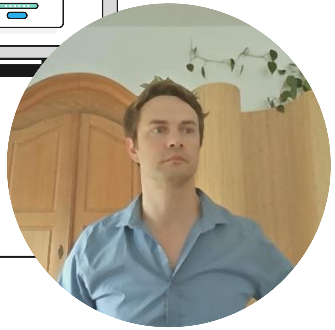
Grid Forming Inverters

From a BESS perspective



About the speaker

Daniël de Waal
Energy Storage Lead @ Centrotec SE (rebranding to REVOLT)

- Professionally registered Electrical Engineer (ECSA) with 10+ years of international experience in BESS and hybrid power.
- Lead the development of utility-scale energy storage projects across Europe, Africa, and Asia, supported more than 4.5 GW / 15.8 GWh of BESS development.
- Experienced in design, technical due diligence, techno-economic simulations, vendor selection, contract negotiations, tender management, procurement, and engineering risk management.

Aim of the content

- **Aim**: to provide engineers and energy professionals with a practical understanding of Grid-Forming inverter technology from a Battery Energy Storage System (BESS) perspective.
- **Learnings**: the principles behind GFM, how it differs from conventional Grid-Following control, where it is applied, and the engineering and commercial implications for modern power systems
- **Target audience**: Engineers (any), developers, consultants, and technical decision-makers involved in the design, integration, or operation of Battery Energy Storage Systems (BESS) that has an interest in Grid-Forming-Inverters
- **Not aimed at**:
    - Detailed power electronics or inverter hardware design
    - Mathematical derivations of control algorithms
    - PSCAD or EMT simulation
    - In depth protection system design
    - Battery chemistry, cell design, or BMS fundamentals

Session overview

Section 1: Introduction and background

Section 2: Engineering and Controls

Section 3: Grid Codes, Design, and Project Impacts

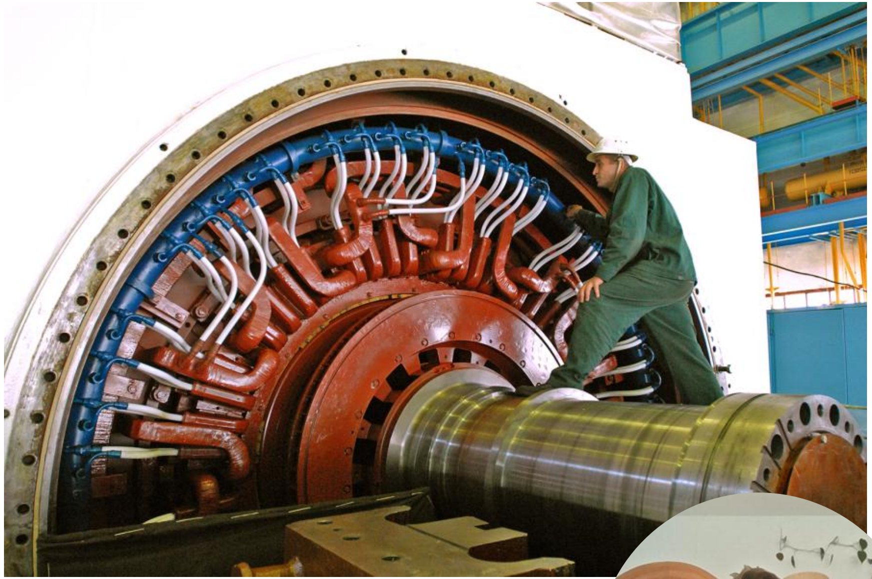
Section 4: FAQs, Misconceptions, and Key Takeaways

Section 1: Introduction & Background

Power systems background

- Traditional grids were built around large synchronous generators.
- Coal, gas, nuclear and hydro power plants provide:
  - Voltage regulation
  - Frequency stability
  - Fault current
  - Inertia
- Due to the transition to renewable energy, there are reduced Synchronous Generators (Alternators) connected to the grid.

↑ RE ⇒ ↓ SG ⇒ ↓ Inertia ⇒ ↑Rate of Change of frequency (RoCoF) ⇒ Harder to control grid frequency



What is inertia?

Inertia:

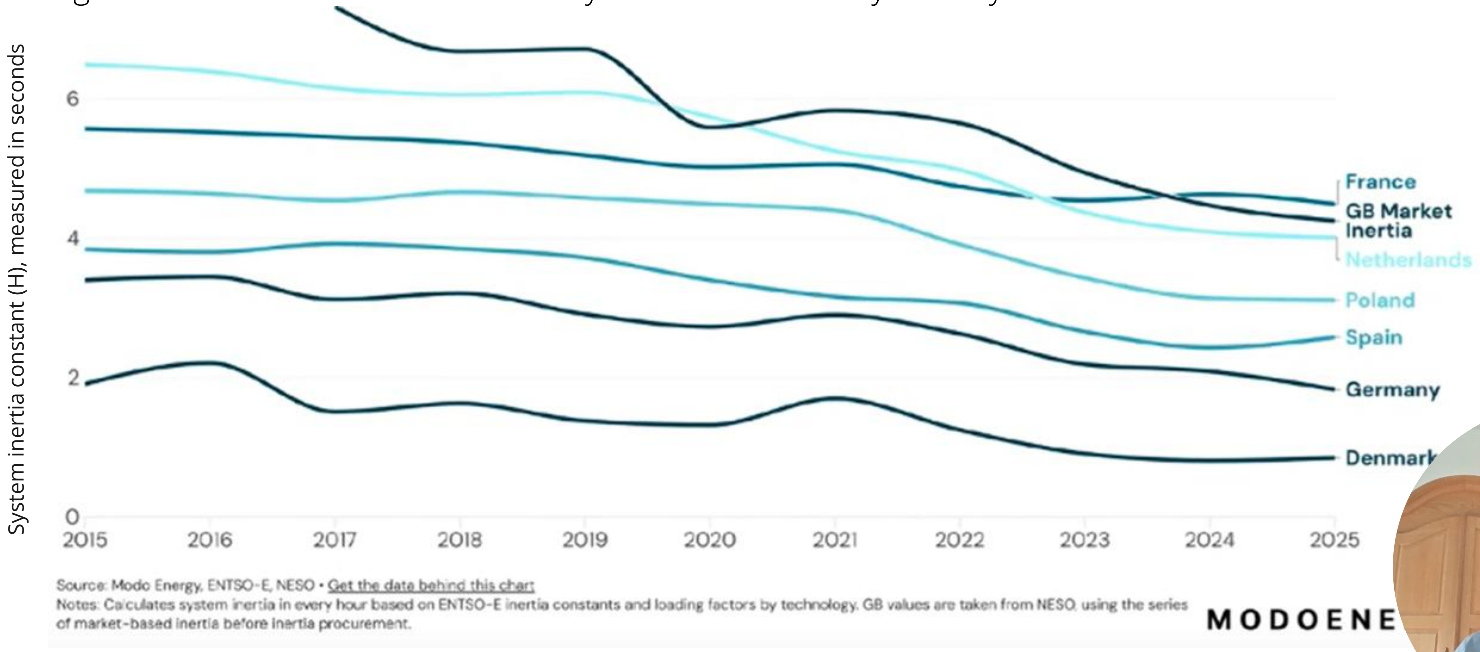
- Resists changes in system frequency
- Traditionally from rotating machines
- Limits RoCoF after disturbances
- In BESS: inertia via fast control response (typically 20 ms to 200 ms)

$$H = \frac{\frac{1}{2}J\omega^2}{MVA}$$

H = Inertia constant in MWs / MVA
J = Moment of inertia in kgm^2 of the rotating mass
ω = nominal speed of rotation in rad/s
MVA = MVA rating of the machine

