A Global Update on GFM Projects and Specifications

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Outline

- Background information, please refer to the last year's ESIG webinar here
- What is "grid forming"? Potential use-cases for grid forming capability
- Grid forming specifications and testing landscape at glance
- Deeper dive into some grid forming specifications and testing
- Grid forming requirements vs incentives
- Grid forming BESS projects built and under construction
- Conclusions

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

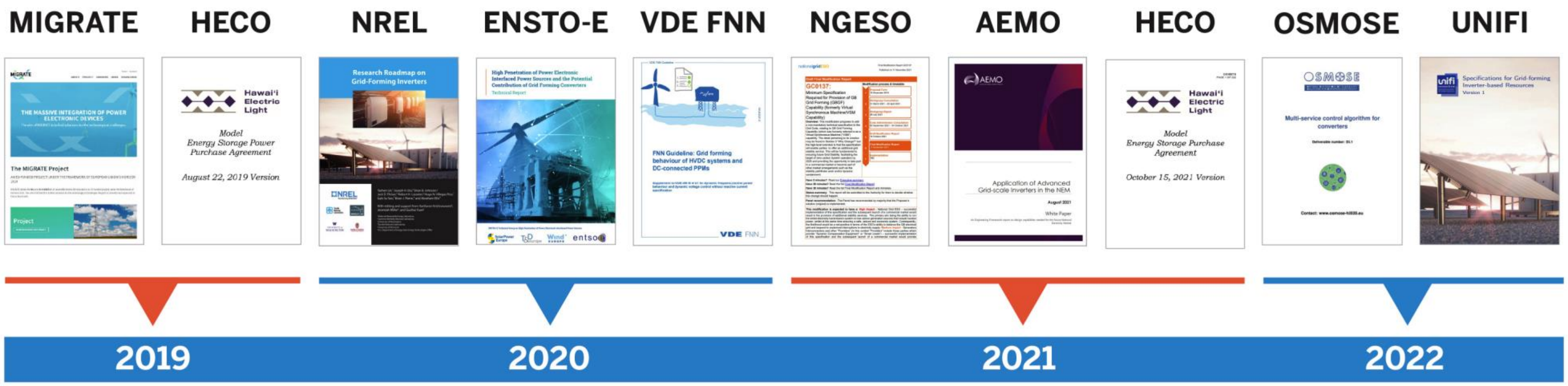
Potential Use-Cases for Grid Forming Controls

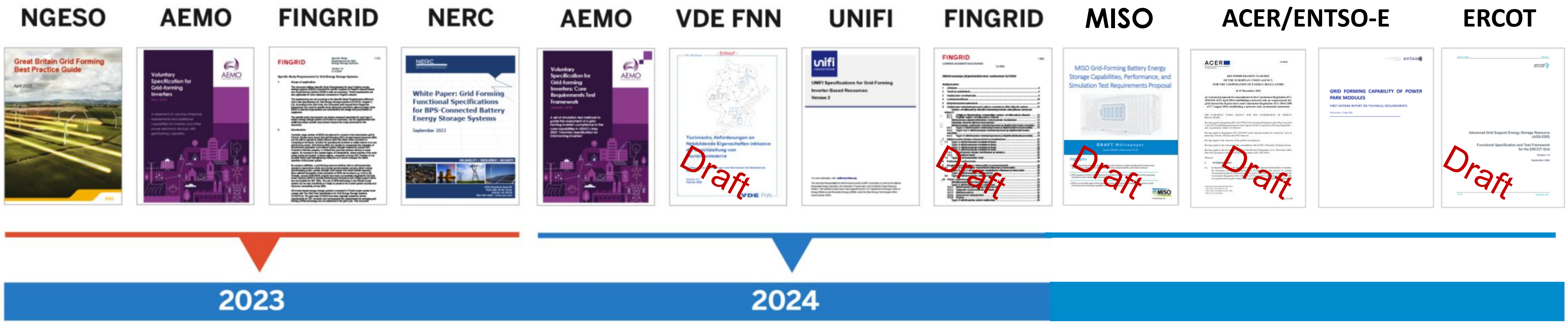
- Weak grid operation
- Damping of voltage and frequency oscillations
- Resisting voltage phase angle change (phase jump response)
- Resisting frequency change / limiting RoCoF (substituting/supplementing inertial response of synchronous generation)
- Fast fault current injection (balanced and unbalanced)
- Mitigation of sub-synchronous control interactions
- Support of islanded operation (when required)
- Black start (when required)

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

Grid Forming Testing and Specs Landscape At Glance

Links to all these specification documents can be found here





This presentation contains presenter's interpretation of the requirements, please refer to original documents for exact specifications

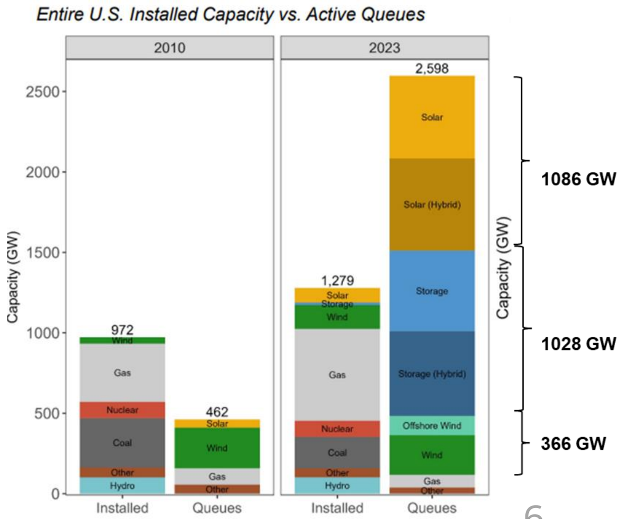
Grid Forming Testing and Specs Landscape, cont.

