G-PST/ESIG WEBINAR SERIES

Survey of Grid-Forming Inverter Applications

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For Q&A: Go to slido.com & enter event code to submit your questions.

This presentation is being recorded

ESIG High Inverter-Based Resource Task Force

Objective:

- Develop an understanding of the options for stable operation of future power systems with a very high share of Inverter-Based Resources (wind, solar and storage), and a roadmap for making the transition from the power system of today, working with research organizations, OEMs, and system operators to build a consensus.

White paper:

- "The Role of Grid Forming Technology to Enable Energy Systems Integration"
  - Introduction
  - System Needs
  - Technologies to Serve System Needs
  - Brief Description of Grid Forming Control Methods
  - Characterization of Grid Forming Resources to Support System Needs
  - **International Project References of Grid Forming Applications**
  - Experiences with Interconnection Requirements for Grid Forming Resources
  - Study Tools
  - Future Outlook for Grid Forming Resources

Acknowledgements

- Jason MacDowell, Sebastian Achilles, Sid Pant, Shruti D Rao, GE
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- Andrew Roscoe, Siemens Gamesa Renewable Energy
- Helge Urdal, Urdal Power Solutions
- Gary Custer, Thorsten Bülo, SMA
- And many others!

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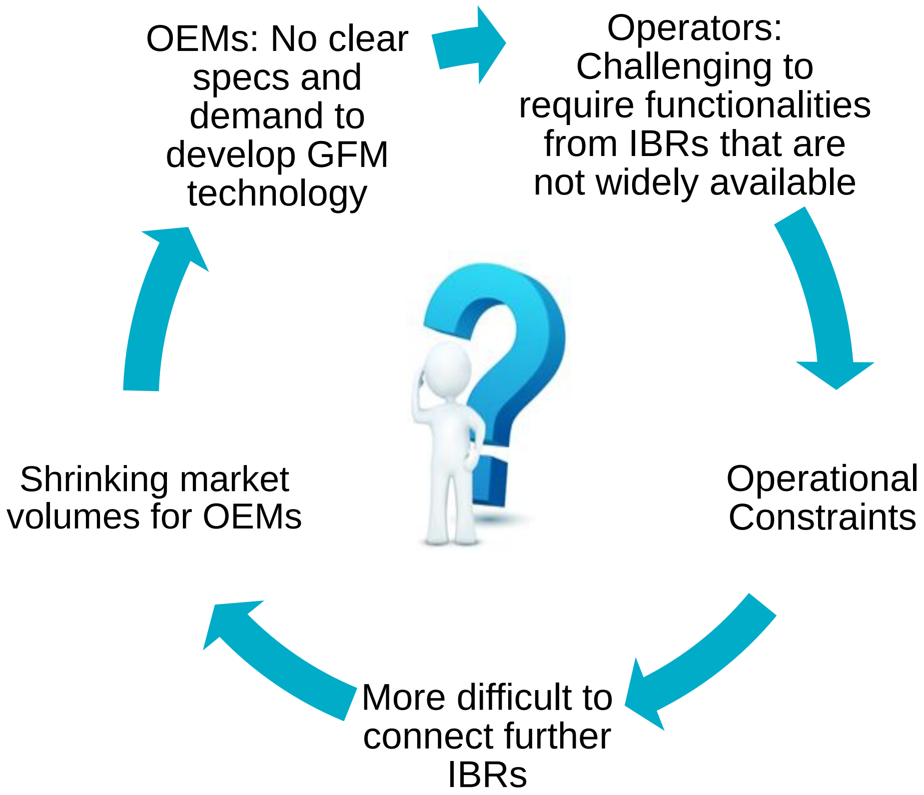
Grid Following vs Grid Forming Definitions

