Advantages & Challenges of High % IBR and Introduction to Grid Forming IBR

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Moving to system dominated by inverter-based resources (IBRs)

Conventional synchronous resources

Inverter-based resources (IBRs)

Key points

- Grid strength is a more urgent problem than low inertia
- Export stability is a more urgent problem than low inertia
- Performance of IBRs is critical: Consider adopting IEEE P2800 interconnection requirements when it is finalized and consider project-specific needs based on OEM input

- The sky is not falling: we have available solutions and are adding to those
- IBRs are different from synchronous generators and that's important for the future
- We are the middle of a transition from synchronous generator-centric to IBR-centric systems. It is both important to improve stability in our existing framework (regulators can help) *and* to determine the paradigm shift to IBR-centric systems (operators, OEMs and researchers' role)

Grid-following (GFL) vs Grid-forming (GFM) Inverters

Grid following (Inverter follows): Inverters measure the grid voltage and frequency, and then try to inject the correct real and reactive power to “follow” the voltage.

- *Requires voltage reference*
- *Performance driven by current regulators*
- *Most resources today are grid-following but vary widely in capability*

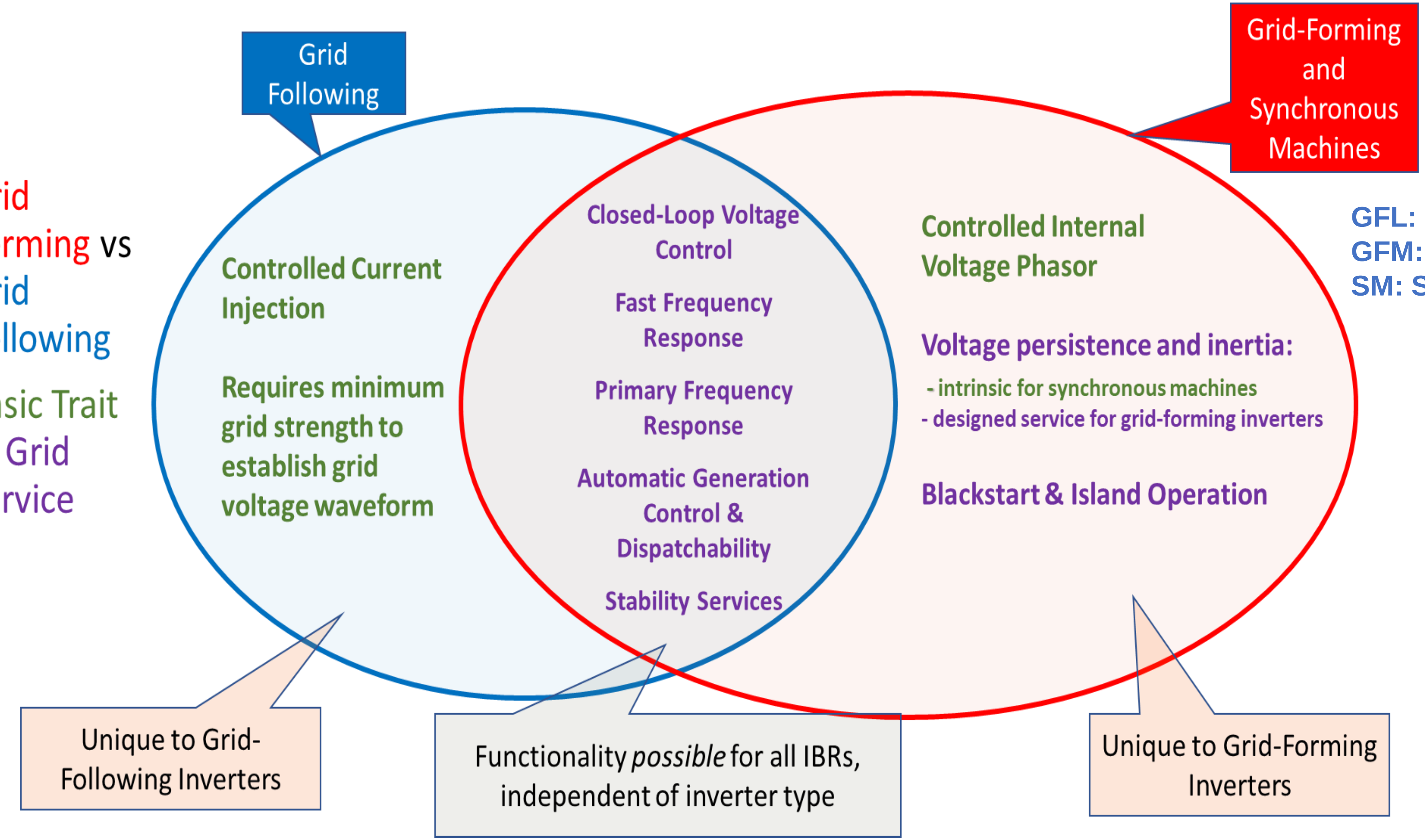
Grid forming (Inverter leads): Create a local voltage and frequency, and then try to move that voltage to cause the correct real and reactive power to flow into the grid.