	System Operator or Regulatory Body	Research Orgs or Industry WGs
Published	• NG ESO GC & Guide • FNN VDE • HECO • AEMO • Fingrid	• MIGRATE / OSMOSE • UNIFI V.2 • NERC IRPS
Draft	• ACER/ ENSTO-E RfG 2.0 • ERCOT • MISO	
Planned	• AESO • IESO • Florida Power & Light	• CIGRE JWGB4/C4.93 • IEEE SA

The table is not exhaustive but provides some examples

- High level vs detailed functional specifications
- Functional specifications vs test-based vs both
- Split into “core” & advanced capabilities vs not split
- Voluntary vs mandatory
- In addition to existing GFL req., unless conflicts
- For all types of resources vs all IBRs vs just BESS

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
- Limiting of RoCoF
- Active Power Sharing
- Behavior at the current limit
- Counter Unbalances
- Counter Harmonics
- Provide Damping
- No Control Interactions/ Interoperability
- Low system strength operation
- Islanded Operation & Re-synch
- Surviving Loss of Last Synch Machine
- Black Start

Response to Voltage Phase Angle Step / Phase Jump

- Voltage phase angle jump response is expected by definition of grid forming
- Nearly-instantaneous active power response to a voltage phase angle step at a POI, by injecting or absorbing power to oppose the change in voltage phase angle. (AEMO, NESO, Fingrid, NERC, UNIFI, ERCOT, MISO, ENTSO-E RfG 2.0, VDE FNN)
- Initial response time < 5 ms (NESO, AEMO with a reference to NESO) or within a few ms (Fingrid)
- Full (Fingrid) or 90% (AEMO, MISO, ERCOT, VDE FNN) response in one cycle (ERCOT), or in < 10 ms (Fingrid*, VDE FNN) or in < 15 ms (AEMO, MISO)
- The relevant system operator in coordination with the TSO shall specify the temporal parameters of the dynamic performance regarding voltage stability (ENTSO-E RfG 2.0)
- A 60 degrees Phase Jump Angle Withstand capability is required (NESO)

* Note: In Fingrid's BESS studies document, full response time is just a recommendation and is removed in the Fingrid's grid code modification draft

Source: "Requirements and verification procedures for gridforming units – the German approach to ensure power system stability under very high penetration of inverter-based sources", presented by K. Malekian, E. Quitmann (Enercon), T. Bülo (SMA), J. Massmann (Amprion), M. Schmieg (DigSilent), C. Wulkow (VDE FNN), 23rd Wind & Solar Integration Workshop, Helsinki, Finland, October 8-11th

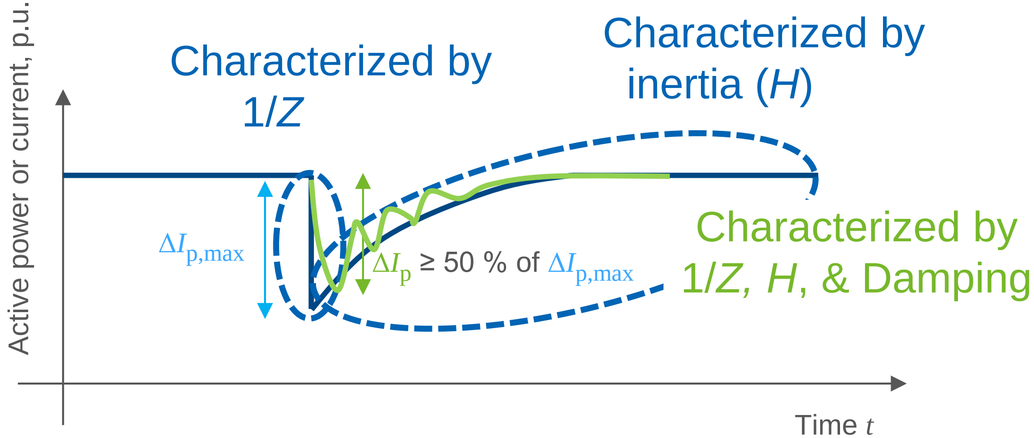
Technical requirement: Active power and current contribution in a phase angle jump

A voltage angle jump ($\Delta\theta$) should result in:

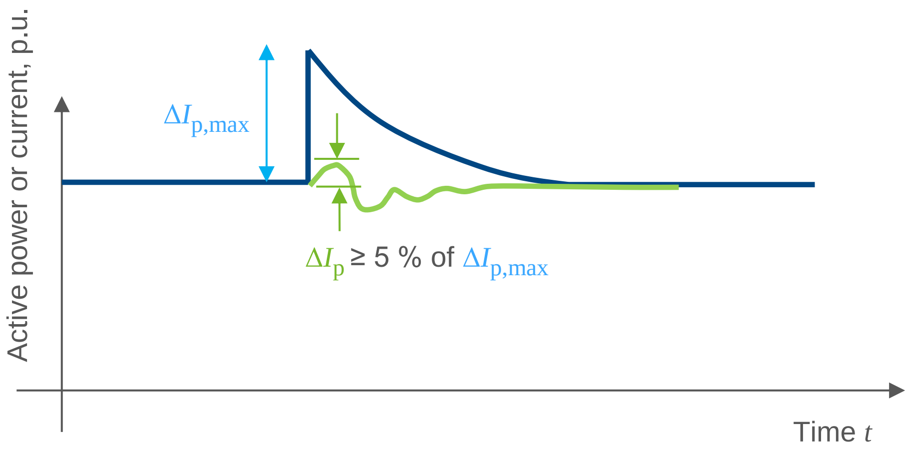
- an active current change ΔI_p of 50 % of theoretical value $\Delta I_{p,max}$ based on maximum impedance or at least in an active power change of 45 % P_{Emax} in the offered direction of inertia
- an active current change ΔI_p of 5 % of theoretical value $\Delta I_{p,max}$ based on maximum impedance or at least in an active power change of 5 % P_{Emax} in the not-offered direction of inertia

$$\Delta I_{p,max} = -\sin(\Delta\delta)/Z_{max} \quad \text{in p.u.}$$

Voltage angle jump in the **offered direction** of inertia (this case: negative inertia)

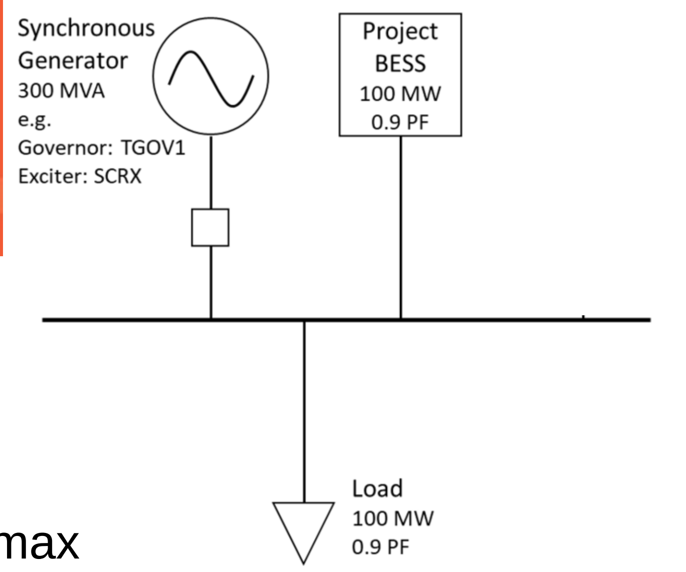


Voltage angle jump in the **not-offered direction** of inertia



The calculated effective impedance in case of a phase angle jump is not expected to be the same as the effective Impedance in case of a voltage amplitude change.

