Overview of Grid Forming Interconnection Requirements

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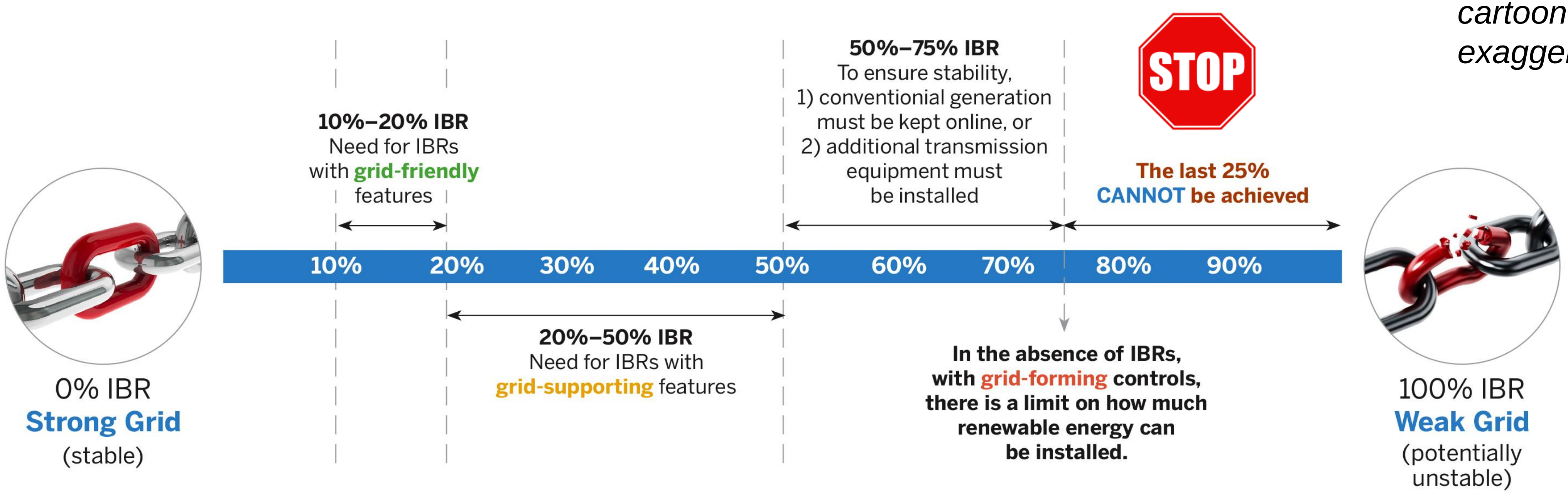
Where are We Today and What is the Issue?

<u>Disclaimer</u>: this figure is a cartoon and as such is an exaggeration



1. Keeping conventional generation online leads to high renewable curtailment.
2. Additional transmission equipment is expensive and time-consuming to install (and renewable curtailment continues in the meantime).

IBR – Inverter-Based Resource (wind, solar, battery storage)

What is Grid Forming ?

NERC definition:

- Grid Forming IBR controls **maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame.** This allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during challenging network conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid
- There are many variations of both grid-forming and grid-following controls. Both are subject to physical equipment constraints including voltage, current and energy limits, mechanical equipment constraints (on WTGs) as well as external power system limits.
- Further, performance requirements for GFL plants, will also apply to GFM inverters unless explicitly identified as inapplicable.

Sources: NERC, Grid Forming Technology Bulk Power System Reliability Considerations , December 2021
ESIG, Grid Forming Technology in Energy Systems Integration, March 2022