- *No reliance on external grid voltage to generate power*
- *Stabilizes grid by quickly adjusting power to reduce voltage angle & frequency changes*
- *Many different types/implementations starting to be deployed*
- *Can operate without or with very few synchronous machines electrically nearby*

A bit oversimplified, but close enough - the point is this behavior is fundamentally different, and fails differently

How do GFL, GFM and SM resources compare?

- Grid Forming vs Grid Following
- Basic Trait vs Grid Service



GFL: Grid Following
GFM: Grid Forming
SM: Synchronous Machine

Source: J. Matevosyan, et al. Future with Inverter-Based Resources, IEEE PES Power and Energy, Nov/Dec 2021

Technology Transitions for IBR Stability

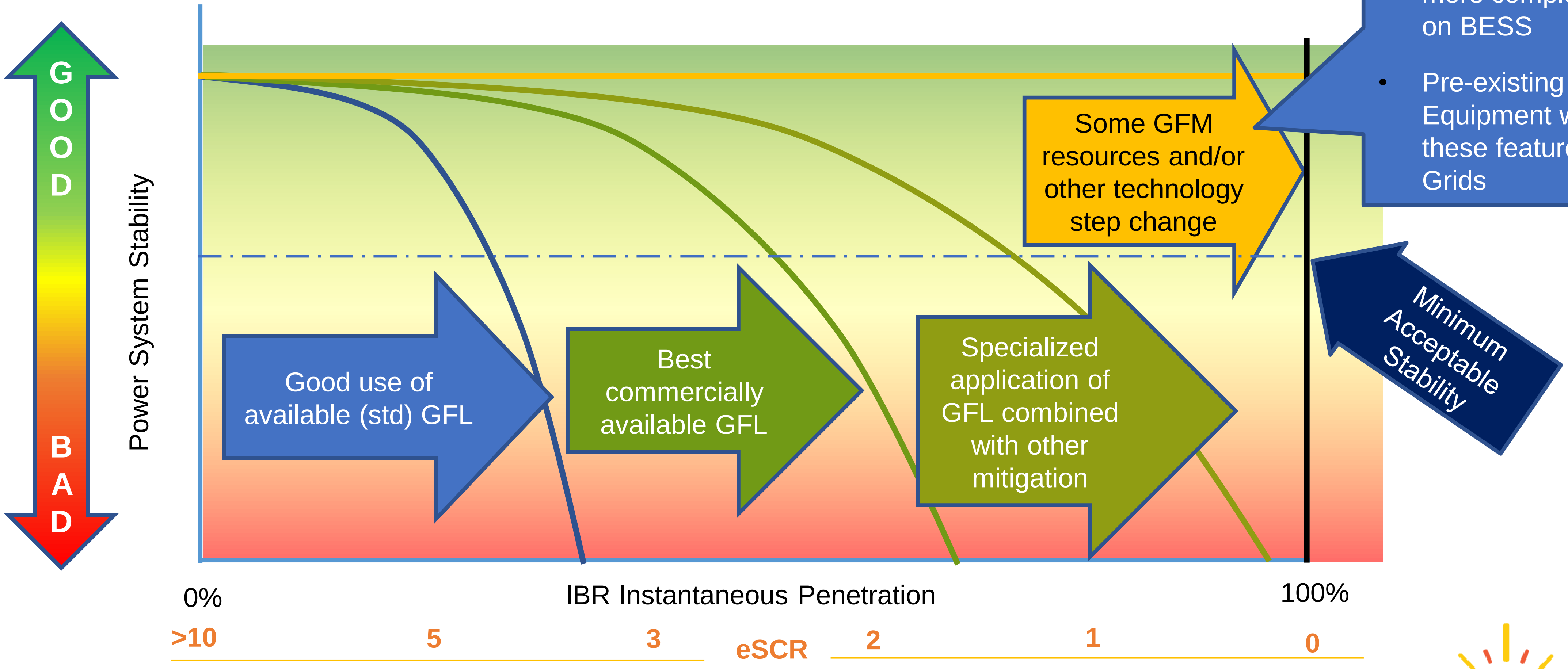
- **Grid Friendly features**
- **High ride-thru**

