations grow in undamped systems



Ex: Sub-synchronous resonance (SSR) can break shafts



Western US: Long radial lines use series compensation to lower reactive losses



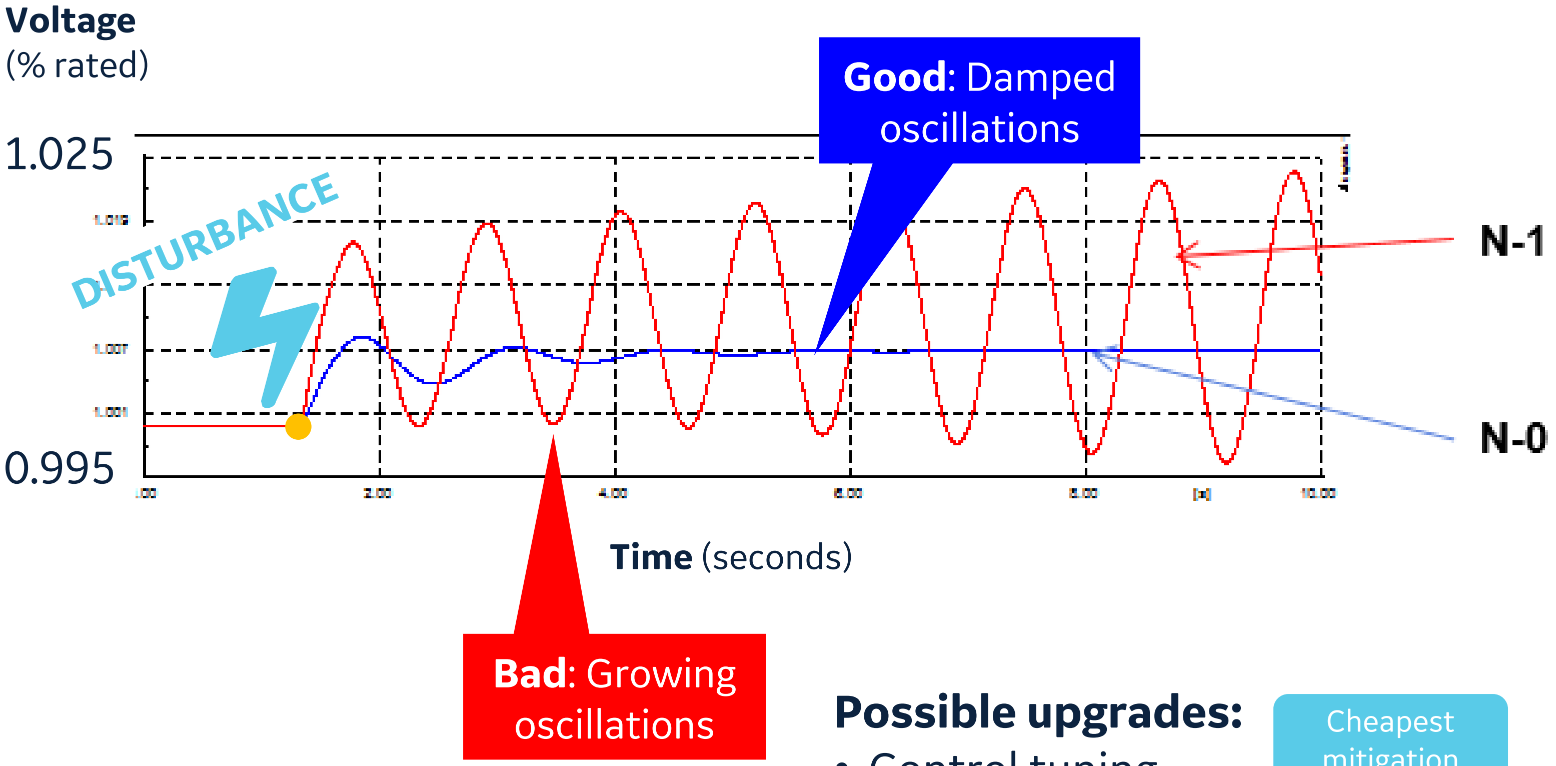
Mohave 1971: SSR breaks 1st GE generator shaft

New IBRs can trigger power oscillations ...