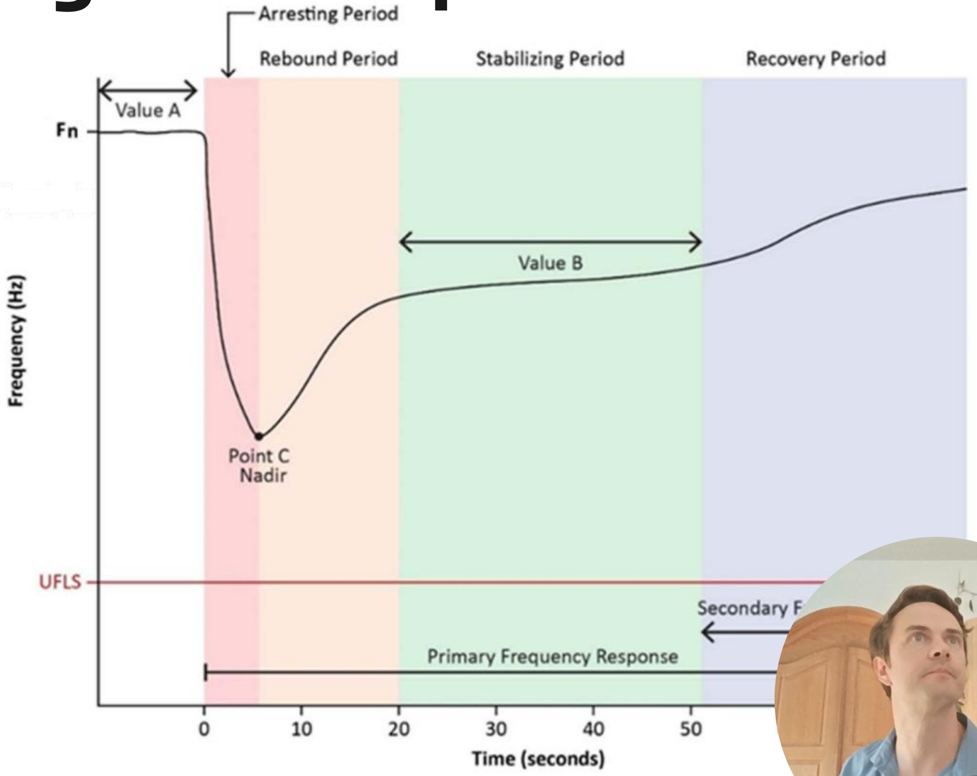
Inertia drop by country

System-level inertia has been falling across Europe.
Image shows P10-values of calculated system level inertia by country in seconds.



Why is it becoming more important?

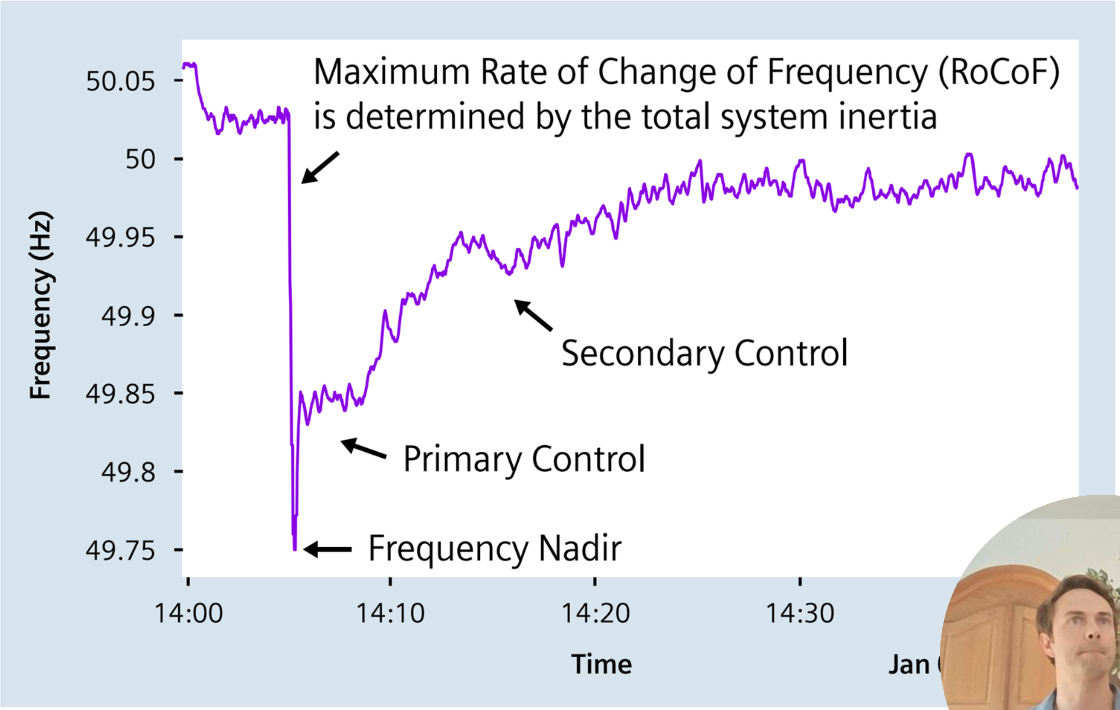
Fn: Nominal Frequency (50 Hz)
A: Pre-disturbance steady-state frequency
B: Post-primary-response steady-state
C: Nadir/Local minima for transient
UFLS: Under Frequency Load Shedding



Why is it becoming more important?

Frequency incident of the 8th of January 2021, following a minor system split in the European power system (Frequency in Germany).

Load shedding starts at around 49.2 Hz - 49 Hz



Ref: Grid-forming converters White paper, Siemens Energy, Germany, 2024

What is Grid-Forming?

Grid-Following (GFL)

- Synchronises to existing grid
- Injects current using grid voltage reference
- Requires stable grid
- Behaviour: Current source

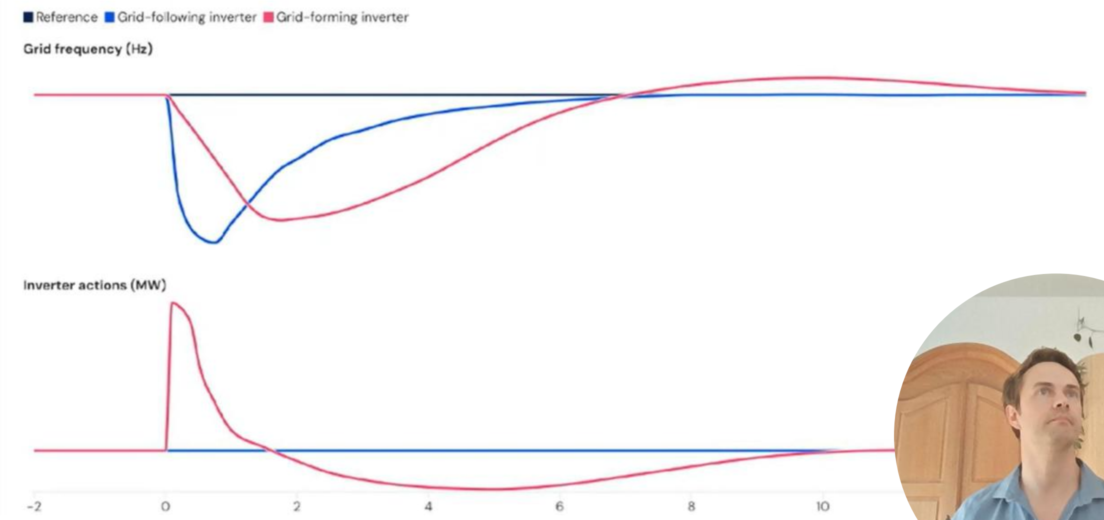
Grid-Forming (GFM)

- Sets voltage and frequency independently
- Operates without grid (black start capable)
- Stabilises weak grids
- Behaviour: Voltage source

Why is it becoming more important?