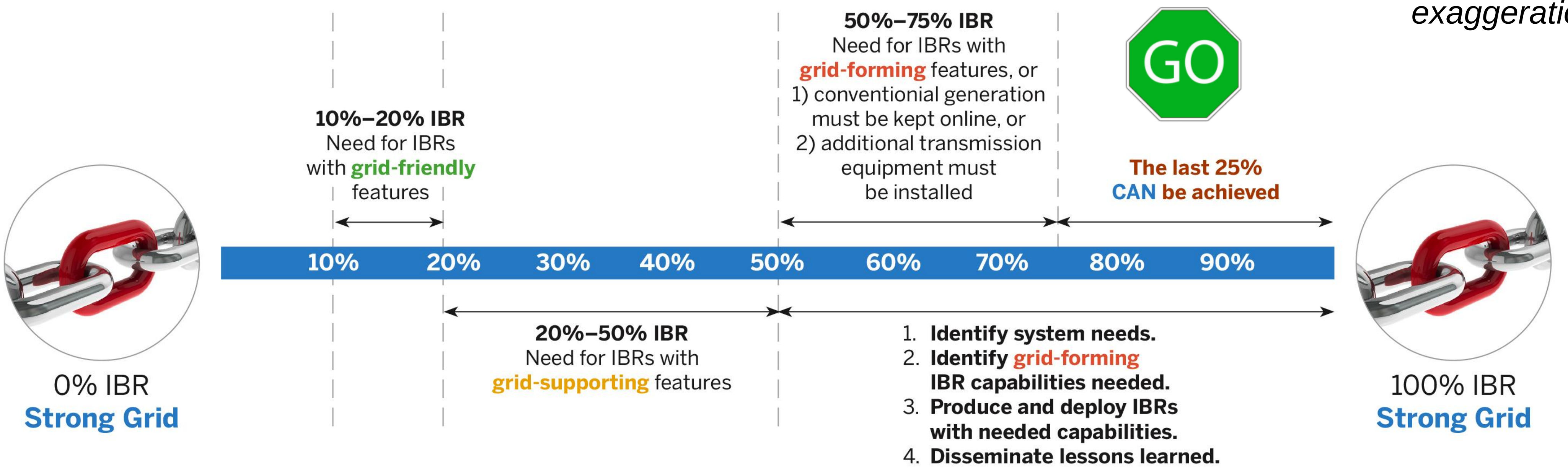
Potential Use-Cases for Grid Forming Controls

- Weak grid operation
- Damping of voltage and frequency oscillations
- Response to phase-jump
- Limit initial RoCoF (substitute/supplement) inertia response
- Fast fault current (balanced and unbalanced)
- Sub synchronous control interractions
- Black start

Source: Adopted from Y. Cheng, Preliminary assessment of Grid Forming Inverter-based Energy Storage Resources in the ERCOT Grid ERCOT IBRWG, August 2023

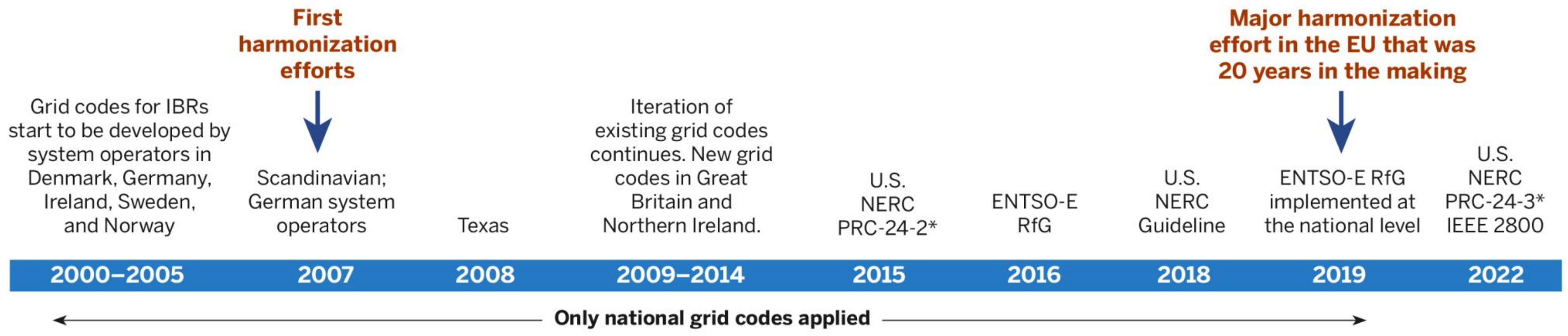
Towards Very High IBR

<u>Disclaimer</u>: this figure is a cartoon and as such is an exaggeration



Deploying grid-forming capabilities from IBRs, especially battery storage, **<u>is cheaper and faster</u>** than adding new transmission assets, which would require additional investment and may take much longer to build.