- **Weak Grid features**
- **GETS & FACTS**
- **Control Interaction Mitigations**

- **Further Control Advances**
- **Synchronous Condensers**

- **Grid Forming**
- **Islanded operation**
- **Enhanced Fault contribution**

- Not resolved for large interconnected systems
- Features in Wind and PV products more complex than on BESS
- Pre-existing Equipment without these features in Grids



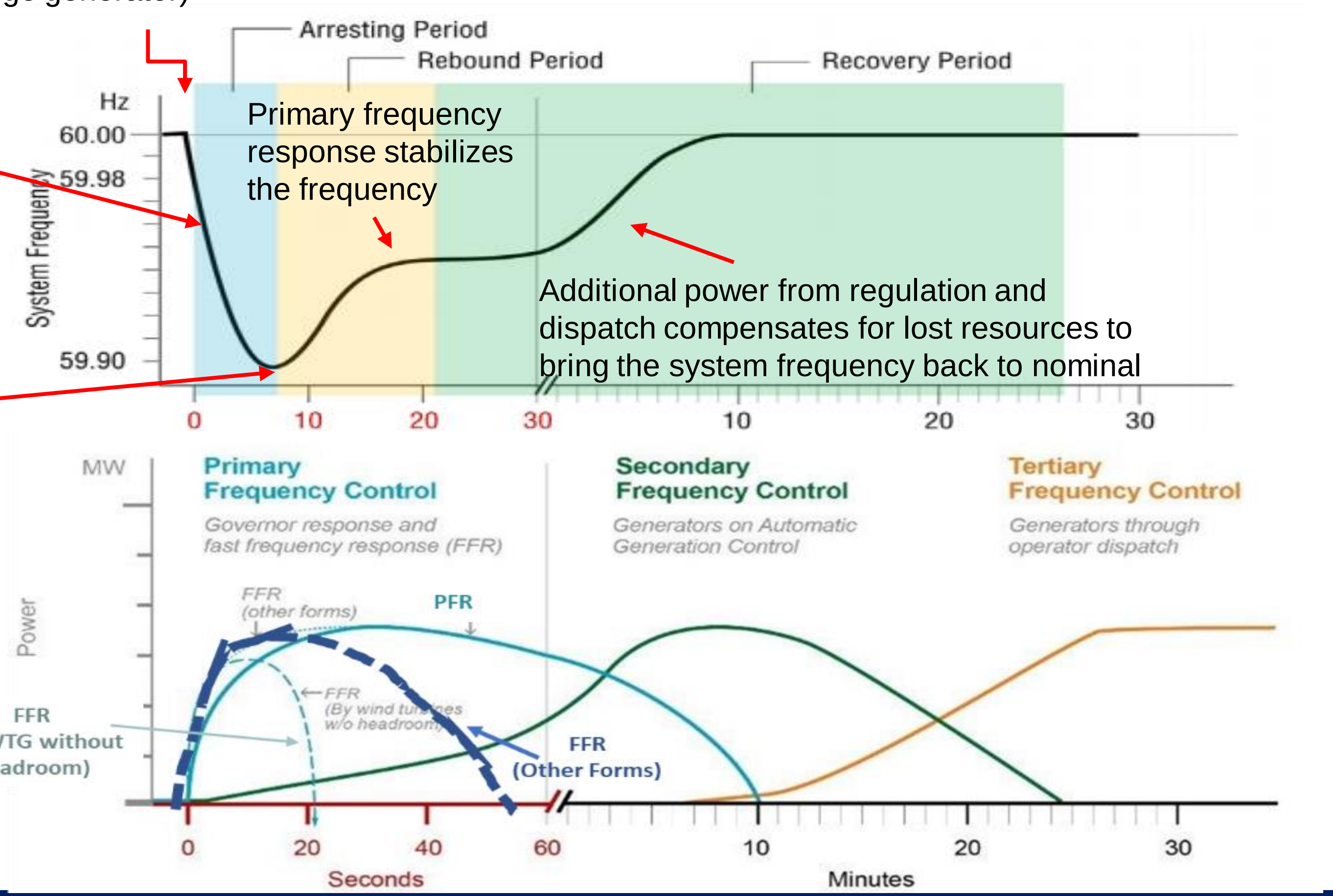
Courtesy: N. Miller, Hickory Ledge

Frequency Response – What's different with IBR?

Disturbance – (e.g. Loss of large generator)

Synchronous Inertial Response (SM) and Fast Frequency Response (GFL IBR) sets initial slope

Fast frequency response and initial primary frequency response establish the minimum frequency point ("nadir")



Courtesy J. Eto, J. Undrill, M. O'Malley et al, "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration o Variable Renewable Generation", 2010

Annotations by M. Ahlstrom, Nextera

https://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

Design/operational considerations:

- MW Contribution
- Speed
- Controllability
- Tunability
- Timing
- Headroom
- Interoperability

The grid needs frequency responsive controls ***from ALL resources over various timeframes*** to stably and reliably recover from loss of large power plants or smaller grid segments

Grid Inertia & Fast Frequency Response

Number	Resource	Type of Inertial response	Can it support like sync machines?	Required/paid in 2021	Expected to be required in 2025	Lifecycle
1	Synchronous machine (GT, Steam, most Hydro)	Inherent/physical	-	-	-	