- ***Grid-Following:*** *Most IBRs currently in service rely on fast synchronization with the external grid (termed "grid-following") to tightly control their active and reactive current outputs. If these inverters are unable to remain synchronized during grid events or under challenging network conditions, they are unable to maintain controlled, stable output.*
- ***Grid-Forming:*** *The primary objective of grid-forming controls for IBRs is to maintain an internal voltage phasor. When grid-forming controls are applied in bulk power system (BPS) connected IBRs, the voltage phasor is held constant in the sub-transient to transient time frame. This allows the IBR to immediately respond to changes in the external system and provide stability in the controls during challenging network conditions. This phasor must be controlled to maintain synchronism with other devices and control active and reactive currents to support the grid. When grid-forming controls are applied in non-BPS connected IBRs (for example black-start or microgrids), this synchronization functionality is removed or limited, and the voltage phasor may be held relatively constant over time. This allows the plant to operate in an electrical island and define the grid frequency.*
- *There are many variations of both grid-forming and grid-following converter 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.*

Circular Problem



Examples of Islanded or Weakly Interconnected Systems	Max Instantaneous Penetration (IBR/Demand)
Ireland	95%
Tasmania	92%
ERCOT	66%
South Australia	150%

Solutions: Pilot/Test Projects in the field or interconnection requirements based on system needs (ahead of widely available technology)

Handful of Pilots/Test Projects Around the World and First Interconnection Requirements for GFM

- Number of BESS for microgrids and black start of simple cycle gas turbines (GE)
- BESS on St Eustatius island (SMA)
- Dersalloch Wind Farm in Scotland (Siemens Gamesa)
- Dalrymple BESS in South Australia (Hitachi ABB)
- Hornsdale BESS in South Australia (Tesla)
- Drivers behind GFM Trails in Australia
- Stability Pathfinder in Great Britain (National Grid ESO)
- Proposed (non-mandatory) Grid Forming Interconnection Requirements in Great Britain (National Grid ESO)

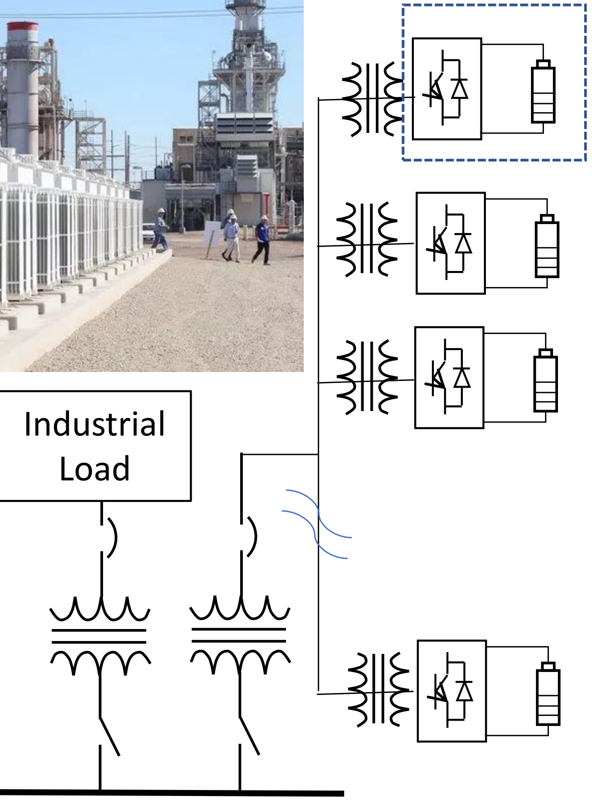
If you know of other practical examples and bulk grid applications please reach out to julia.matevosyan@ercot.com

GE Grid Forming BESS for Black Start

Key GFM BESS Projects:

- Metlakatla Power & Light 1MW/1.4MWh-1995
- Vernon CA 5MW/2.5MWh- 1996
- Battery Energy Storage System of 30MW/22MWh- IID for GT blackstart, 2017
- Black start of simple cycle HDGT with 7.5 MW x 7.5 MWh BESS, 2019
- Black start of combined cycle HDGT with 13 MW x 13 MWh BESS, 2020
- DOE SETO project – Advanced Grid Forming Inverter Controls, Modeling and System Impact Study for inverter dominated grids, started 2020

30 x 1.25MVA



Imperial Irrigation District (IID) 30MW, 20MWh BESS project -2017

Source: Shruti D Rao, Sudipta Dutta, Min Lwin, Dustin Howard, Ryan Konopinski, Sebastian Achilles, Jason MacDowell, “Grid-forming Inverters –Real-life Implementation Experience And Lessons Learned”, IET RPG 2021