Timeline of Harmonization Efforts for IBR Grid Codes in Europe and the United States



*NERC PRC-024-2 only sets out a protective setting requirement and not a performance requirement to ensure ride-through capability

- Grid codes specify the capabilities that generators must have in order to interconnect to the grid.
- Diversity in grid codes requires multiple product designs and increase equipment costs.
- Comprehensive harmonized grid code for IBRs took 20 years to develop in Europe.
- The U.S. still has no harmonized grid code for IBRs today.
- **We cannot take 20 years to develop and harmonize grid codes for grid-forming IBRs!**

Grid Forming Specs Landscape At Glance

- **MIGRATE:** EU-funded project on the Massive Integration of Power Electronic Devices (2019)
- **HECO:** Model Energy Storage Power Purchase Agreement (2019)
- **NREL:** Research Roadmap for Grid Forming Inverters (2020)
- **ENTSO-E:** High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters (2020)
- **VDE FNN:** Guideline Grid forming behavior of HVDC systems and DC-connected PPMs (2020)
- **NGESO:** GC0137 Minimum Specification Required for Provision of GB Grid Forming Capability (2021)
- **AEMO:** Application of Advanced Grid-Scale Inverters in the National Electricity Market (2021)
- **HECO:** Model Energy Storage Power Purchase Agreement (2021)
- **OSMOSE:** EU-funded project (continuation of MIGRATE) that defined grid forming capability and new services (2022)
- **UNIFI:** Specifications for Grid-Forming Inverter-Based Resources – Version 1 (2022)
- **NGESO:** Great Britain Grid Forming Best Practice Guide (2023)
- **AEMO:** Voluntary Specification for Grid-Forming Inverters (2023)
- **FINGRID:** Specific Study Requirements for Grid Energy Storage Systems (focuses on grid forming requirements) (2023)
- **NERC:** Grid Forming Functional Specifications for BPS-Connected Battery Energy Systems (2023)

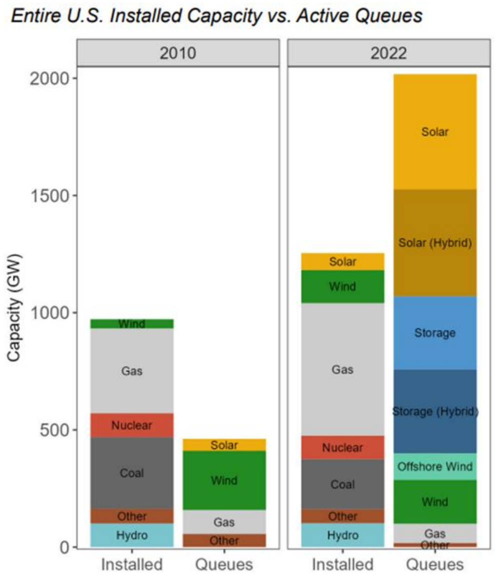
Source: Adopted from UNIFI, GFM Inverter Technology Specifications: Review of Research Reports and Roadmaps

Grid Forming Specs Landscape, cont.

	System Operator or Regulatory Body	Research Orgs or Industry WGs
Published	1. NG ESO GC & Guide 2. FNN VDE 3. HECO 4. AEMO 5. Fingrid	1. ENTSO-E HPoPEIPS 2. MIGRATE / OSMOSE 3. UNIFI V.1
Draft	1. ENSTO-E RfG 2.0	1. NERC IRPS
Planned	1. ERCOT 2. Florida Power & Light	1. CIGRE JWGB4/C4.93 2. UNIFI V.2 3. GPST GFM IC

- High level vs detailed functional specifications
- Functional specifications vs test-based vs both
- Split into "core" & advanced capabilities vs not split
- Voluntary vs mandatory
- For all resources vs all IBRs vs just <u>BESS</u>

Source: E. Quitmann, [ESIG Spring Technical Workshop, 2020]



Source: LBNL, Queued Up
https://emp.lbl.gov/queues

Common Functionalities

- Response to voltage phase angle step
- Response to voltage magnitude step
- Response to ± ΔMW events
- Behavior at the current limit
- Counter Unbalances
- Counter Harmonics
- Provide Damping
- Low system strength operation
- Islanded Operation
- Black Start

AEMO – High Level Specifications Example
‘Core’ Capability Requirements

- Nearly-instantaneous (< 5 ms) **reactive response to an external voltage magnitude step**, to oppose the change in voltage.
- Nearly-instantaneous **active power response to a voltage phase angle step**, by injecting or absorbing power to oppose the change in phase angle.
- The response when the inverter is at a limit, and in transition to and from a limit condition, must be smooth and stable.
- The behavior at a limit should not be detrimental to stability and to harmonic performance (for example, clipping of current waveforms).
- **Inertial response** from GFM inverters should be inherent (no calculation of frequency), providing a near-instantaneous active power response to a grid disturbance (e.g. load or generation trip)
- If the inertia is configurable, it needs to be tuned based on network conditions and requirements (high inertia constant may increase power oscillations, particularly in strong systems).