IN GRIDS WITH ...	RESULT	AFFECTS	FREQUENCY
IBRs w/high AC cable shunt capacitance	Shunt resonance	IBRs	~180 - 600Hz
IBRs & HVDC	Controls confusion (e.g. due to SSR, weak grids)	IBRs, SMs	~10 - 40 Hz
Series capacitors	Sub-synchronous resonance (SSR)	Synchronous machines (SM)	~ 10 - 40 Hz
High speed exciters	Local mode power oscillation	SMs	~ 3 Hz
Fast exciters/fast governor response	Inter-area power oscillation	SMs, IBRs	~1 Hz

Fast ↕ *Slow*

Texas example: Voltage may be N-0 stable but not N-1



Possible upgrades:

Cheapest mitigation

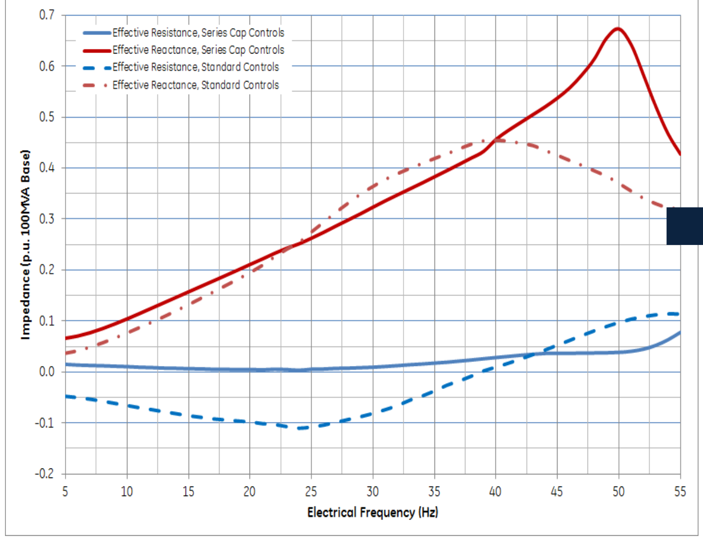
- Control tuning
- Synchronous condensers
- Line reinforcements
- FACTS devices

DISTURBANCE @t = 1s

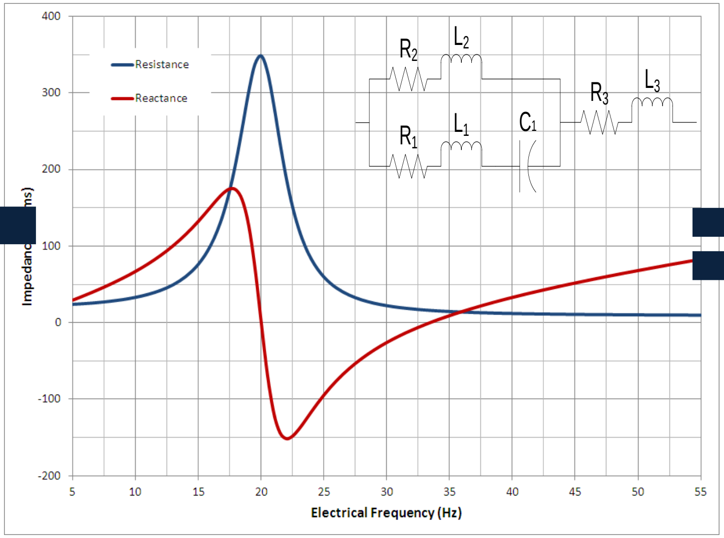
- Interaction between wind plant control layers may create **unwanted voltage oscillations**
- **N-0 grid may be strong enough** to damp out oscillations
- **N-1 grid may not be strong enough** and oscillations may grow and lead to unit tripping/ blackouts

Frequency scan to screen for small signal stability risks

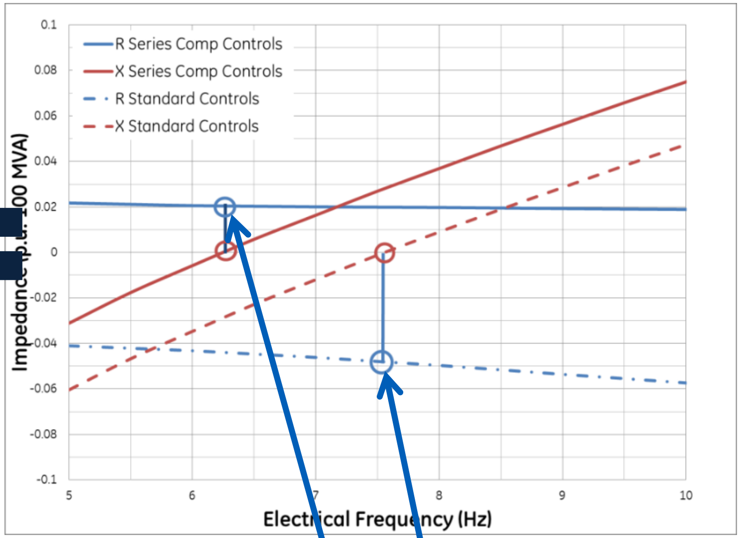
WIND PLANT SCAN



SYSTEM SCAN
(WIND PLANT DISCONNECTED)