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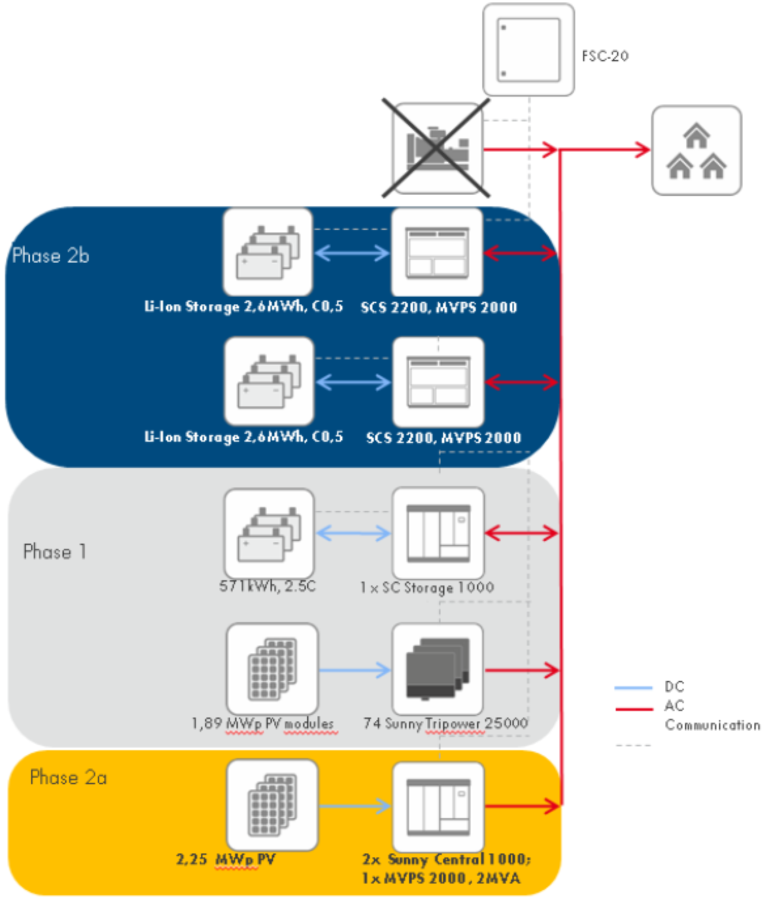
Microgrid example: St. Eustatius

Commercial Pilot deployed in November 2017

- 2.3 MW peak load, 14 GWh yearly energy consumption
- 9 diesel gensets 4 MVA, 4.15 MW PV, 5.9 MWh Li-Ion BESS 2/3 with GFM
- Plant controller sends start/stop signals to gensets, does frequency and voltage control during genset-free operation, transfers frequency and voltage control to the genset controller while the gensets are running
- Load distribution between several parallel GFM units (no communication)
- Diesel-off mode (100% Storage + Solar)
- Seamless immediate load transfer after generation contingency (simultaneous loss of all gensets at peak load), 0.6 Hz frequency dip, restored within 3 s, no load shedding.
- Voltage ride-though for various faults and operating modes.



Source: https://www.smainverted.com/st-eustatius-100-solar-power-in-the-caribbean/
O. Schömann, T. Bülo, C. Hardt, A. Falk, P. R. Stankat "Experiences with Large Grid Forming Inverters on the Island of St. Eustatius, Portability to Public Power Grids", 8th Solar Integration Workshop, 2018

Testing Existing Siemens-Gamesa Wind Turbines in GFM Mode: Grid-Connected Operation

23 direct-drive full converter wind turbines, 69 MW, operated in GFM mode for 6 weeks (May – June 2019) in Dersalloch, Scotland.