Response to voltage magnitude step

Response to voltage phase angle step

Behavior at the current limit

Response to ± ΔMW events

https://aemo.com.au/-/media/files/initiatives/primary-frequency-response/2023/gfm-voluntary-spec.pdf?la=en&hash=F8D999025BBC565E86F3B0E19E40A08E

AEMO – High Level Specifications Example Other 'Core' Capability Requirements

- **Surviving Loss of Last Synchronous Machine (SM)**: operate stably in a grid without any other GFM inverters or SMs; remain stable for a transition from a grid with SMs to one without (and back); provide frequency and reactive support, unaffected by these transitions. All of that, provided the resultant state of the system is within the operating envelope of the GFM inverter.

Islanded Operation

- **Operate stably under a very low short circuit ratio**, as defined by the system operator; provide system strength support to nearby GFL inverters during and after disturbances.

Low system strength operation

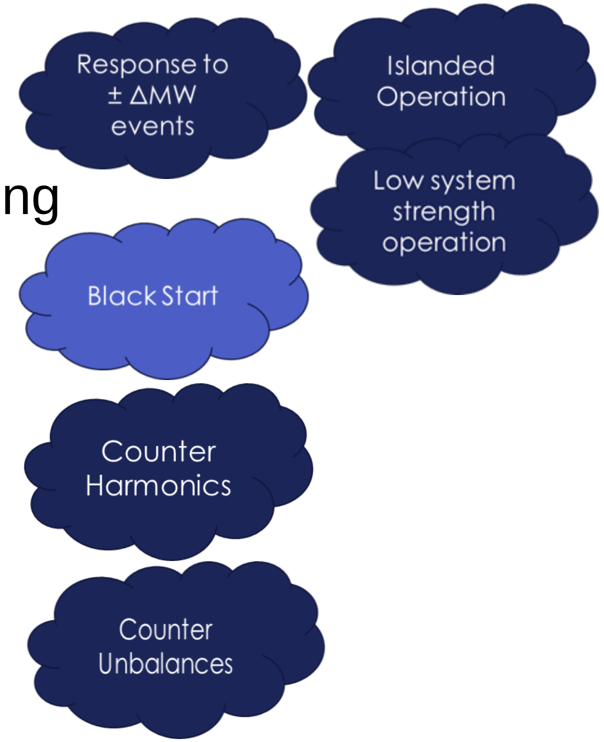
- **Provide positive damping for oscillations**: following a disturbance GFM inverter output should be adequately damped; add damping to the system for the oscillatory phenomena:
  - SSCI (either between GFL inverters or GFL inverter and grid)
  - Rotor angle modes of oscillation inter-area modes of oscillation
  - Oscillations at harmonic frequencies which result from interactions of electrical and control resonances.

Provide Damping

Source: AEMO, Voluntary Specification for Grid-forming Inverters, May 2023

AEMO – High Level Specifications Example 'Additional' Capabilities

- Larger headroom and energy buffer
- Current capability above continuous rating
- Black start capability
- Power quality improvement



Source: AEMO, [Voluntary Specification for Grid-forming Inverters](), May 2023

National Grid ESO, GC0137 – Example of More Detailed Grid Forming Requirements

GC0137 grid code change, defines a non-mandatory technical specification for GFM plants. At a high level GFM IBR shall:

- Comprise an internal voltage source (IVS) and physical reactance
- Remain synchronized with the system and maintain a load angle between 0 and 90 degrees,
- Be capable of supplying:
  - Phase Jump Active Power (inherent, < 5 ms, response to phase change between IVS and POI)
  - Real Inertia Power (inherent, < 5 ms, response to changes in phase and frequency)
  - RoCoF Response Power (incl. Real Inertia Power and Control Based Real Droop Power)
  - Damping Active Power (inherent, < 5 ms, response to oscillations)
  - Voltage Jump Reactive Power (inherent, <5 ms, reactive power response to a step or ramp change in the difference between IVS and POI voltage magnitudes.
  - Fast Fault Current Injection (reactive current that starts to rise in <5 ms when the voltage falls <0.9 pu; deployment up to 1 pu shall be achieved in < 30 ms)