Phase Jump Test (AEMO, MISO, ERCOT, Fingrid)



Test setup is used with the following conditions

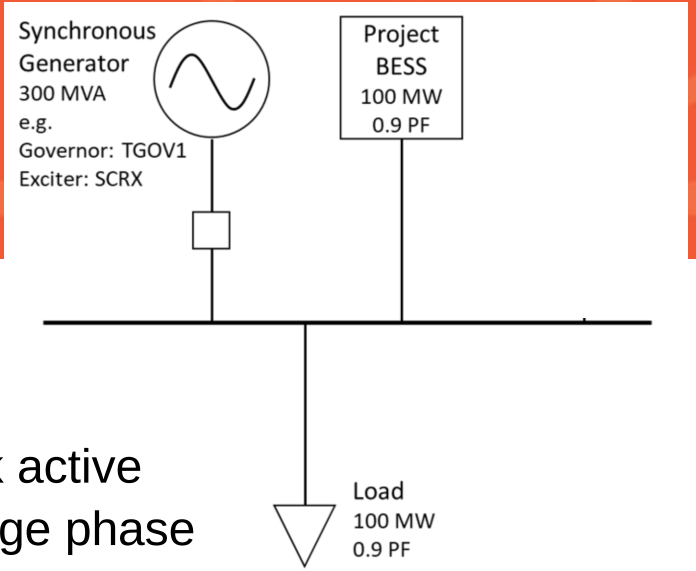
- SCR = 3, system equivalent X/R=6.
- Initial dispatch is generating with 50% of nominal power (AEMO, MISO); or max discharging with approximately zero reactive power (ERCOT); or various combinations of SoC, power output levels, at ESCR and maximum SCR level (Fingrid).

Test Sequence

1. Angle of the voltage source behind the equivalent grid impedance is decreased instantaneously by 10 deg (AEMO, MISO, ERCOT, Fingrid).
2. A few seconds later, angle of voltage source is increased by 10 deg (AEMO, MISO, ERCOT, Fingrid).
3. Repeat 1 and 2 with +/- 25-deg change (MISO, ERCOT) or +/- 30-deg (AEMO, Fingrid).
4. Repeat 1 and 2 with a +/- 60-deg change (AEMO).

- NESO Best Practice guide recommends tests from +/-5 to +/-50 deg (in 5 deg steps)

Phase Jump Test (AEMO, MISO, ERCOT, Fingrid)



Success Criteria

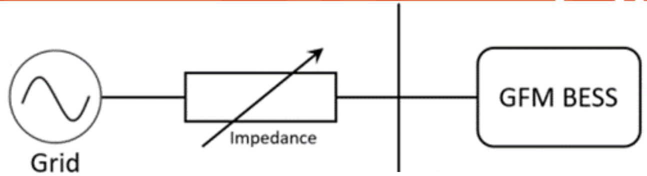
- Instantaneous active power response to oppose the angle change, with peak active power change of at least 0.2 pu (of rated active power) for each 10-deg voltage phase angle change, if current limit allows (ERCOT).
- For each of the 10-deg voltage phase angle jump, response time to 90% of initial change in instantaneous active power should occur within one cycle (ERCOT) or 15 ms (AEMO, MISO) or full response within <10 ms (Fingrid).
- Active power settles to pre-disturbance level shortly after each phase jump (AEMO, MISO).
- If active power / current reaches limits for the 60 deg phase change, the plant should return to pre-event power levels in a stable manner (AEMO).
- Any oscillation shall be settled (AEMO, ERCOT, MISO).
- Any distortion observed in phase quantities should dissipate over time (AEMO, MISO).

Response to voltage magnitude step

- Voltage step response is expected by definition of grid forming
- Nearly-instantaneous reactive current response to an external voltage magnitude step, to oppose the change in voltage (AEMO, NESO, Fingrid, NERC, UNIFI, ERCOT, MISO, ENTSO-E RfG 2.0, VDE FNN).
- Initial response time < 5 ms (NESO, AEMO with a reference to NESO) or within few ms (Fingrid)
- Full (Fingrid) or 90% response in one cycle (ERCOT) or in < 10 ms (Fingrid*, VDE FNN) or in < 50 ms depending on the nature of the event (MISO)
- The relevant system operator in coordination with the TSO shall specify the temporal parameters of the dynamic performance regarding voltage stability (ENTSO-E RfG 2.0).

* Note: In Fingrid's BESS studies document, full response time is just a recommendation and is removed in the Fingrid's grid code modification draft

Voltage Step Test (ERCOT, Fingrid)



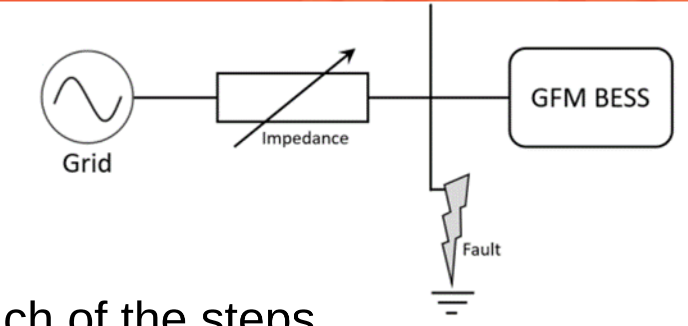
Test setup is used with the following conditions

- Z_{th}=0 and BESS is at max discharging with approximately zero reactive power (ERCOT)
- SoC at 50 %, P = 0 MW, Q = 0 Mvar, at grid's X/R and VCSCR (Fingrid)

Test Sequence

- The magnitude of the voltage source is changed instantaneously by +/-3% (i.e., from 1.0 pu to 0.97 pu, to 1.0 pu and then to 1.03 pu) (ERCOT) or +/-2% (Fingrid) with a few seconds between the tests.