2	Standard IBR	no response	NO	Default	Default	Frequency support will be required
3	Grid following IBR with Fast Frequency Response (FFR)	FFR controlled response	NO*	Brazil, Canada, Australia, Ireland, GB, Texas	+NAM (P2800)	Applied to GFL technology, depends on adoption of GFM
4	IBR with grid forming features (several levels of performance)	controlled, intended to replicate sync machines*	YES	No market mechanism. Few special BESS application. Draft voluntary requirement in GB.	GB, ENTSO-E, Australia, Germany, Texas(?)	

Observations:

A A system with resources 1,2 and 3 will have a limit of IBR penetration due to large system stability. These are now applied based on a minimum system inertia level required from synchronous machines or similar wide system metrics. The manifestation of this requirement is commitment of synchronous generation "outside of economic merit" (Wind and solar assumed with no production cost)

B Item 4 is the result of the industry reacting to A

System Characteristics and IBR Impacts: Frequency Stability Risks

Frequency Stability Risks

Occasional	Acute	Chronic
• Under intact system conditions, the system is relatively immune to fast and severe frequency events; • Challenges tend to be weighted towards congestion management.	• Frequency control concerns can limit operation; • Periods of poor frequency containment during credible events; • Control of frequency following possible or planned system splits is difficult.	• System often has risk of substantial frequency control problems and high RoCoF.