Response to voltage phase angle step

Response to ± ΔMW events

Provide Damping

Response to voltage magnitude step

National Grid ESO, GC0137 Grid Forming Requirements

- Control Based changes have a bandwidth limited to 5 Hz (to avoid AC System resonance problems)
- Phase Jump Active Power and Real Inertia Power can have frequency components to over 1000 Hz.
- If a unit is designed with black start capability, then it is required to have grid forming capability
- A minimum Phase Jump Angle Limit, for the unit to remain in linear control (without hitting current limits), of 5 degrees is recommended and
- A 60 degrees Phase Jump Angle Withstand capability is specified.
- The RoCoF response power is assessed for 1Hz/s, while RoCoF withstand capability is requested up to 2 Hz/s
- The cumulative energy delivered is defined for a 1Hz/s System Frequency fall from 52 Hz to 47 Hz in MWs, but also an inertia constant value (H) must be declared by the service provider.

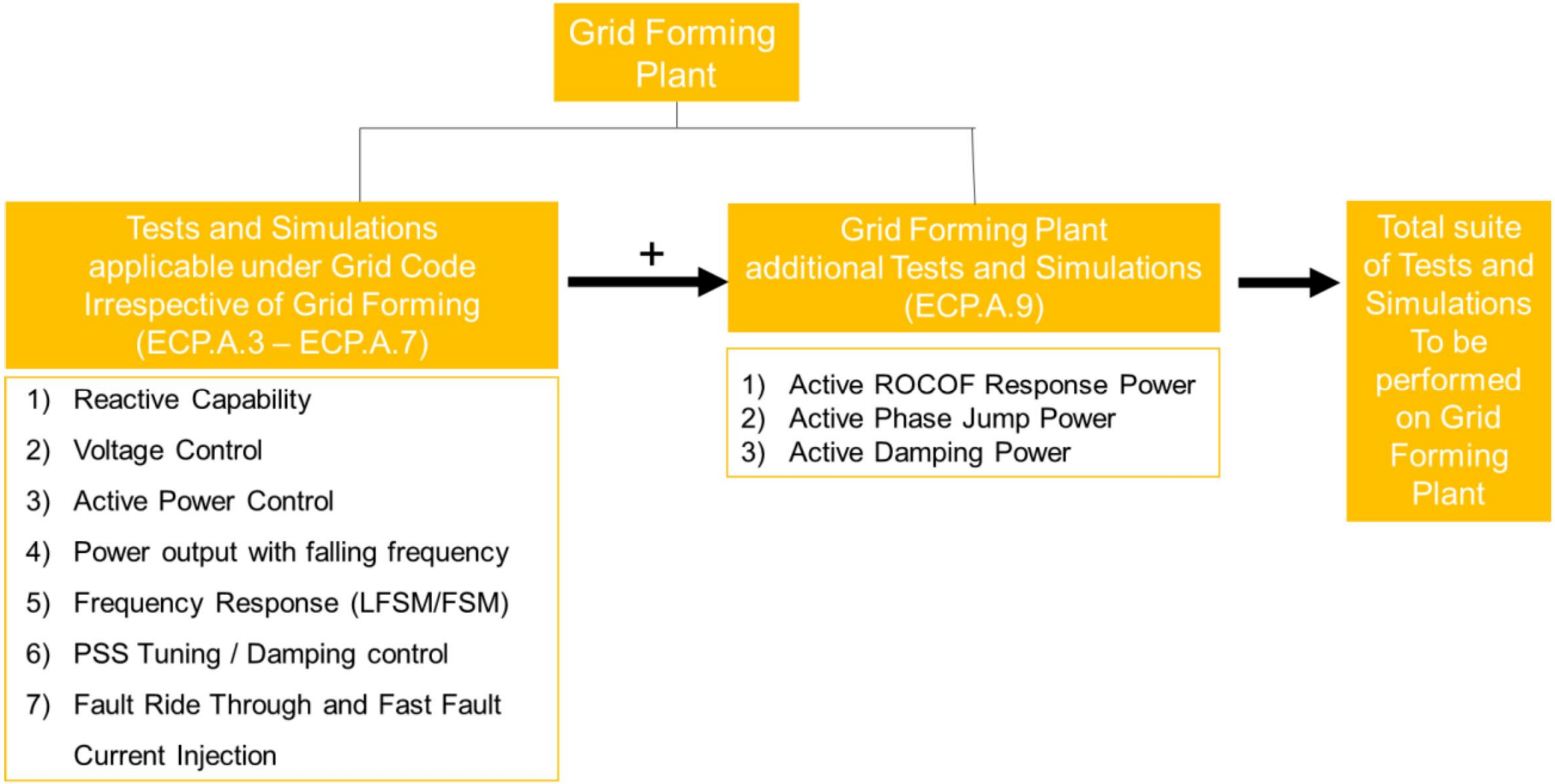
Black Start

Behavior at the current limit

Response to ± ΔMW events

Source: NG ESO, [GC0137 Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability](), Final Modification Report, October 2021

Great Britain Grid Forming Best Practice Guide – Example of Recommended Testing and Verification



Additional tests & simulations for GBGF Plants:

- Testing examples of Active RoCoF Response Power under extreme and full range of system frequencies
- Testing examples of Active Phase Jump Power under normal operation
- Testing examples of Active Damping Power
- Discussion on Phase Jump Angle Withstand Value