- Virtual Synchronous Machine control method used.
- Various inertia constants tested during the trail H=0.2s, 4s and 8s.
- Six large underfrequency events with RoCoF up to 0.11 Hz/s and frequency drop up to -0.5 Hz.
- Additionally, large frequency event was induced with RoCoF=-1 Hz/s, Δf=-3 Hz, H=8 s.
- No significant grid voltage phase steps occurred but small steps were induced (up ~0.2°).
- The wind power plant was able to respond to the events autonomously and immediately with power injections as expected with the inertia levels configured.
- No turbine trips due to stalling, over-power, over-current etc. during the grid events.

Limitations:

- Turbine's ability to respond may be effected if wind speed is declining during the response.
- Turbines ability to respond at low or zero power output is extremely low.

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Source: A. Roscoe, et.al. "Practical Experience of Operating a Grid Forming Wind Park and its Response to System Events, 18th Wind Integration Workshop, 2019

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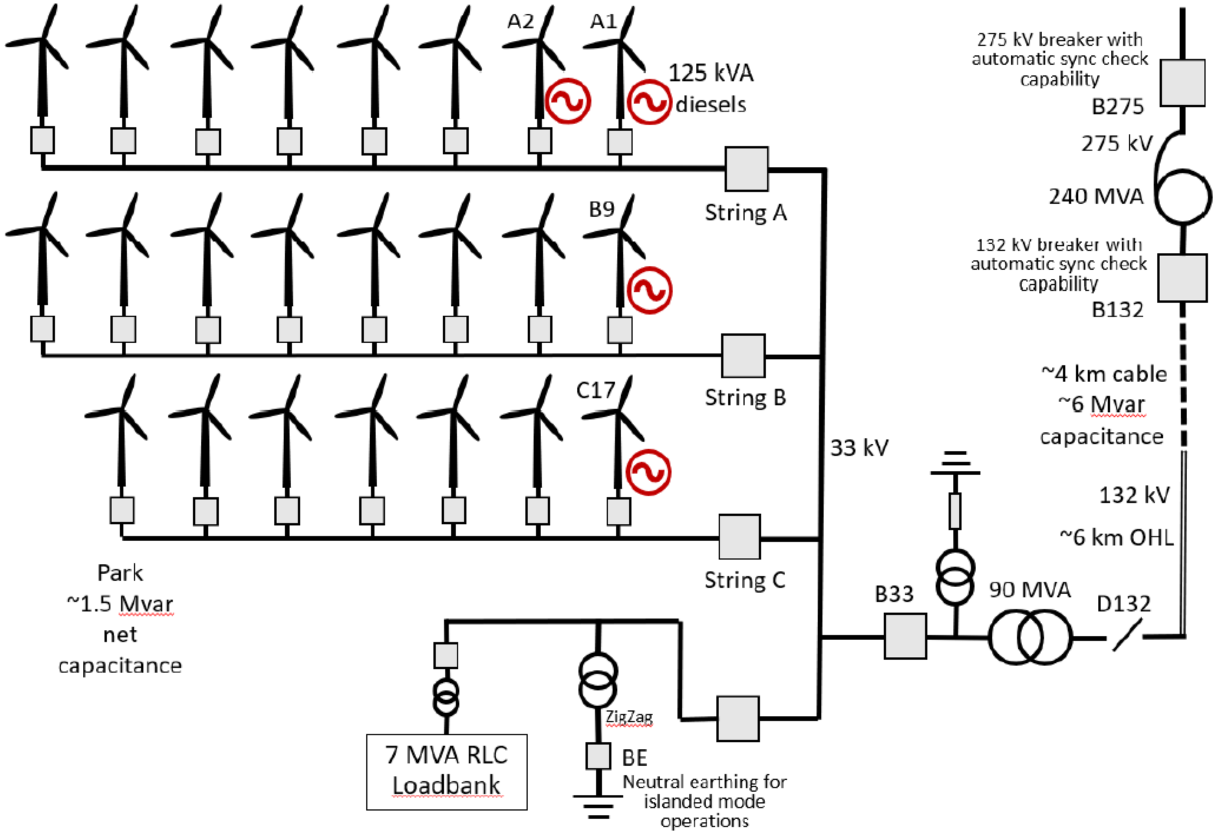
Testing Existing Siemens-Gamesa Wind Turbines in GFM Mode: Island Operation and Black Start

In August-October 2020 it was successfully demonstrated that Dersalloch wind farm