GFM can help with the grid's

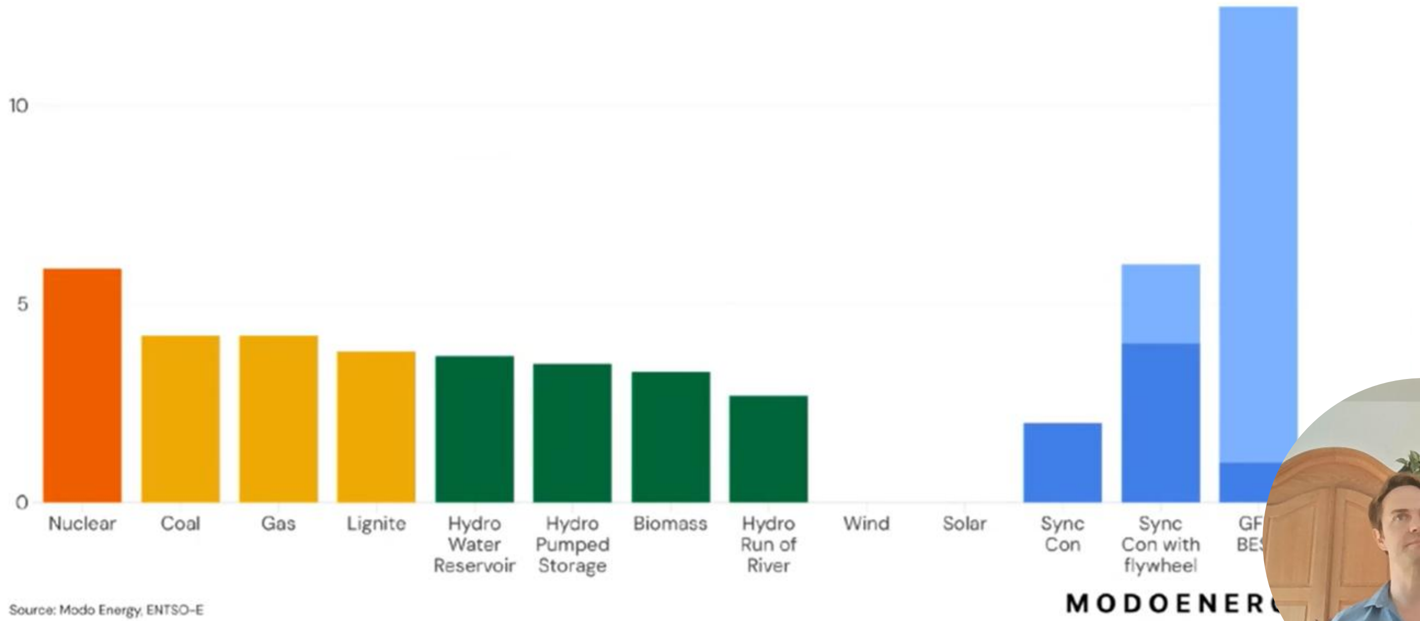
- Inertia
- Voltage setting in weak grids
- Fault level
- Oscillation damping
- Blackstart and island grids



Ref: Modo Energy, 2025

Why is GFM becoming more important?

Inertia contributions when spinning differ by technology type. Inertia constants by technology in seconds. Blue shading indicates range you can apply.



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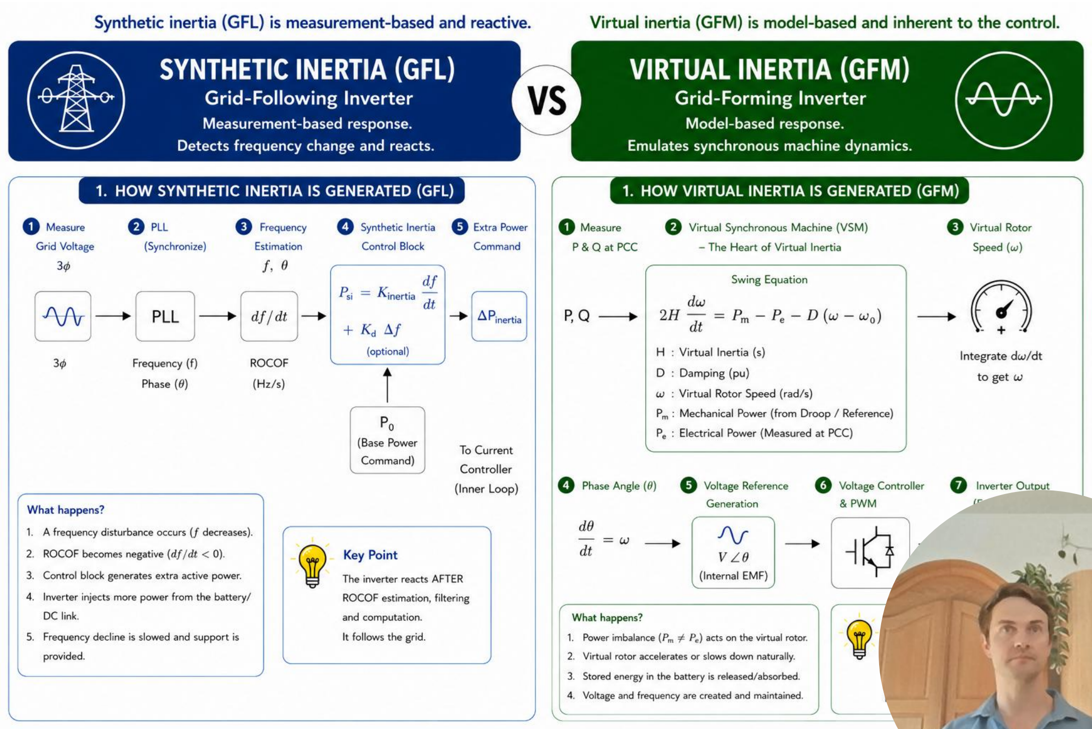

Inertia and BESS project costs

Scope item	GFL cost	GFM cost	GFM additional cost	Notes
Inverter system	€60–100/kW	€75–130/kW	+€15–30/kW	Hardware margin + advanced controls + R&D premium
Engineering studies	€5k–55k	€25k–255k	+€20k–170k	Includes modelling, studies, OEM support, validation
Grid compliance & certification	€10k–30k	€20k–80k	+€10k–50k	Dynamic performance requirements
Commissioning & tuning	€10k–40k	€20k–120k	+€10k–80k	Longer and more complex tuning
SCADA / EMS integration	€10k–25k	€15k–55k	+€5k–30k	Additional control modes
Totals PCS	**€35k–150k**	**€80k–350k**	**+€45k–200k (~130%)**	
Project overall CAPEX			**2%-10%**	

Quiz

Which of these is typically NOT a driver for Grid-Forming adoption?