Voltage Step Test (ERCOT, Fingrid)



Success Criteria

- Instantaneous reactive power response to oppose the voltage step for each of the steps (Fingrid, ERCOT), with an initial peak reactive power change of at least 0.03 pu on the rated power base. Reactive power does not return to the pre disturbance level within 6 cycles (ERCOT).
- Response time to 90% of initial change in instantaneous reactive power should occur within 1 cycle (ERCOT) or 1±0.1s (Fingrid*).
- Any oscillation shall be damped.
- The final reactive power after each 3% step change is expected to reach to the maximum reactive capability of the plant in an attempt to regulate the original voltage set point at 1.0 pu. (ERCOT)

* Note: In Fingrid's BESS studies document, full response time is just a recommendation and is removed in the Fingrid's grid code modification draft

Voltage Step Test, cont. (Fingrid)

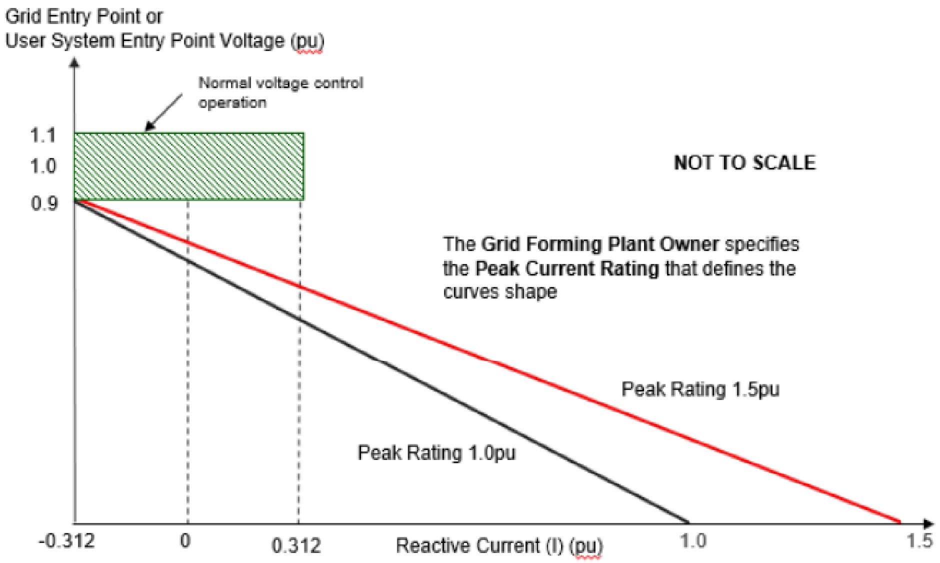
- Voltage magnitude change ± 10%, carried out at ESCR and minimum SCR levels. Tested at various combinations of SoC and output levels:
  - A1 - SoC at energy buffer minimum level (i.e. 5 % where the battery can still supply power), P = 0 MW, Q = 0 Mvar
  - B1 - SoC at 50 %, P = Pmax,p, Q = Qcap-max
  - B2 – SoC at 50 %, P = 0 MW, Q = 0 Mvar
  - B3 - SoC at 50 %, P = Pmax,p, Q = Qind-max
  - B4 – SoC at 50 %, P = Pmax,p, Q = 0 Mvar
  - B5 – SoC at 50 %, P = Pmax,d, Q = 0 Mvar
  - C1 – SoC at energy buffer maximum level (i.e. 100 %), P = 0 MW, Q = 0 Mvar
- Combination of 100 ms 3-ph fault, voltage magnitude change from 1 pu to 0.9 pu and phase jump +20 deg. Tested at SoC at 50 %, P = 0 MW, Q = 0 Mvar. Success Criteria: GFM BESS shall ride through the event.

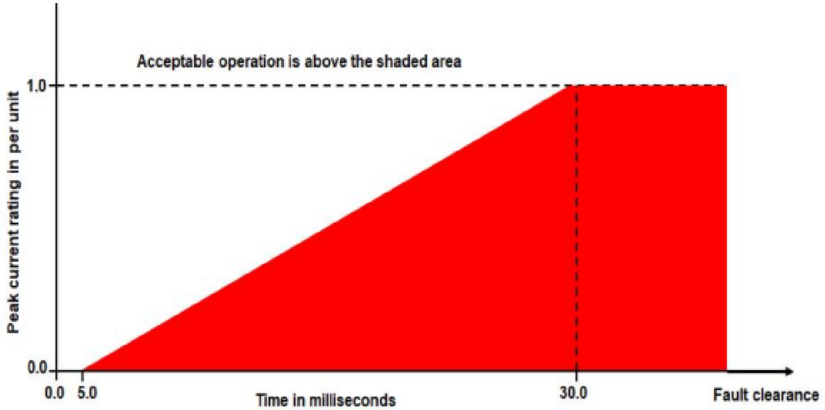
Voltage Magnitude and Phase Step Site Test (Fingrid)

- A change in voltage magnitude and phase is introduced **by changing grid topology** (e.g. disconnection of a line) in the main grid by Fingrid or the DSO.
- Acceptance criteria: the GFM BESS is required to perform as defined in GFM specifications (i.e. nearly instantaneous response opposing the change, stable and well damped),
- The phasor domain transient and EMT models shall be validated by repeating the test with corresponding simulation scenario.

Fast Fault Current Injection (NESO)

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) (NESO)





Limiting RoCoF

- RoCoF limiting response is expected by definition of grid forming.
- 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) (AEMO, NESO, NERC, MISO,ERCOT, VDE FNN; UNIFI and Fingrid though not explicitly calling for inertia)
- Initial response time < 5 ms (NESO, AEMO with a reference to NESO) or within a few ms (Fingrid)
- Full response in < 10 ms (Fingrid*)
- ENTSO-E RfG2.0 has a similar requirement for overfrequency for Type B PPMs and both over and under-frequency for Type B storage and Type C & D PPMs. For Type C and D, the relevant TSO may require the provision of additional energy beyond the inherent energy.
- The relevant system operator in coordination with the TSO shall specify the temporal parameters of the dynamic performance regarding voltage stability (ENTSO-E RfG 2.0).

* Note: In Fingrid’s BESS studies document, full response time is just a recommendation and is removed in the Fingrid’s grid code modification draft

Limits for Thresholds for Type B, C and D _ower-Generating Modules in ENTSO-E RFG