COMBINED SCAN



- - - - - - - *Standard controls*
——— *Tuned controls for small signal risk*

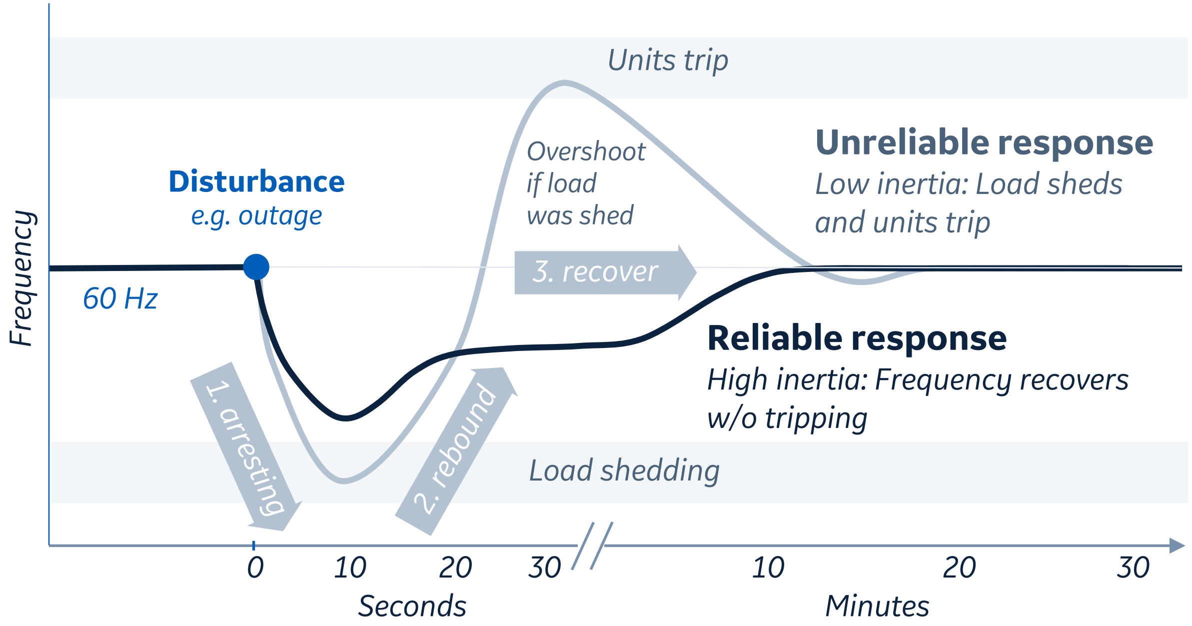
Negative resistance => **Potential unstable Resonance**

Tuned IBR controls => Positive resistance => **Positive damping & Stable oscillation**

Frequency scan steps:

1. **Determine equivalent impedances** for wind plant & grid
2. **Generate plot of total reactance and total resistance** as a function of frequency.
3. **Generate combined frequency scan** by adding the effective resistance & reactance for the wind plant + system
4. **Screen for frequencies with negative resistance**. For combined frequency scan plot, frequencies at which the resistance is negative for a zero impedance correspond to unstable oscillations.

"Frequency stability": Grid disturbances disrupt frequency … does a high IBR grid have appropriate frequency response to recover to 60 Hz?



HIGHER IBRs CAN MAKE FREQUENCY RESPONSE MORE "BOUNCY"

Post-disturbance period	Equipment response		Risk w/high IBRs
	SMs	IBRs	
1. Arresting *(<5 sec)*	**Inertia** High inertia w/ mechanical rotation	**FFR** Fast frequency response … low inertia	Frequency drops too quickly
2. Rebound *(10-20 sec)*	**Governor** response	**PFR** Primary frequency response	PFR doesn't react quickly enough -> load shedding
3. Recovery *(>20 sec)*	**Regulation**		Conflict with FFR & PFR

*Stable frequency response possible w/high IBRs … **controls coordination req'd.***