A. Regulatory requirements

B. Additional revenue opportunities

C. Black-start capability

D. Higher battery energy and power density

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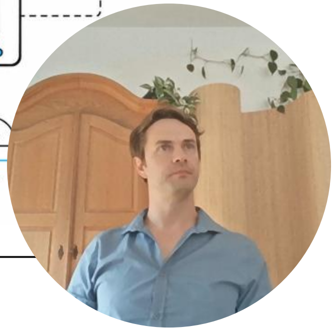


Section 2: Engineering & Controls

Comparison of Controls

Key Attributes to Unlock Stability

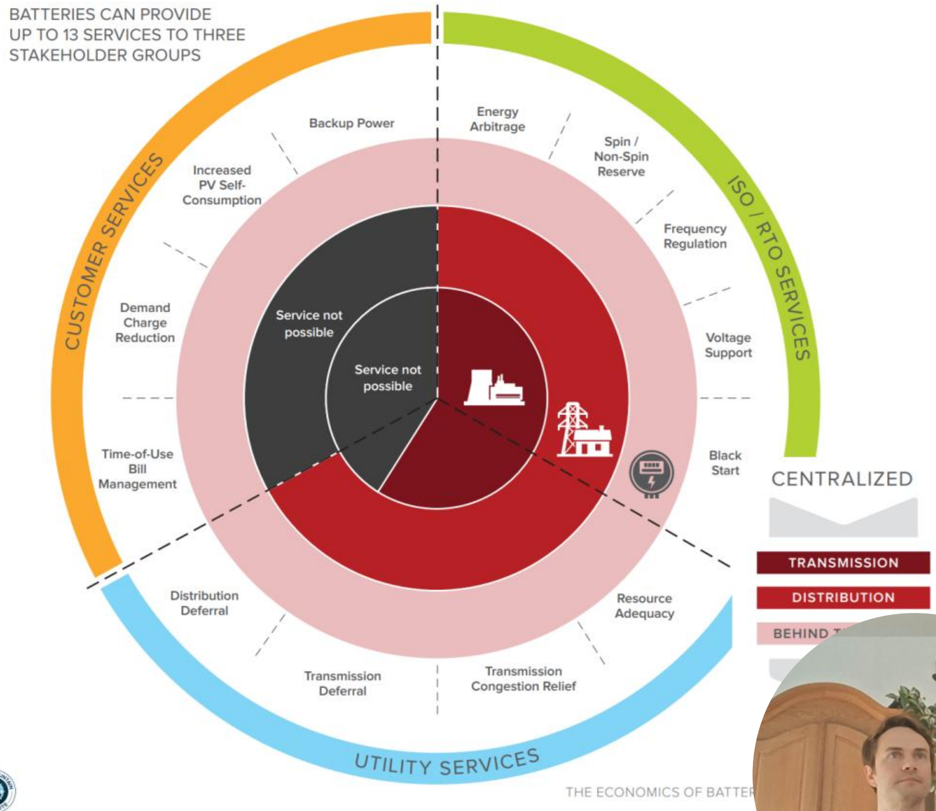
GFL

- Behaves as a current source
- Utilizes Phase-Locked Loop (PLL) to track Grid
- Follows F.OS(PPC) commands regardless of grid
- Thereby respecting battery limits via F.OS
- Inherent “deadtime” and delay to provide grid support due to measurement and dispatch
- Cannot self-supply/black-start/restore grid

GFM

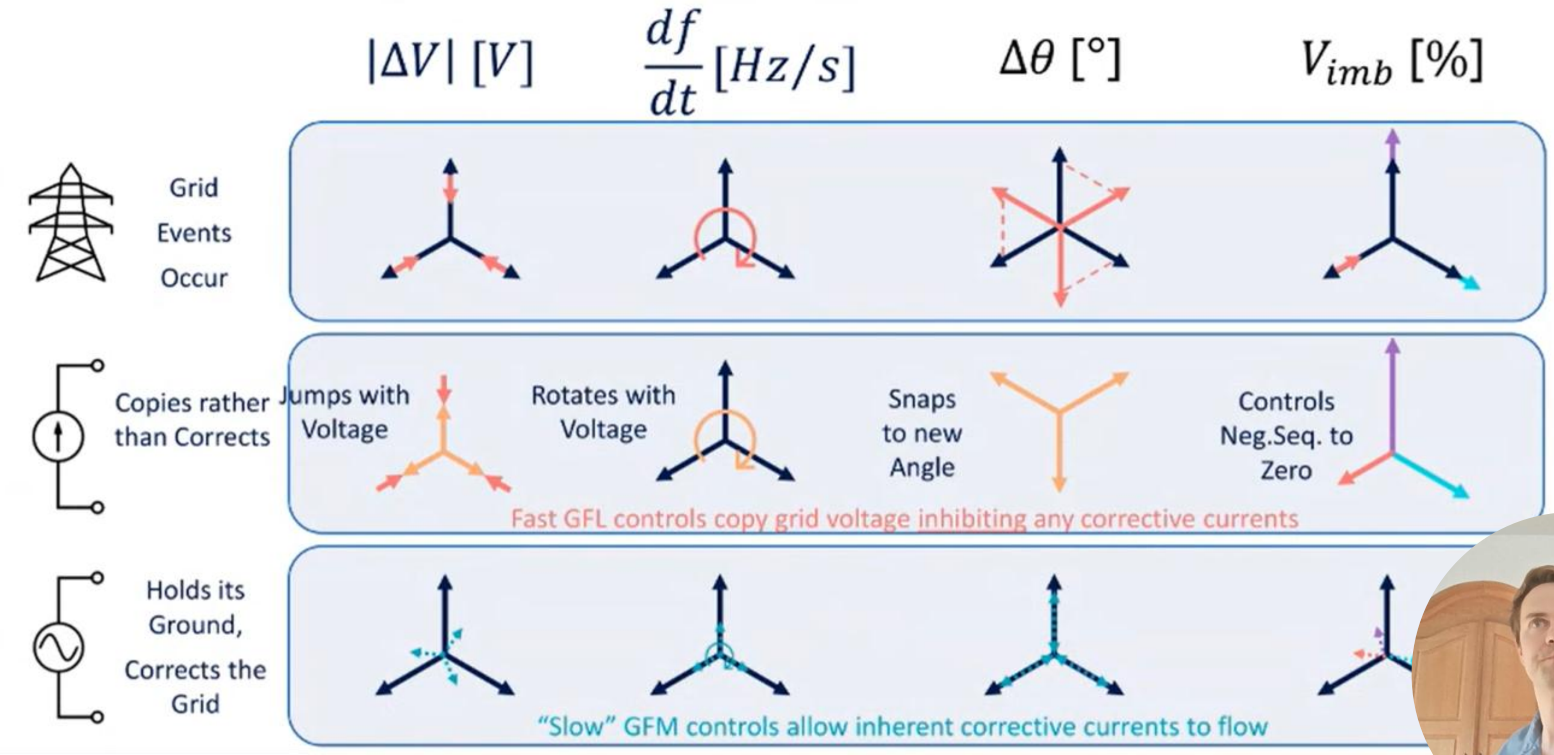
- “Voltage source behind an impedance”
- Establishes grid via own controls (Droop/VSM)
- Has autonomy to react to transient grid needs
- Does not intrinsically respect battery limits
- Inherent & Immediate response to grid events limited only by physics
- Can self-supply/black-start/restore the grid

BESS use cases



Ref: RMI, The Economics Of Battery Energy Storage, 2015

Visualising Instantaneous Responses



Ref: Fluence, 2025

Approaches to driving GFM BESS

Regulatory prescription

Regulatory Response & Standards Evolution

Local system strength constraints (xSCR, Inertia, Voltage stiffness) are becoming binding constraints for renewable connections.