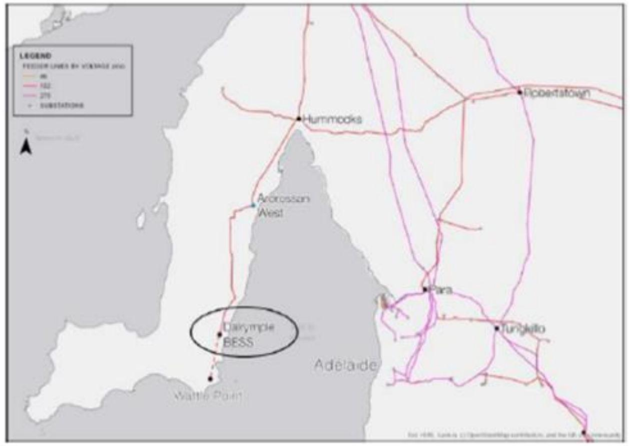
- Can operate autonomously in islanded mode with small number of wind turbines operating in GFM mode.
- Can re-synchronize from islanded to grid-connected mode of operation.
- Can black start the wind farm from a number of black start-capable wind turbines, extending energization to the transmission network all the way up to 132kV/275kV transformer and re-synchronization with the grid.

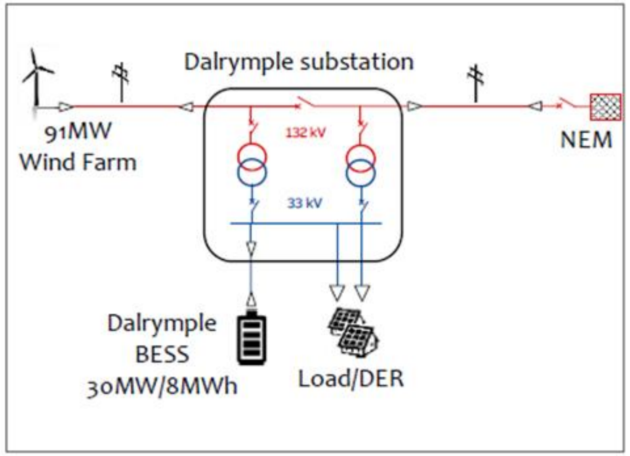


Source: A. Roscoe, et.al. "Practical Experience of Providing Enhanced Grid Forming Services from an Onshore Wind Park", 19th Wind Integration Workshop, 2020

Hitachi ABB Energy Storage for Commercial Renewable Integration (ESCRI) in GFM mode

- Dalrymple BESS in South Australia is the largest grid-connected GFM BESS in the world, at 30 MVA and 8 MWh.
- Virtual Synchronous Machine control method is used
- It is the first large scale, grid-forming BESS connected to Australian transmission system
- Installed in 2018, near the end of a long 132 kV single-circuit radial feeder close to 91 MW wind farm, local load up to 8 MW and 2 MW of local rooftop PV
- In the first six months of operation, reduced the loss of supply in the area from ~8 hours to 30 minutes.





Source: "Grid Forming Energy Storage: Provides Virtual Inertia, Interconnects Renewables and Unlocks Revenue", https://go.hitachi-powergrids.com/grid-forming-webinar-2020
Contribution to the ESIG White Paper by Luke Robinson, AEMO

Hitachi ABB Energy Storage for Commercial Renewable Integration (ESCRI) in GFM mode

The services provided by the project include:

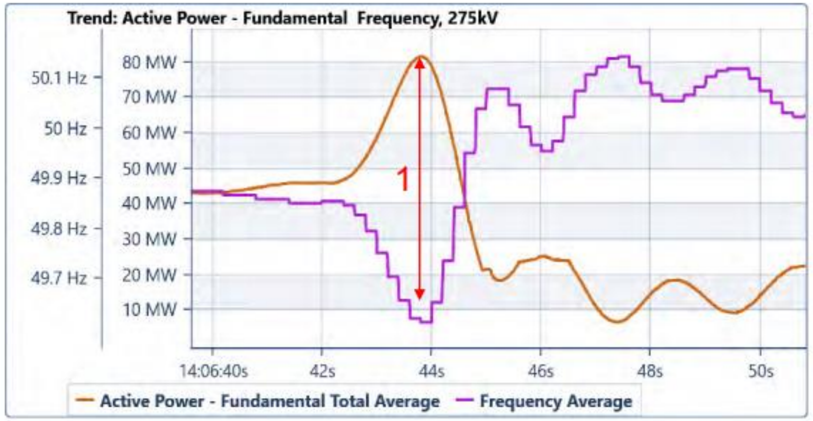
- **Inertia** –can provide virtual inertial response, reducing RoCoF after a sudden loss of load or generation. This is different to Fast Frequency Response (FFR).
- **System Strength** –can operate at very low Short Circuit Ratios (<<1.5). It is also able to provide system strength support via short-term fault current overload (2-3 pu).
- **Islanded operation** – regulates the frequency in the microgrid by utilizing virtual inertia, primary and secondary frequency control. Additionally, can adjust the system frequency to invoke curtailment of behind-the-meter DER to avoid over generation conditions.
- **Black start capability** – can black start the local 33 kV distribution network with 8 MW demand. Voltage is ramped up slowly to prevent inrush current and harmonics (soft energization).
- **System Integrity Protection Scheme (SIPS)** – providing fast active power injection into the grid following a significant loss of generation. The GFM BESS can be operating at full capacity within 250 ms if a network event is detected at the interstate AC interconnector, 370 km away in the South East of South Australia.

Source: Contribution to the ESIG White Paper by Luke Robinson, AEMO
Cherevatskiy, Sproul et al, Grid Forming Energy Storage System addresses challenges of grids with high penetration of renewables (A case study), 18th Wind Integration Workshop, 2019

Tesla Hornsdale BESS

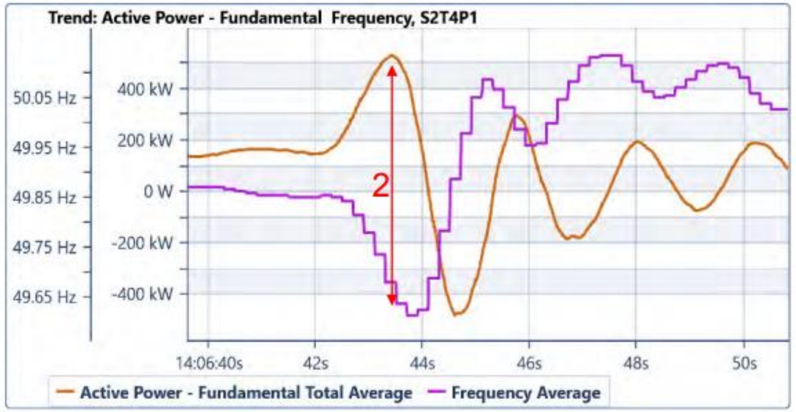
- BESS co-located with the Hornsdale Wind Farm in South Australia
- Installed in 2017, 100 MW/129 MWh provided energy and FCAS
- In 2020 expanded to 150 MW/194 MWh
- Two inverters currently operate in virtual machine mode (VMM)
- The VMM component runs in parallel with the conventional GFL component
- Under stable system conditions, the inverter's behavior is driven by the current source component
- During grid disturbances, VMM produces an active power response proportional to RoCoF and produces a reactive current in response to changes in voltage
- "Real life"- tested in a frequency event created by a coal plant explosion and subsequent trip of neighboring units on 5/25/2021
- "Virtual machine mode" to the rest of that battery is expected by the end of the year once extensive modelling and testing is complete.