CE- Central Europe, TX-Texas, GB-Great Britain, AU-Australia, IR-Ireland, HI-Hawaii

Grid Forming can provide fast inertia-like response to support frequency within equipment limitations

Source: J. Matevosyan, et al. Future with Inverter-Based Resources, IEEE PES Power and Energy, Nov/Dec 2021

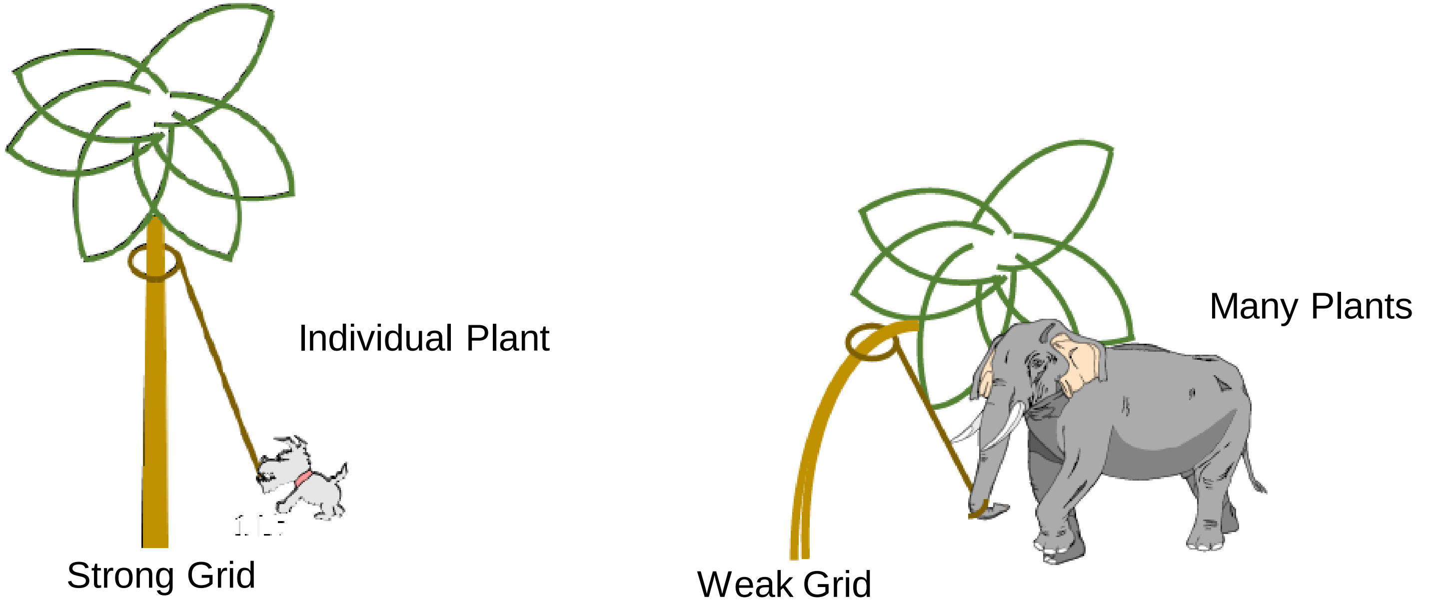
Is the bulk grid relatively weak or strong?

Strong Grids are relatively stable and are influenced less by individual plants

Weak Grids are very sensitive – system voltage, frequency and angle are highly influenced by plant behavior

Ways to resolve weak grids:

- New controls from IBRs (**Grid Forming** Controls*)
- Reinforcements from **SMs** (including synchronous condensers, gas, hydro, nuclear, etc.)
- Reinforcements from **Transmission**
- **Interoperability** between resources to maintain stability



Source: Miller, NREL/GE WWSIS III

Strong grid controls can be fast and stable

Designing controls for weak grids is like running on ice – SLOW DOWN!

Stability Issues in Weak Grids

Failure to ride through disturbances

Weak systems make ride-through more difficult, especially following a network disturbance, leading to wider system issues, such as under-frequency or loss of voltage support. Phase-Lock-Loop (PLL) stability.