Grid codes worldwide are being updated to require GFM "within inherent limits" – lower cost, but you get what you pay for.

FINGRID ercot entsoe MISO

Specific needs basis

Enhanced GFM Capabilities Mandated

Grid codes in select regions go above and beyond 1 p.u. to address specific needs and shortfalls based on geography, topology, and expected grid development.

Potentially for fault current and/or active power overloading.

Hawaiian Electric COORDINADOR red eléctrica

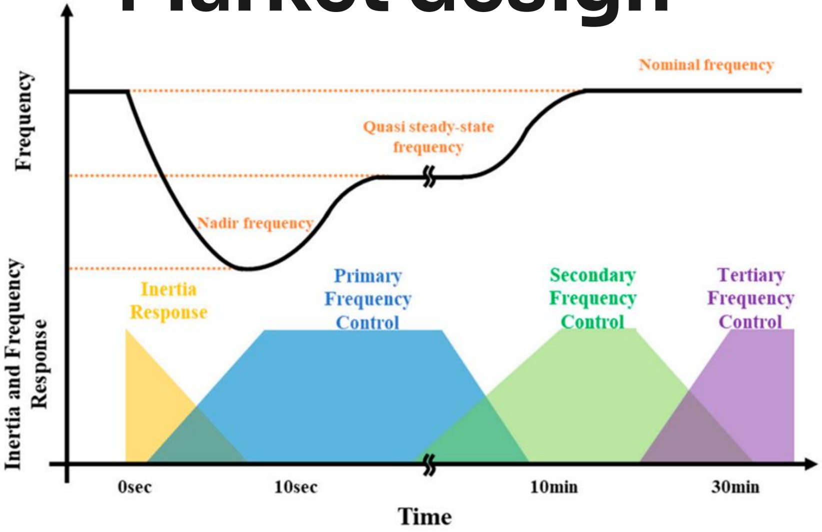
Incentive based

Economic Imperative & Multi-Service Value

GFM-capable assets can provide system strength (GFM-Inertia, Voltage Strength, Black-start/Grid Restoration) enabling new revenue or allowing plant to avoid strength charges *and* participate in energy arbitrage and capacity markets — improving economics.

NESO TenneT AEMO amprion

Market design



From January 2026, Germany's four transmission system operators (TSOs) will procure inertia services under a fixed-price model.

Key features include:

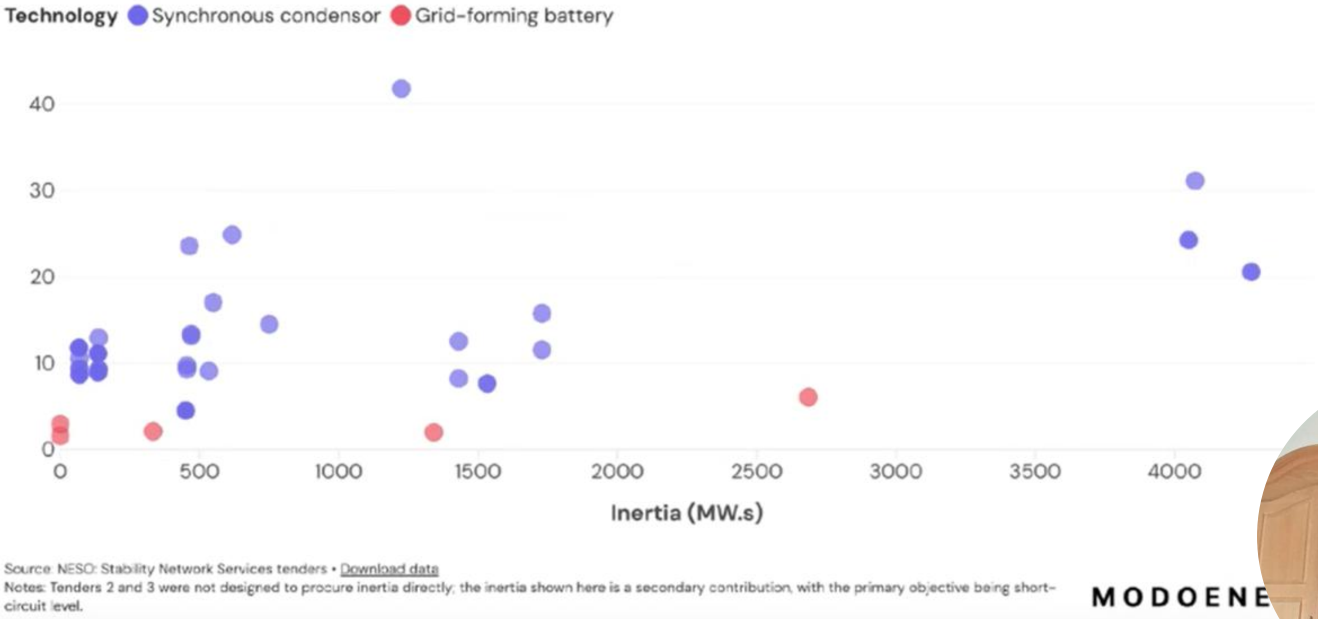
Long-term contracts: The first procurement period runs from 22 January 2026 to 21 January 2028.
Fixed remuneration: Payments are based on registered megawatts (MW) of grid-forming capacity.
Prequalification: Only assets certified as grid-forming are eligible.
Transparency: Prices for future rounds will be published six months in advance.

Metric	Germany FCR	Germany aFRR	Germany mFRR	Germany Inertia	UK DC	UK DM	UK DR	UK Stability (P
Purpose	Arrest frequency deviation	Restore frequency	Replace reserves	Provide synthetic inertia & system strength	Fast post-fault response	Continuous balancing	Continuous regulation	Provide inertia, voltag
Response initiation	<1s	<30 s	2.5 min	Immediate (grid-forming)	≤0.5 s	≤0.5 s	≤2 s	Immediate (grid-for
Full response	30 s	5 min	12.5 min	Instantaneous (<1 s)	1 s	1 s	10 s	Instantaneous (<1
Delivery duration	2 hours	4 hours	4 hours	Continuous while contracted	15 min	30 min	60 min	Continuous while c
Grid-forming required	No	No	No	Yes	No	No	No	Yes

Ref: Critical Inertia Calculation Method of Generators Using Energy Balance Condition in Power System, 2024