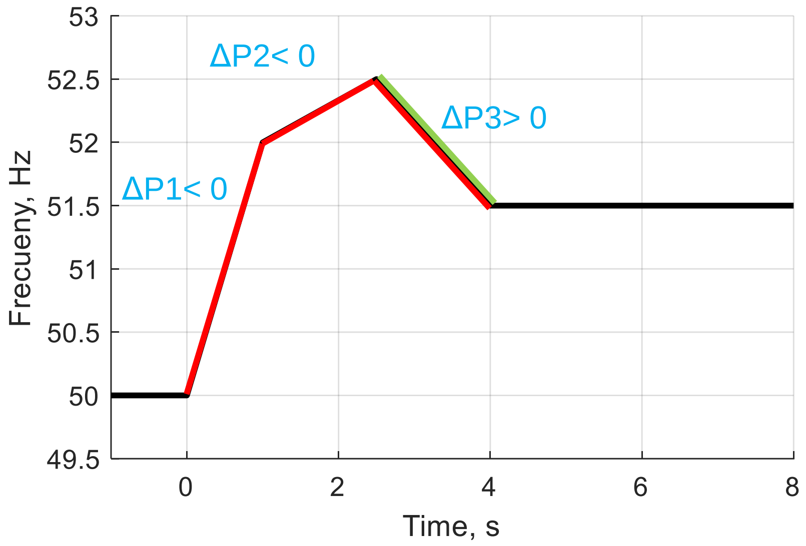
Synchronous areas	Limit for maximum capacity threshold from which a power-generating module is of Type B (<110 kV)	Limit for maximum capacity threshold from which a power-generating module is of Type C (<110 kV)	Limit for maximum capacity threshold from which a power-generating module is of Type D (≥ 110 kV)
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1,5 MW	10 MW	30 MW
Ireland and Northern Ireland	0,1 MW	5 MW	10 MW
Baltic	0,5 MW	10 MW	15 MW

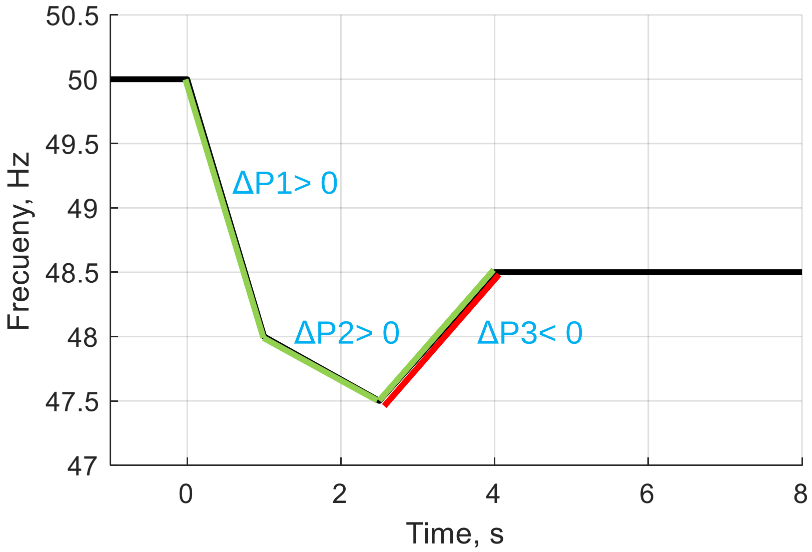
Connection point below 110 kV and maximum capacity of 0,8 kW or more – Type A;

Limiting RoCoF, cont.

- 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). (AEMO)
- Larger headroom and energy buffer can be defined (AEMO as advanced capability)
- The RoCoF response power is assessed for 1Hz/s, while RoCoF withstand capability is requested up to 2 Hz/s (NESO)
- 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. (NESO)

Technical requirement: Maintenance of the inertia (Ta)





ΔP [% P_n] = - $T_a \cdot$ (RoCoF / $f_n \cdot$100%)

ΔP ~ - ($T_a \cdot$ RoCoF)

Hidden requirement for $T_{a,max}$

Based on the energy buffer of the unit (E_{max}), this results in an upper energy limit for T_a.

The system should be able to pass through these RoCoF curves without restricting the effective T_a (i.e. 2H)

Positive Inertia

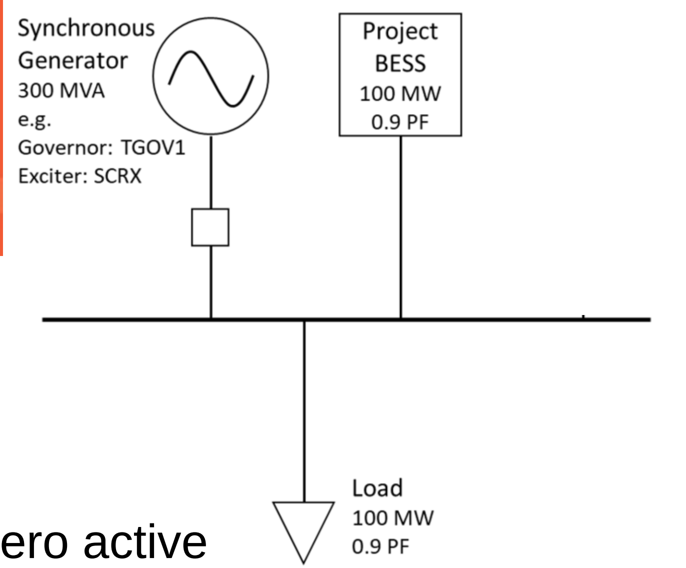
Negative Inertia

"Official" range for offered T_a:
$T_{a,min}$ = 0 (H_{min}= 0 s)
$T_{a,max}$ = 25 s (H_{max}= 12.5 s)

Important note: Whether the $P(f)$ controller (P-f characteristic) is activated or deactivated when riding through is up to manufacturers.

Source: "Requirements and verification procedures for gridforming units – the German approach to ensure power system stability under very high penetration of inverter-based sources", presented by K. Malekian, E. Quitmann (Enercon), T. Bülo (SMA), J. Massmann (Amprion), M. Schmieg (DigSilent), C. Wulkow (VDE FNN), 23rd Wind & Solar Integration Workshop, Helsinki, Finland, October 8-11th

RoCoF Test (AEMO, MISO, ERCOT, Fingrid)



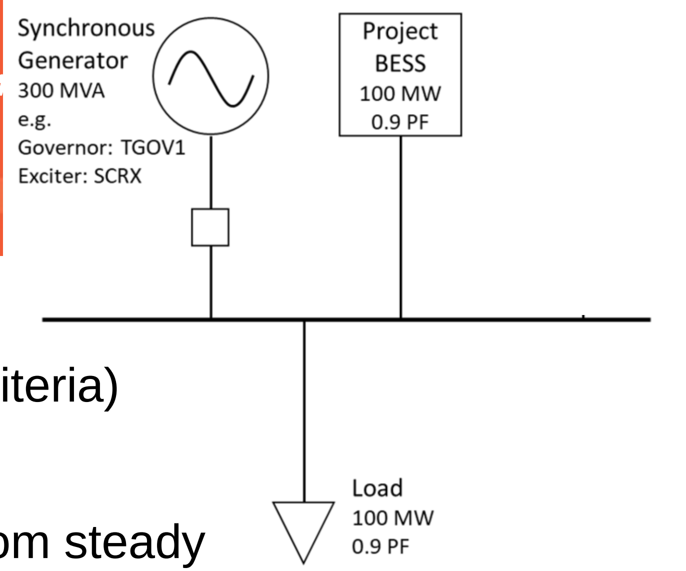
Test setup is used with the following conditions