Converter control interactions

The weaker the interconnection, the more likely controls will be to influence each other and interact negatively with each other

Converter control instability

If the network is weak enough, controls may enter unstable region with no external influence needed (small signal instability)

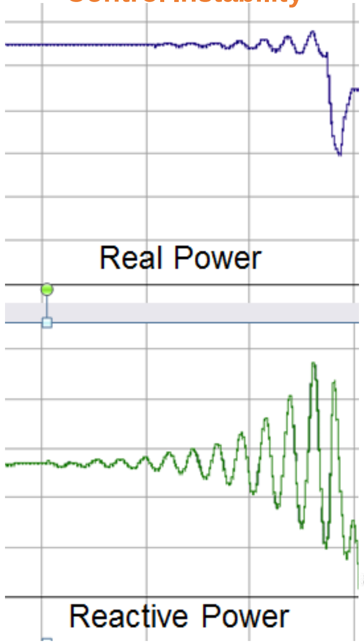
Cycling between converter control modes

If system is weak, various turbine control modes may cycle multiple times as turbine attempts recovery, introducing severe transients into the system

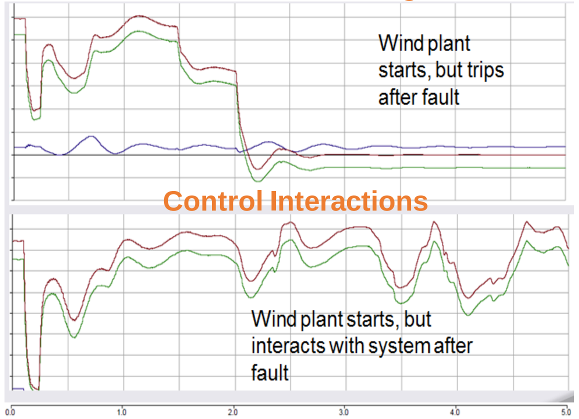
Steady-State Voltage Collapse and Power Transfer

Voltage collapses more sensitively as real & reactive power flows through weak grid (mostly non-source dependent)