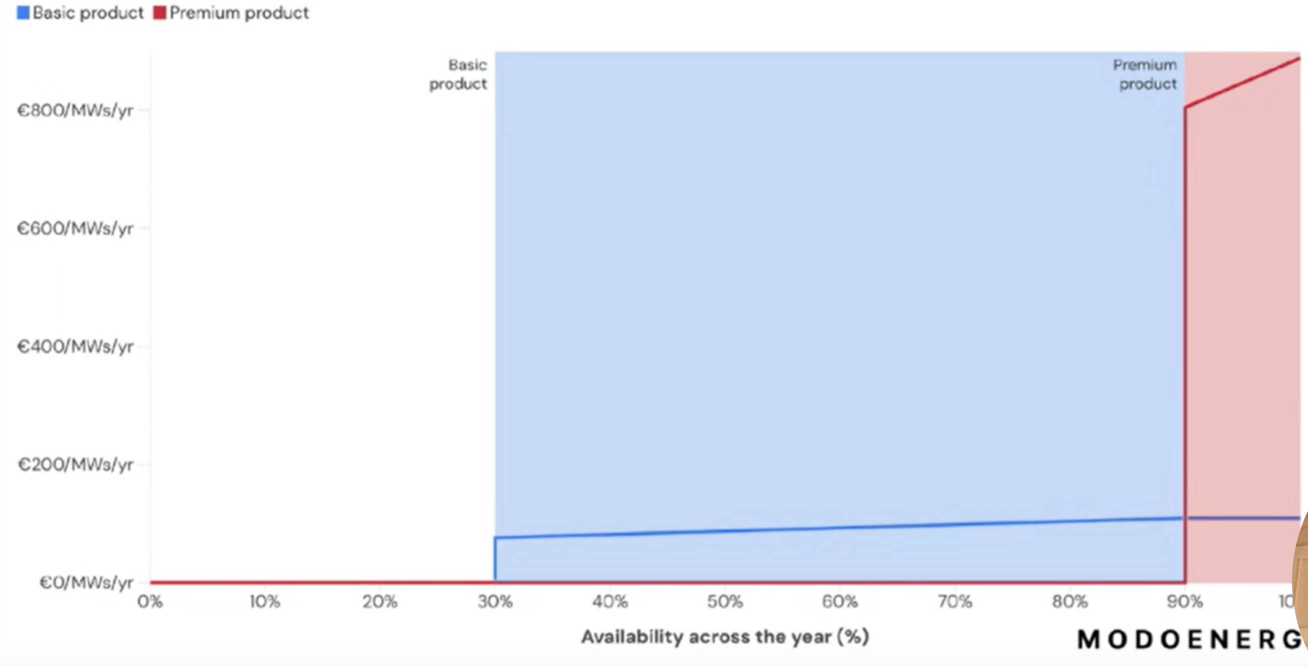
What are countries doing about it?

Grid-forming batteries deliver more competitive inertia compared to synchronous condensers in GB.
Contract cost ($ mil/year) for NESO Stability Pathfinder tenders.



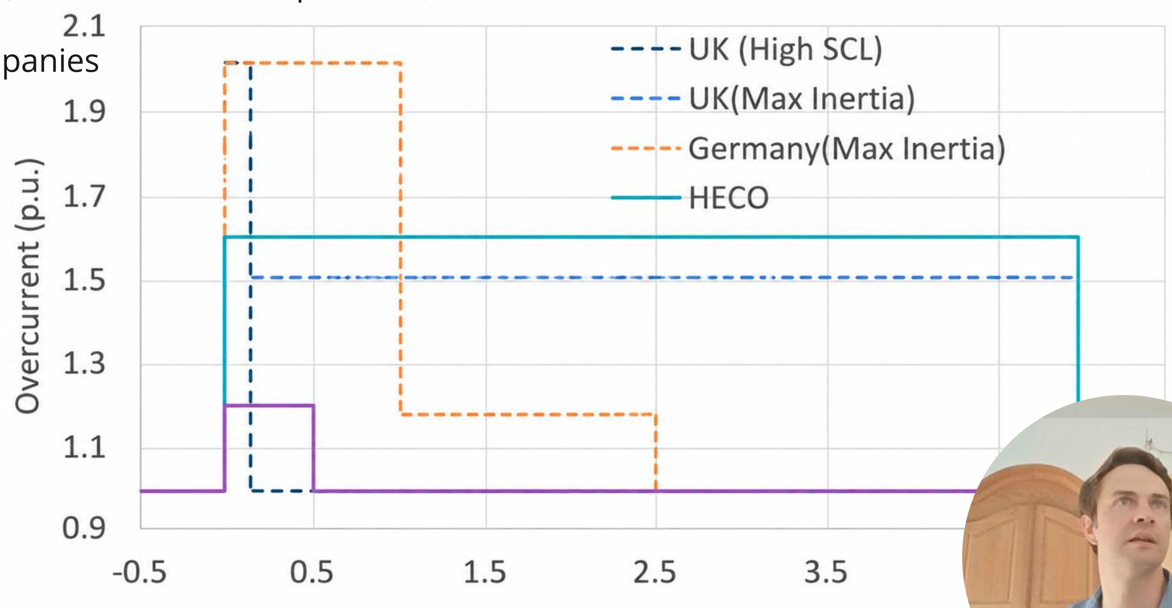
What are countries doing about it?

Germany procures inertia on a “market” basis, with pricing based on availability.



Quantifying GFM

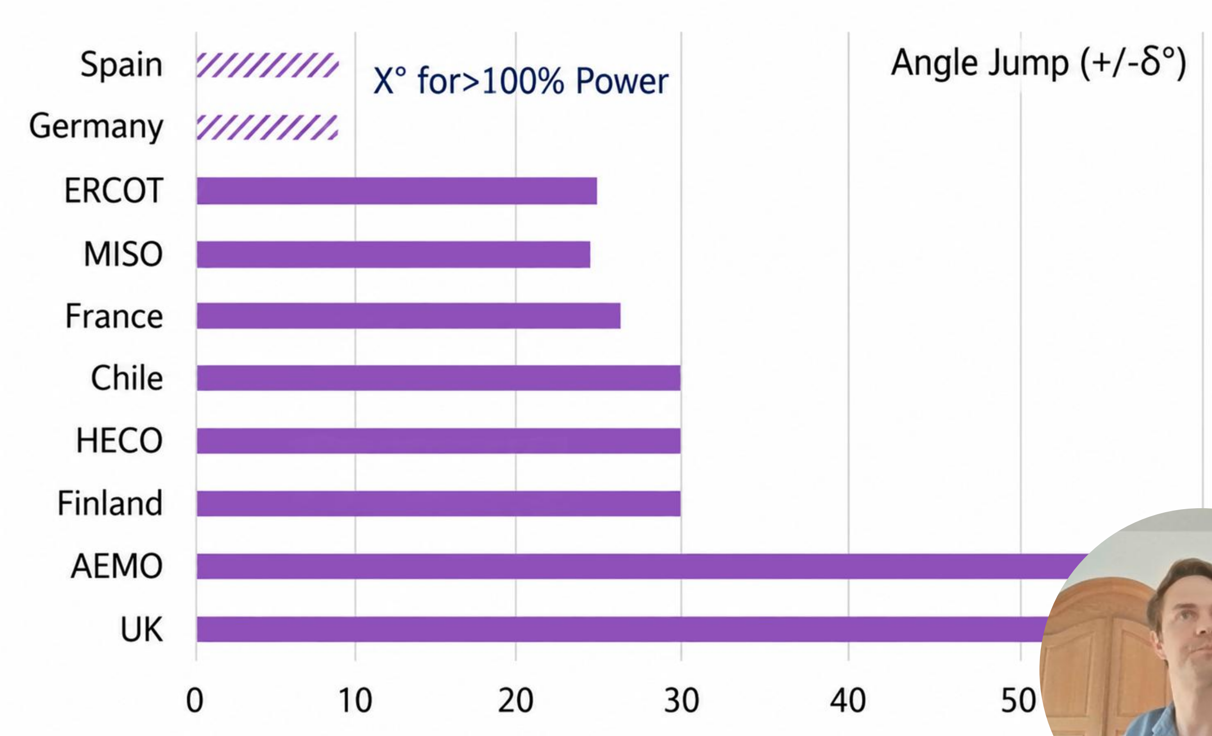
Requirements and Testing Vary Greatly
AGS = Advanced Grid Support (ERCOT USA GFM equivalent)
GFM ≠ GFM ≠ AGS.
HECO = Hawaiian Electric Companies