- VMM event captured 25/5/2021
- "H" Constant = 50
- Clear response of VMM responding to ROCOF



Site Response

[1] Max active power response at max frequency deviation



VMM Enabled Inverter Response

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[2] Max active power response at max RoCoF

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Source: https://reneweconomy.com.au/virtual-machine-hornsdale-battery-steps-in-to-protect-grid-after-callide-explosion/
https://arena.gov.au/assets/2021/06/arena-insights-webinar-advanced-inverters-presentations.pdf

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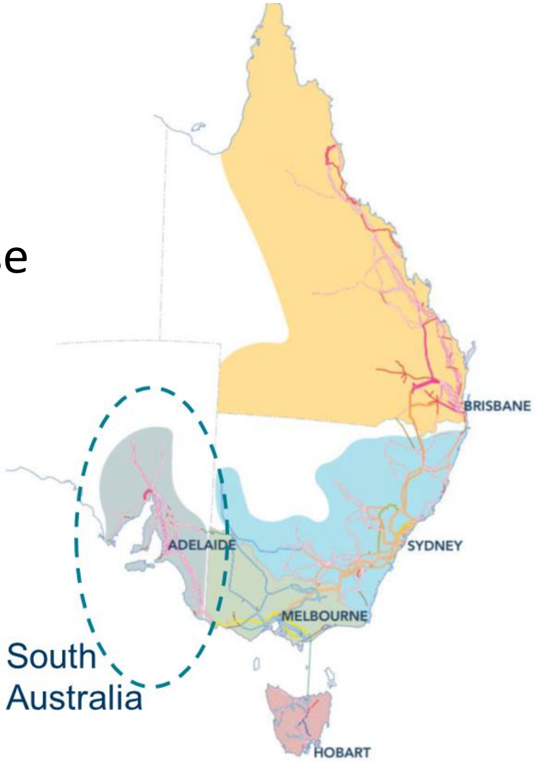
Drivers behind GFM Trials in AEMO

- Australian Energy Market Operator (AEMO) enforces minimum inertia and system strength requirements in parts of the grid, e.g. South Australia.
- New IBRs should not reduce system strength in the area.
- Screening and full studies (EMT simulations) to assess the impact and propose mitigation measures such as:
  - Network upgrades,
  - Synchronous condensers,
  - Contracting synchronous generation for provision of system strength,
  - **Use of GFM technology** allowing the resource to stably operate down to 0 short circuit ratio,
  - Controller tuning of the existing IBRs
  - Remedial Action Schemes (post-contingency)
- Interconnecting entity is responsible for the cost of implementation of these measures.



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National Grid ESO Stability Pathfinder

Phase I: Most cost-effective way to increase inertia and system strength across GB

Concluded in January 2020 with 12 awarded contracts to 5 providers in 7 locations

Stages:

1. Identified stability needs across GB
2. Launched request for information
3. Launched tender
4. Published results

Specifies attributes such as:

- Short circuit level contribution ≥ 1.5 p.u.
- Inertia ≥ 1.5 p.u
- Steady state voltage & frequency
- Transient voltage & angle stabilization
- Fast fault current injection
- ROCOF withstand
- Transient overvoltage
- Performance under min short circuit level

Phase II: Most cost-effective way to increase both stability (short circuit level) & inertia in Scotland

Expression of Interest for Phase II closed on January 8, 2021 and NG ESO is reviewing the submitted solutions.

Stages:

1. Identified stability needs across GB (complete)
2. Launched request for information (complete)
3. Launched Expression of Interest (complete)
4. Launch Feasibility Study (pending)
5. Launch Tender (pending)

Specifies attributes (in addition to Phase I req.) such as:

- Voltage source behind impedance behavior
- Inertial power (start in <5ms)
- Phase-jump power (start in <5ms)
- Fast fault current injection (start in <5ms)
- Power oscillation damping

Source: https://www.nationalgrideso.com/future-of-energy/projects/pathfinders/stability/Phase-1
https://www.nationalgrideso.com/future-of-energy/projects/pathfinders/stability/Phase-2

National Grid GC0137 Grid Forming Requirements

Proposed non-mandatory GB GFM Requirements:

- Must have internal voltage source behind reactance
- Maintain synchronism and stability up to 60° phase jump
- Supply RoCoF Response Power (and withstand 2Hz/sec), phase jump power, damping (DF between 0.2-5.0), fast fault current injection (i_q between 1.0-1.5pu), control-based real & reactive power
- Control power with bandwidth < 5 Hz to avoid oscillations
- Operate at a minimum short circuit level
- Must stably inject current for balanced and unbalanced faults that increases with the fall in the retained voltage without exceeding the peak current rating
- Demonstrate all attributes of performance for GFM via type-tests and simulation models