- Discussion on the test for Active Phase Jump Power during faulted conditions

Source: NGESO, Great Britain Grid Forming Best Practice Guide, April 2023

Fingrid: Specific Study Requirements for Grid Energy Storage System – Example of Specifications and Testing Requirements

A GFM BESS shall be able to self-synchronize, operate in stand-alone mode and provide synchronization services: synchronizing power, system strength, fault current and virtual inertial response (within current inverter rating)

- When the GFM BESS is reaching the current limit, stability and grid support must still be maintained, switching to GFL mode at the limit is not permitted.
- GFM BESS shall continue providing GFM operational characteristics even at its highest and lowest allowable state of charge.
- GFM shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame, including:
  - Phase jump performance: resist near-instantaneous voltage phase angle sub-transient time frame
  - System strength: resisting the change in voltage in the sub-transient time frame
  - Seamless transition between islanded and grid-connected operation
- Positive damping: GFM shall present a positive resistance to the grid within frequency ranges 0-47 Hz and 53-250 Hz to prevent adverse interactions.

Behavior at the current limit

Response to voltage phase angle step

Response to voltage magnitude step

Islanded Operation

Provide Damping

Source: Fingrid, Specific Study Requirements for Grid Energy Storage Systems, June 2023

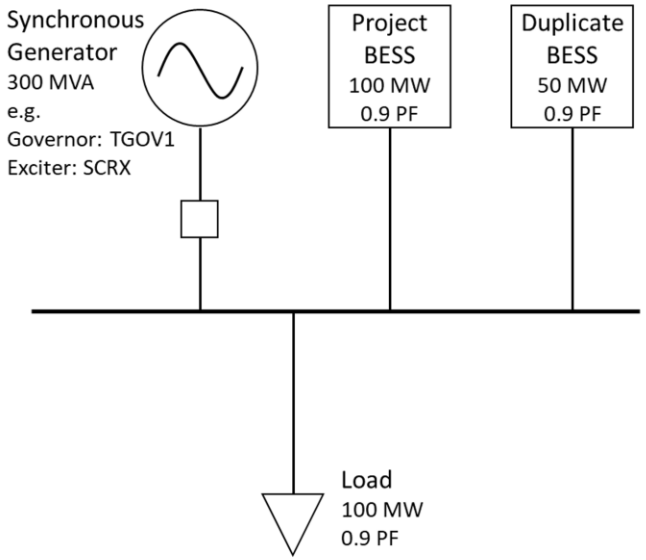
Fingrid: Specific Study Requirements for Grid Energy Storage System – Example of Specifications and Testing Requirements