Ref: Fluence, 2025

Quantifying GFM

Angle jump withstand



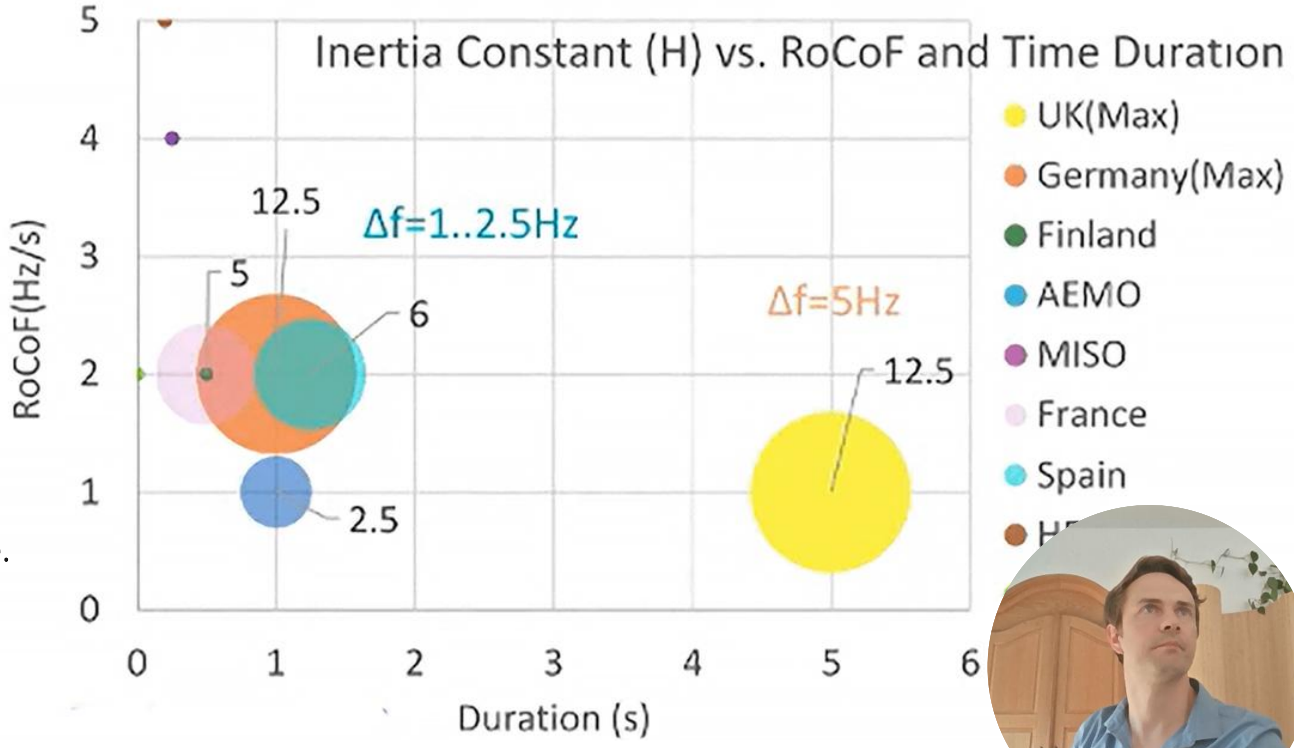
Ref: Fluence, 2025

Quantifying GFM

The graph illustrates how intense a frequency change the TSO (Transmission System Operators) see.

E.g. UK has quite long duration:
1 Hz/s for 5 seconds

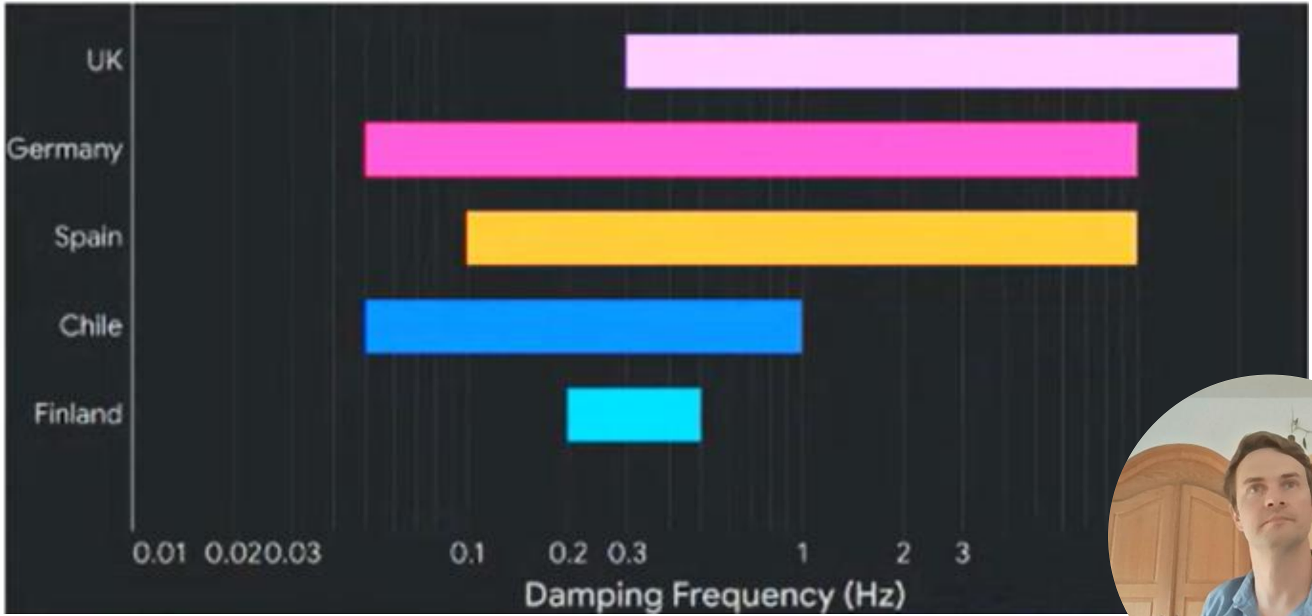
Bubble size indicates minimum inertia you have to bring to the table.



(How long the RoCoF is sustained)

Quantifying GFM

Power oscillation damping capabilities



Quiz

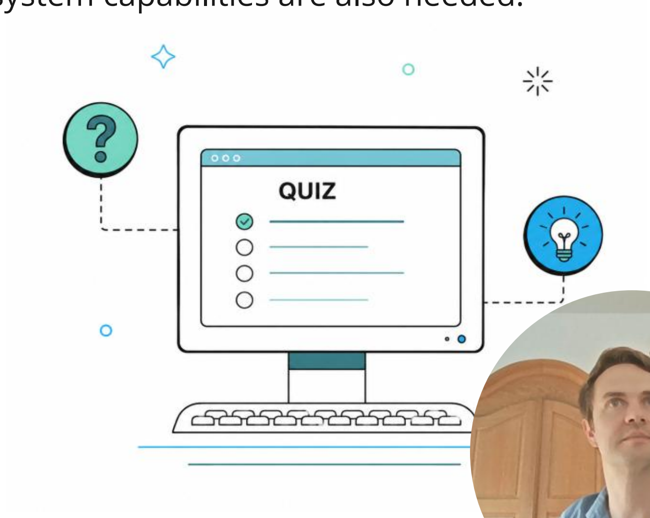
Which statement is correct?