- SCR = 3, system equivalent X/R=6. (AEMO, MISO, ERCOT)
- Initial dispatch is generating with 50% of nominal power (AEMO, MISO) or zero active power output with approximately zero reactive power (ERCOT)
- SoC at 50 %, P = 0 MW, Q = 0 Mvar (Fingrid)

Test Sequence

- Ramp frequency by +/-1 Hz from nominal at RoCoF=4 Hz/s (AEMO, MISO) or at RoCoF=1 Hz/s (ERCOT) or at RoCoF=0.1 Hz/s (Fingrid) stay at each frequency for 5 s (AEMO, MISO) or 2 s (ERCOT)
- Ramp frequency -1 Hz from nominal and back at 0.24 Hz/s (Fingrid)
- Ramp frequency -1 Hz from nominal at 2 Hz/s (Fingrid)

RoCoF Test, cont. (AEMO, ERCOT, MISO, Fingrid)



Success Criteria (same for ERCOT, AEMO, MISO, Fingrid has higher level criteria)

- Plant active and reactive power output should be well controlled.
- System frequency and voltage should not oscillate excessively or deviate from steady state levels for any significant amount of time.
- Voltage settles to a stable operating point when frequency is not ramping.
- Active power should settle according to its frequency droop and deadband settings when frequency is not ramping.
- Any oscillation shall be adequately damped
- The equivalent inertia constant should be greater than 2.5 s, $H \approx 60 * \Delta E$ [s], where: ΔE is the area under the per unit active power production of the BESS from *0* to *0.5* s, when the RoCoF is 1 Hz/s and nominal frequency is 60 Hz. (only ERCOT)

Active Power Sharing

- Active power sharing (through droop type of response) comes across **in all specifications** in frequency response requirements (also applied to GFL IBRs), island operation requirements and loss of last synchronous machine requirement / tests.
- A GFM IBR is expected to autonomously share power (e.g., incrementally increase or decrease power burden within its capability) with other generation resources using the principles of droop akin to the operation of conventional synchronous generators or GFL IBRs (UNIFI)

Behavior at the Current Limit

- All specs by definition of GFM require
  - Inherent (not control-based), nearly-instantaneous current injection in response to faults, voltage magnitude and phase angle jumps, frequency events etc. with characteristics (active/reactive, injection/absorption) opposing the change on the grid.
  - Responses are expected **within equipment limits**,
- Some specifications explicitly comment on benefits, if additional current and energy headroom is available (e.g. AEMO, ERCOT, NESO, ENTSO-E leaves it to relevant TSOs to specify any additional current requirements).
- Only very high-level guidance about expected behavior at the limit
- Some requirements have explicit section on the behavior at the current limits, others have it included in respective response requirements.

Additional Specifics of Behavior at the Current Limit in Various Codes

- The IBR plant shall be capable of stable operation when reaching current limits, without interruption, in a continuous manner and returning to GFM response as soon as the limitations are no longer active. (ENTSO-E RfG 2.0, MISO, AEMO, VDE FNN, ERCOT and Fingrid have similar req.)
- The GFM IBR should provide a magnitude and duration for IBR short-term rated current (ISRC), e.g., “provides 1.5 times full-rated current for 2 s”. This value can also be programmable. (UNIFI, NESO, AEMO in advanced capability)
- Operation Under System Unbalance: If the provision of large amounts of negative sequence current introduces stress to equipment, reduction or limitation of the magnitude of the current may be allowed after discussion with the system operator. In such a case, a negative sequence current limit may be imposed besides the total current limit. (UNIFI)
- The current shall not be artificially limited below the true capability of the equipment (Fingrid).
- Mode switching at the limit is not allowed (Fingrid, MISO) / not recommended (NESO)

Additional Specifics of Behavior at the Current Limit in Various Codes

- If an inverter initially operating at a limit is subject to a disturbance that would move it away from the limit, that response should be near instantaneous, and smooth (AEMO, ENTSO-E RfG 2.0, MISO, VDE FNN)
- A minimum Phase Jump Angle Limit, to remain in linear control (no hitting current limits), of 5 deg is recommended. Maximum RoCoF Limit, to remain linear control of 1 Hz/s is recommended. (NESO)
- Response at a limit should also not lead to reduced harmonic performance, compared with non-limited operation (for example, clipping of current waveforms). (AEMO)
- In case if current limits of the unit are reached a current clipping is to be limited to a duration of less than 40 ms (VDE FNN)
- GFM BESS shall continue providing GFM operational characteristics even at its highest and lowest allowable state of charge (Fingrid)

Counter Unbalances

- Voltage balancing: GFM shall provide a closed loop path for unbalanced current to flow. Additional site tests and high-level acceptance criteria: measurement of power quality (Fingrid)
- GFM IBR should provide positive and negative sequence current to ensure its internally generated voltage remains balanced when in the continuous operation region conditions (e.g., 0.9–1.1. p.u. voltage range and disturbances (AEMO, NERC, UNIFI, Fingrid).
- The GFM IBR should not actively oppose or prevent the flow of negative sequence current for small levels of voltage unbalance (UNIFI, MISO)

Counter Harmonics

- GFM inverter could provide “passive, damping response in the harmonic frequency range” thereby reducing harmonic voltage distortion within the power system (AEMO as advanced capability).

- These harmonic currents could reduce the fundamental frequency current that the GFM inverter injects in response to a phase angle jump or a RoCoF event prior to reaching current limits. The background harmonic levels may need to be considered when sizing a GFM plant for a specified application (AEMO as advanced capability).

- The harmonic distortion of voltage waveforms produced by a GFM IBR should comply with the requirements of the system planner. As a result, a GFM IBR may inject harmonic currents at its point of interconnection to aid in reducing the amplitude of voltage harmonics induced by other power system components. It is not required, that GFM IBRs actively mitigate voltage harmonics emanating from the AC grid side (UNIFI).