Counter Unbalances

- Voltage balancing: GFM shall provide a closed loop path for unbalanced current to flow
- Additions to active power control and frequency control requirements
- Additions to voltage control and reactive power control requirements
- Required simulation studies: a table with the list of disturbances to be tested & acceptance criteria, simulation software and BESS operating scenarios (prescribed values of SOC, P and Q). The list includes **loss of last synchronous generator** in test network model – *similar to HECO & NERC's white paper test and AEMO's requirement*
- Additionally, hardware type test reports are required
- <u>Additional site tests and high-level acceptance criteria: for phase jump, island operation (upstream 110 kV breaker is opened), measurement of power quality</u>
- Monitoring period after grid code tests – 30 days

Source: Fingrid, [Specific Study Requirements for Grid Energy Storage Systems](), June 2023

NERC IRPS, Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems, White Paper – Example of Test Based Requirements



Source: NERC IRPS White Paper (2023)

GFM Model Test System

- ✓ A synchronous generator with simple excitation & governor model
- ✓ A load with active & reactive components
- ✓ GFM BESS model under test
- ✓ Duplicate GFM BESS model, rated at half (MVA and MW) of the model under test

Trip synchronous machine under following conditions:

1. **BESSs Initially Discharging and Ends at Higher Level of Discharging:** Assess GFM BESS performance when operating within limits and in discharging state.
2. **BESS Initially Charging and Ends Discharging:** Assess GFM BESS performance when operating within limits and transitioning from charging state to discharging state.
3. **BESS GFM Performance at Maximum Active Power:** Assess GFM BESS performance when operating at or near limits.

Success Criteria

- ✓ Stable initial conditions, no oscillations, within limits
- ✓ Voltage & frequency settle to stable, acceptable operating point within tolerance of droop & deadband
- ✓ Well damped, well-mannered recovery with no excessive oscillations, all oscillations settled
- ✓ Waveform distortion dissipates
- ✓ Active/reactive power settles according to demand and droop characteristic

Planned Specifications – Example ERCOT

- Recent notable disturbance events (in 2021 and 2022) have indicated reliability risks.
- ERCOT focuses on improvements IBR capabilities and performance and strengthening of the grid – both are needed to maintain the reliable operation.
  - Adoption of NERC Reliability Guidelines, IEEE 2800 ride through requirements
  - Recommendation of synchronous condensers to strengthen West Texas grid
- ERCOT has 17.5 GW of committed batteries in the interconnection queue (out of 111.6 GW requests)
- Conducted a preliminary study on benefits of grid-forming batteries in West Texas.
- Study showed that, while GFM batteries cannot solve all the issues, but
  - Can improve system dynamic response in weak grids and support GFL IBRs in resource-rich areas
  - Still require proper control settings and coordination
- Next steps: development of grid-forming requirements for batteries including but not limited to performance, models, studies, and verification.

Source: Adopted from ERCOT's Preliminary assessment of Grid Forming Inverter-based Energy Storage Resources in the ERCOT Grid ERCOT IBRWG, August 2023

Voluntary Requirements – Market Incentives?

- Great Britain – Stability Pathfinder, Phase 2 in 2022 awarded five GFM Batteries, GC0137 GB Grid Forming Requirements apply.
- National Grid ESO followed with development of Stability Market Design, developing eligibility rules, contract structures, procurement strategies for the future stability market. Mid-term stability market is expected to launch in 2023.
- In December 2022, Australian Renewable Energy Agency backs eight grid-scale GFM BESS, $2.7B
- AEMO has minimum system strength requirements in certain areas (not yet incentivizing GFM BESS)
- Fingrid only allows GFM BESS to build in weak grid areas, ERCOT proposed a similar idea in their Dynamic Stability Assessment of High Penetration of Renewable Generation in 2018.

Conclusions

- If IBRs are built with grid-forming controls, stability can be provided by the resource itself, the need for additional mitigation can be greatly reduced, and higher share of IBRs (up to 100%) achieved.
- Grid code requirements and/or market products are needed for grid-forming IBRs to be deployed in an efficient and timely manner.
- It took 20 years in Europe to develop grid codes for present-day IBR technology, while the U.S. still does not have harmonized grid codes. **We do not have another 20 years to develop requirements of grid-forming IBRs!**
- There have been a number of activities in the U.S., Europe, and Australia in the past three years to accelerate the deployment of grid-forming IBRs.
- However, the challenge is broad and global. Much more work is needed — and quickly — to seize this window of opportunity and deploy grid-forming controls at lest on BESSs next in line to be connected to the grid.