Proposed GB GFM spec targets the same performance attributes as a synchronous machine

Capability	GBGF-S	GBGF-I	Conventional
Phase Based Phase Jump Power in one cycle	Yes	Yes	No
RoCoF response Power	Yes	Yes	No
Damping Power	Yes	Yes	Yes
Operate in Synchronism with the System	Yes	Yes	Yes
Contribution to Fault infeed	Yes - High	Yes – As specified	Yes - Limited
Avoids producing current harmonics > 5 Hz	Yes	Yes	No

For the avoidance of doubt GBGF-I includes VSM0H converters

GB – Great Britain
GBGF-I – Invert-Based Grid Forming Plant
GBGF-S – Synchronous Generators
Conventional – Grid Following Inverter-Based Resource
VSM0H – Virtual Synchronous machine without power

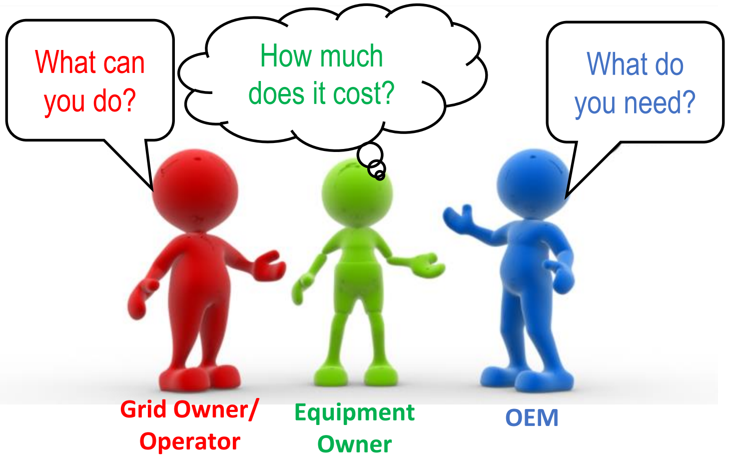
Proposed GB GFM requirements are now under ballot and are expected to be implemented in Q4 2021

Source: https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required

Breaking the circular problem: GFM technology deployment

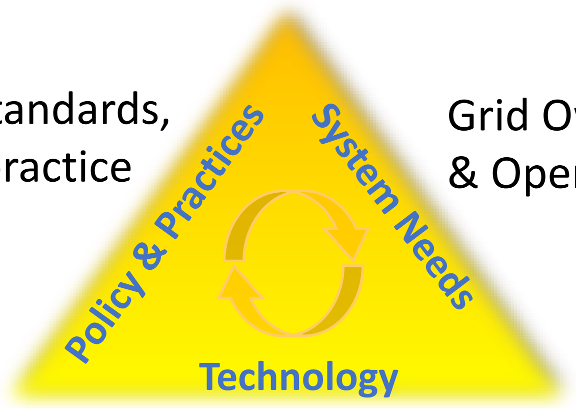
Stakeholder ecosystem

- Regulators
- System / Grid operators
- Transmission companies
- Generation utilities
- Distribution utilities
- Developers & Investors
- OEMs



Codes, standards, trading practice

Grid Owners & Operators



OEMs & Equipment Owners

System needs, trends and the role of stakeholders, requirements & trading mechanisms:

- **Interoperability** between all resources to prevent instability and interactions under all system conditions
- Solutions for loss of **synchronous inertia** and **support grid frequency** to keep the system stable
- System restoration and **black start** as well as **weak grid control stability**
- **Tools, modeling & planning practices** that fully identify system risks and capabilities of equipment to mitigate risks
- **Grid codes, interconnection requirements and market mechanisms** play a critical role in the deployment of new technology capabilities like Grid Forming IBRs to meet above grid needs
- Collaboration between **regulators, system operators, equipment owners and OEMs** is imperative to define requirements and mechanisms to deploy technology and break chicken-egg dilemma (What comes first? Requirements or capabilities?)

https://www.ultain.ie/en/news/spoken-word-conversation-3

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Thank you! Questions?