Provide Damping

- Damping Active Power (inherent, < 5 ms, response to oscillations), A Damping Factor within a range of 0.2 – 5 is permitted, to be agreed on a site-specific basis (NESO) or
- Damping Factor of ≥ 0.3 for the reactive current response to a step change in grid voltage and ≥ 0.5 for the active current response during grid frequency events (VDE FNN)
- The GFM IBR should present positive / non-negative resistance to the grid within a frequency range of common grid electrical resonances and system disturbances (UNIFI), including from 0 to 300 Hz. (NERC, MISO).
- Following a disturbance GFM IBR output should be adequately damped; add damping to the system for the oscillatory phenomena (AEMO, MISO):
  - SSCI (either between GFL inverters or GFL inverters and the grid)
  - Rotor angle modes of oscillation inter-area modes of oscillation
  - Oscillations at harmonic frequencies which result from interactions of electrical and control resonances.
- A small-signal impedance scan across a wide range of frequencies can be used to evaluate the oscillation damping characteristics of a GFM IBR, which should ideally show an impedance phase angle between -90-degree and +90-degree, at most frequencies from 10 to 500 Hz. (AEMO)

Provide Damping

- 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.
  - Tested through dynamic impedance scan in PSCAD in frequency range 1-250 Hz for various combinations of SOC, power output levels. Acceptance criteria: BESS shall provide positive resistance through the frequency range (Fingrid).
- It is especially important that the GFM BESS shall not reduce damping of 0.2-0.5 Hz interarea oscillation modes.
  - Tested in PSCAD by injecting 0.2-0.5 Hz voltage oscillations at PCC, at SoC at 50 %, P = 0 MW, Q = 0 Mvar conditions. Acceptance criteria: the BESS shall provide positive damping to the oscillation (Fingrid).
- Fingrid's grid code modification draft: BESS shall not amplify grid frequency and voltage oscillations
  - Specific attention shall be given for 0.2-1.0 Hz (dq frame) interarea oscillations, 1-15 Hz (dq frame) voltage oscillations, 15-45 (dq frame) oscillations in resonance region caused by series compensation
  - BESS operation shall be stable in small signal perspective as a part of the power system

Provide Damping

- Type D power park modules shall have a power oscillation damping function which helps to attenuate the power oscillations through the control of the active power, reactive power, or both. The power oscillation damping shall be able to damp inter-area oscillations in the range of, at least, 0.1 Hz – 1.0 Hz **(**ENTSO-E RfG 2.0).

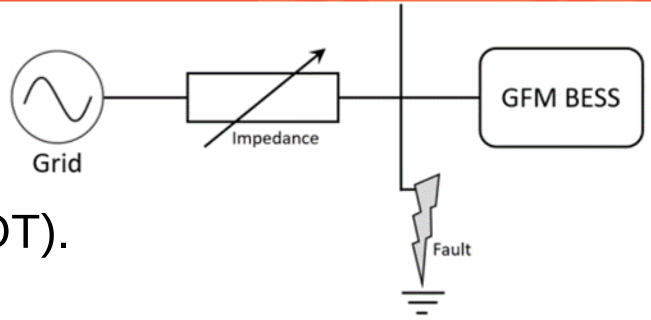
No Control Interactions/ Interoperability

- The GFM IBR should be designed and configured so as not to interact and affect the operation, performance, or capability of other facilities or equipment connected to the electrical system (MISO, NESO).
- The GFM IBR is expected to not introduce any new unstable oscillatory modes into the power system or exacerbate existing oscillatory modes. (UNIFI)
- If GFM BESS is a part of a hybrid power plant, the controls shall be carefully coordinated with the plant-level controls affecting active power, reactive power or voltage so that any adverse interactions are avoided (Fingrid).

Low system strength operation

- Operate stably under a very low short circuit ratio (down to 1.25, 1.2 or 1 in different requirements), as defined by the system operator; provide system strength support to nearby GFL inverters during and after disturbances. (AEMO, UNFI, ERCOT, MISO, VDE FNN)
- In Fingrid's specification a requirement to operate stably under low short circuit ratio is implicit and tested under various short circuit ratio conditions at the perspective connection point, while verifying conformity with other requirements.

SCR Ramp Down with Fault Test (AEMO, ERCOT, MISO)



Test setup is used with the following conditions:

- SCR at the connection point shall be set to 20 (AEMO, MISO) or 10 (ERCOT).
- System equivalent X/R shall be set to 6.
- Initial plant dispatch 100% of continuous rating.

Test sequence

1. SCR at connection point stepped down repeatedly: 10, 3, 2, 1.5, 1.25 (AEMO, MISO) or 10, 5, 3, 1.5, 1.2 (ERCOT)
2. 6-cycle 2 phase-to-ground fault is applied with minimum fault depth of 0.5 p.u. just before each SCR transition. SCR transition to lower level occurs at fault clearing time.

Success criteria

- Plant active and reactive power output should be well controlled and plant should not trip or reduce power for any extended period of time down to the minimum SCR in the test.

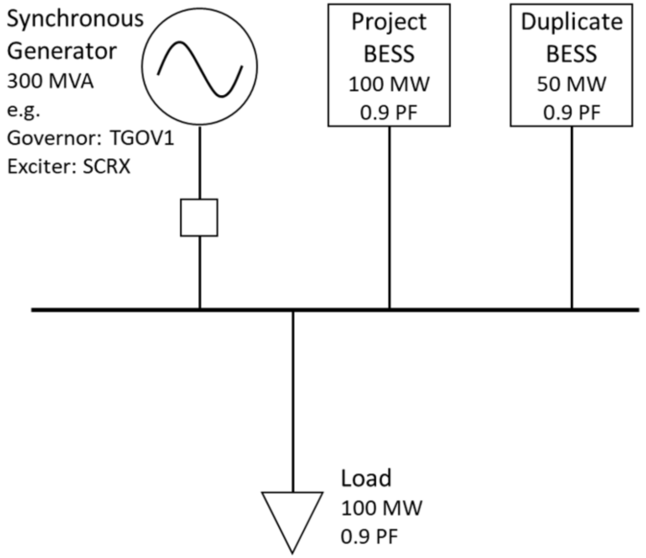
Islanded Operation & Re-synchronization

- Remain stable for a transition from a grid with synchronous machines (SMs) to one without (and back); provide frequency and reactive support, unaffected by these transitions (AEMO).
- Seamless transition between islanded and grid-connected operation is required (if balance of production and loads can be maintained in the island). Help maintain island's nominal voltage and frequency within equipment capabilities. Beyond sub-transient timeframe power sharing with other resources utilizing droop. The response to state change shall be smooth and well damped (UNIFI as additional capability, Fingrid).
- Additional site test, where upstream 110 kV breaker is opened and after some time reclosed. Acceptance criteria: the GFM BESS is required to perform as defined in GFM specifications. The phasor domain transient and EMT models shall be validated by repeating the test with corresponding simulation scenario (Fingrid).

Surviving Loss of Last Synchronous Machine

- Surviving Loss of Last Synchronous Machine (SM): operate stably in a grid without any SMs, when the power balance is reachable within the equipment capability and within the normal voltage and frequency operating ranges (AEMO, Fingrid).
- Other specifications (NERC, ERCOT, MISO, VDE FNN) specify surviving loss of last SM as an ultimate simulation test of GFM capability, and not as actual situation expected in real time operation.