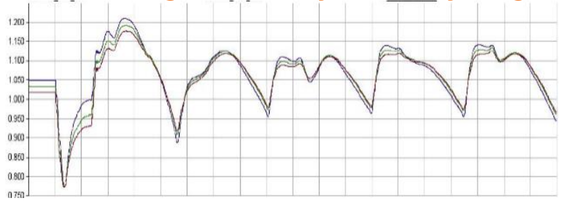
Control Instability



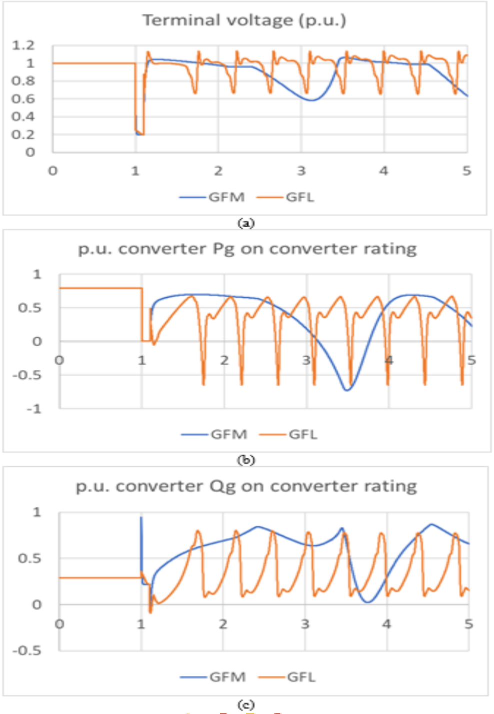
Failure to ride through



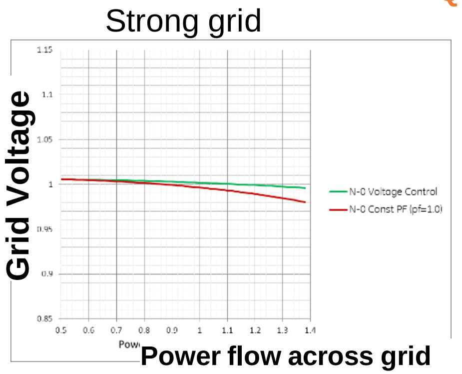
Voltage instability due to cycling

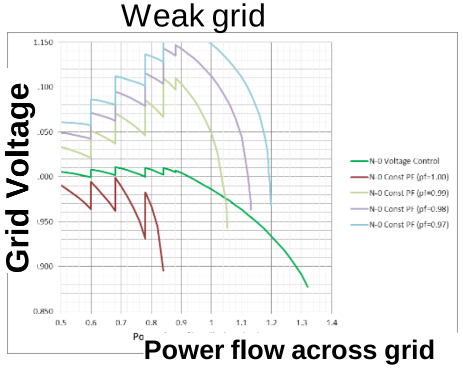


Unstable recovery due to network transfer limits



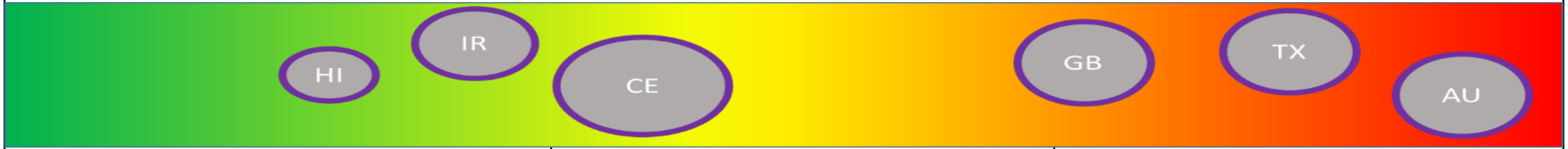
Quasi-Steady State Voltage Collapse





System Characteristics and IBR Impacts: Voltage and Angle Stability Risks

Voltage and Angle Stability Risks



Local	**Regional**	**System-wide**
• Electrical distances are limited; • Interface collapse and system separations a remote concern; • Local voltage support issues possible.	• Significant power imports and exports with dynamic constraints being an occasional factor; • Separation tends to be a high-impact low-frequency event.	• System has high power transfer over ac transmission interfaces, for which voltage instability and angular separation is a primary concern and often imposes operating constraints.

CE- Central Europe, TX-Texas, GB-Great Britain, AU-Australia, IR-Ireland, HI-Hawaii

Properly configured Grid Forming or Grid Following can mitigate SOME voltage & angle stability risks

Source: J. Matevosyan, et al. Future with Inverter-Based Resources, IEEE PES Power and Energy, Nov/Dec 2021

System Characteristics and IBR Impacts: Control Stability Risks

Control Stability Risks

Local	Regional	System-wide
• Some specific locations (e.g. individual nodes or small areas) with low system strength and risk of control interactions.	• Entire regions of very high IBR and little or no synchronous generation with ac transmission to other stronger areas.	• Entire system has extended periods of very low or even zero synchronous short circuit contribution.

CE-Central Europe, TX-Texas, GB-Great Britain, AU-Australia, IR-Ireland, HI-Hawaii

Properly configured Grid Forming or Grid Following can mitigate MOST control stability risks

Source: J. Matevosyan, et al. Future with Inverter-Based Resources, IEEE PES Power and Energy, Nov/Dec 2021

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Acronyms/definitions

- AGC – automatic generation control (utility sends 4-6 sec control signals to secondary reserves)
- BA – balancing authority
- IBR – inverter-based resources (eg wind, PV, batteries and other resources connected to grid through inverter)
- FFR – fast frequency response is a faster version of PFR; autonomous response to frequency deviations
- FRO – frequency response obligation is how much frequency responsive reserves each BA needs to hold
- GFL – grid-following
- GFM – grid-forming
- Inertia – synchronous inertia is an inherent response from synchronous machines including motors
- PFR – primary frequency response (aka governor response) is an autonomous response of a generator to frequency deviations
- ROCOF – rate of change of frequency (how fast frequency falls when a generator trips)
- UFLS – underfrequency load shedding is an autonomous response to drop blocks of load; emergency response to save frequency

References

- J. Matevosyan, et al. Future with Inverter-Based Resources, IEEE PES Power and Energy, Nov/Dec 2021
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