Loss of Last Synchronous Machine Tests (AEMO, MISO, ERCOT, NERC, Fingrid*)



Source: NERC IRPS White Paper (2023)

GFM Model Test System

- 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 SM under various BESS dispatch conditions (e.g. NERC):

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.

Surviving Loss of Last Synch Machine

Success Criteria:

- System frequency and voltage should settle to a stable operating point (ERCOT specifies within 5 seconds) and should not oscillate excessively or deviate from steady state levels and be damped (ERCOT specifies within 10 seconds). (AEMO, MISO, ERCOT, NERC)
- Active and reactive power from each plant should move immediately to meet the load requirement and settle according to its frequency and voltage droop settings. Response time to 90% of initial change in instantaneous active power should occur within one cycle (ERCOT) or 50 ms (AEMO, MISO).
- Any distortion observed in phase quantities should dissipate over time. (AEMO, MISO)
- Voltage does not deviate beyond [0.8, 1.1] pu for longer than 0.1s throughout the test. (AEMO, MISO)

Black Start

- If a unit is designed with black start capability, then it is required to have grid forming capability (NESO)
- GFM inverters may have additional capability to initiate or support a system restart process following a system black event. For this purpose, GFM plants need (AEMO & UNIFI as advanced capability):
  - Sufficient available stored energy to charge the DC link capacitor and energize a part of the grid;
  - High short-term overload capability to supply inrush currents during the energization of transformers and distribution feeders or starting auxiliary motors of conventional synchronous generators;
  - Soft start capability meaning that GFM inverter can ramp its reference voltage from zero to the nominal voltage with any ramp rate, to avoid excessive inrush currents when energizing transformers and transmission lines;
  - A ground reference for a black start path (avoid energizing delta-delta transformer);
  - Reserve sufficient energy or availability of other energy source, to support black start needs when specified;
  - Capability to energize all auxiliary systems necessary to operate the GFM plant, without connection to the grid.

GFM Requirements v.s. Incentives?

- Great Britain – Stability Pathfinder, Phase 2 in 2022 awarded five GFM Batteries, GB Grid Forming Requirements apply to these projects.
- NESO followed up with development of Stability Market Design, developing eligibility rules, contract structures, procurement strategies for the future stability market. Mid-term stability market launched 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 may drive GFM BESS development.
- Fingrid currently 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.
- MISO, ERCOT, Fingrid drafts aim to require GFM capability from all future BESS. ENTSO-E RfG 2.0 from all future Type B-D power park modules
- German Inertia Market, payment for “new” inertia to all resources fulfilling VDE FNN specs, to be implemented in 2025.

German inertia market model (BNetzA's draft)

A market with unlimited volume & fix regional prices* (over 2-10 years) for different product types:

		Minimum availability over a year
1. Positive inertia „Basic Product“	→	30 %
2. Positive inertia „Premium Product“	→	90 %
3. Negative inertia „Basic Product“	→	30 %
4. Negative inertia „Premium Product“	→	90 %

* The regional price for each product is proportional to the offered inertia constant of power plants.

Source: “Requirements and verification procedures for gridforming units – the German approach to ensure power system stability under very high penetration of inverter-based sources”, presented by K. Malekian, E. Quitmann (Enercon), T. Bülo (SMA), J. Massmann (Amprion), M. Schmieg (DigSilent), C. Wulkow (VDE FNN), 23rd Wind & Solar Integration Workshop, Helsinki, Finland, October 8-11th

Meeting the system needs with the help of three pillars

Today — 2025 — 2030

1 TSO-Assets (VINKs)

Goal: Further development of the state of technology of TSO assets and

- Reactive power compensation units will have grid forming properties and short-term storages
- Amprion will build approx. 10 units (with 2,1 GVAr and 15 GWs) contributing towards inertia and system strength until 2030

2 Market based procurement of inertia

Goal: Accelerate the market maturity of generation units, storages and loads with grid forming properties and inertia

- Implementation of a bonus system
- Differentiation between positive and negative inertia
- Close monitoring of procured quantities and delivery levels
- FNN will define technical requirements and verification/compliance procedures

3 Grid Code Requirements

Goal: Contribution from generation units, storages and loads

- Implementation of amended European Guidelines (RfG, HVDC)

Source: "Requirements and verification procedures for gridforming units – the German approach to ensure power system stability under very high penetration of inverter-based sources", presented by K. Malekian, E. Quitmann (Enercon), T. Bülo (SMA), J. Massmann (Amprion), M. Schmieg (DigSilent), C. Wulkow (VDE FNN), 23rd Wind & Solar Integration Workshop, Helsinki, Finland, October 8-11th

Grid-Connected GFM BESS Projects

Project Name	Location	Operator/Utility	MW	Year	Operational (Y/N)
Dalrymple	Australia	AEMO	30	2018	Y
Project #1	Kauai, USA	KIUC	13	2018	Y
Bordesholm	Germany	Versorgungsbetriebe Bordesholm	15	2019	Y
Hornsdale Power Reserve	Australia	AEMO	150	2022	Y
Province Town BESS	USA, MA	Eversource Energy	25	2022	Y
Kauai PMRF	Kauai, USA	KIUC	14	2022	Y
Wallgrove	Australia	AEMO	50	2022	Y
Broken Hill BESS	Australia	AEMO	50	2023	Y
Kapolei Energy Storage	USA, Hawaii	HECO	185	2023	Y
New England BESS	Australia	AEMO	50	2023	Y
Riverina and Darlington Point	Australia	AEMO	150	2023	Y
Blackhillock, Phase 1	Great Britain	NESO	200	2024	N
Victorian Big Battery	Australia	AEMO	300	2024	N
Blackhillock, Phase 2	Great Britain	NESO	100	2025	N
Liddell Battery	Australia	AEMO	500	2025	N
Western Downs Battery	Australia	AEMO	200	2025	N
Blyth Battery	Australia	AEMO	200	2025	N
Bungama BESS	Australia	AEMO	200	2025	N
Lappeenranta BESS	Finalnd	Fingrid	38	2025	N
Kilmarnock South	Great Britain	NESO	300	2026	N
Terang BESS	Australia	AEMO	100	2026	N
Mortlake BESS	Australia	AEMO	300	2026	N
TagEnergy BESS	Australia	AEMO	300	2026	N

Links to the table and additional details on these project is here

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 GFM IBRs!**
- Recently published GFM requirements and specifications agree on high level functionalities needed but detailed requirements and level of specificity still differ widely.
- 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 GFM controls at least on new BESSs.

THANK YOU

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