A. Every Grid-Forming inverter automatically provides black start.

B. Black start always requires Grid-Forming, but additional system capabilities are also needed.

A. Grid-Following is preferred for black start.

B. Black start is only possible with diesel generators.



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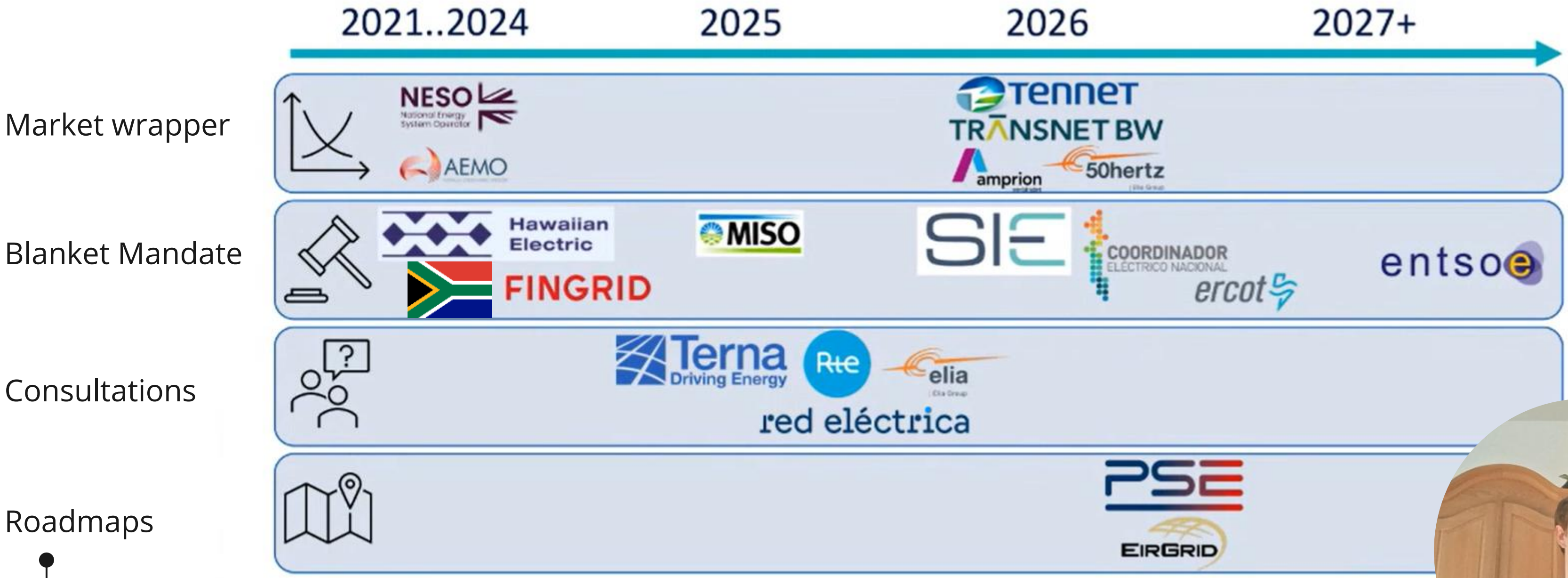
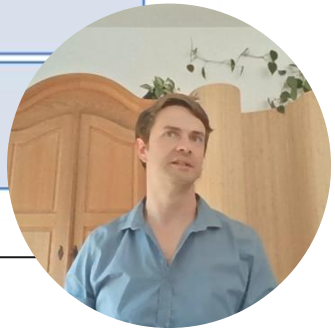
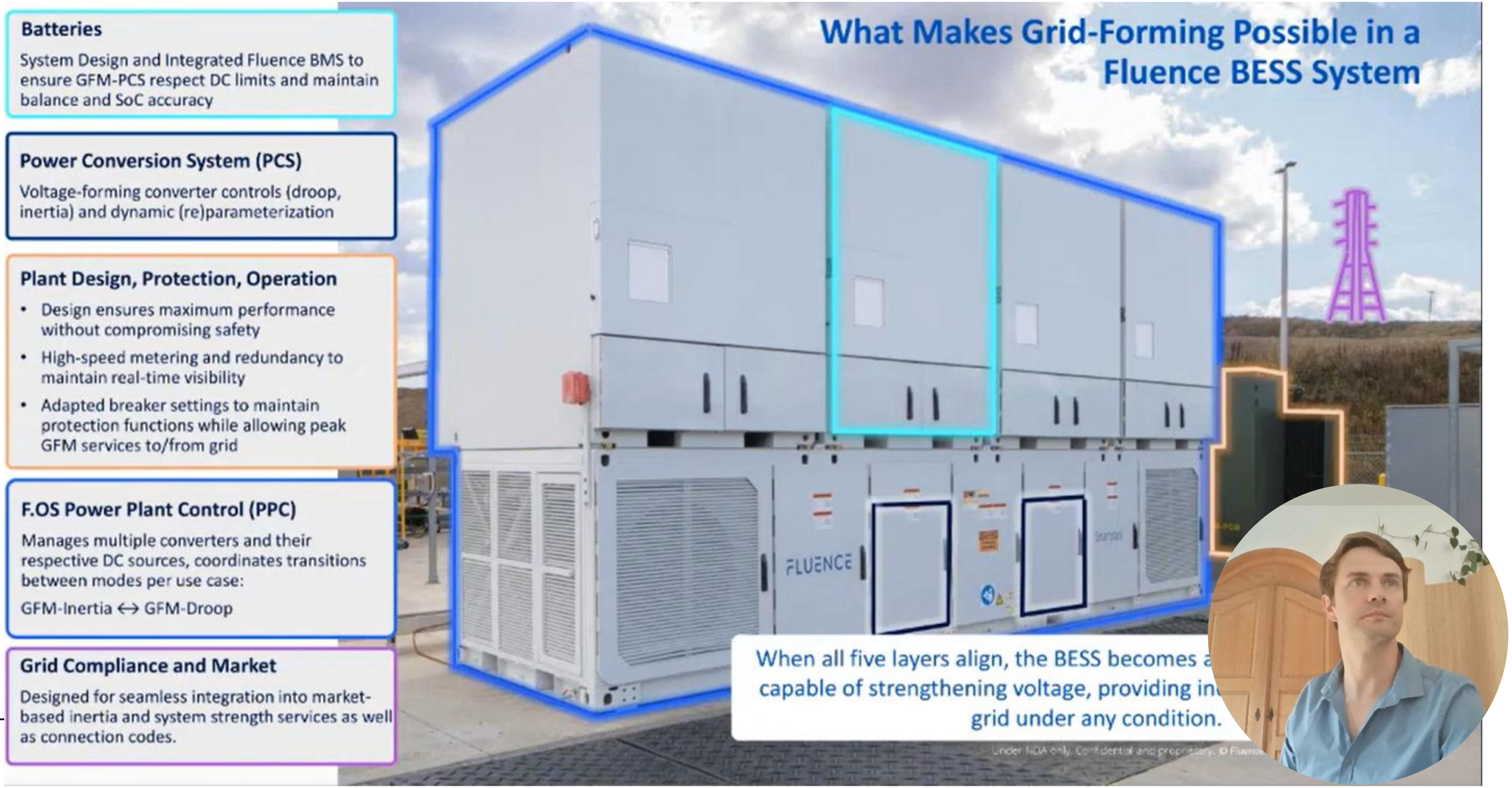
Section 3: Grid Codes and Design Specification

Status of GFM in Grid Codes





GFM example: Fluence



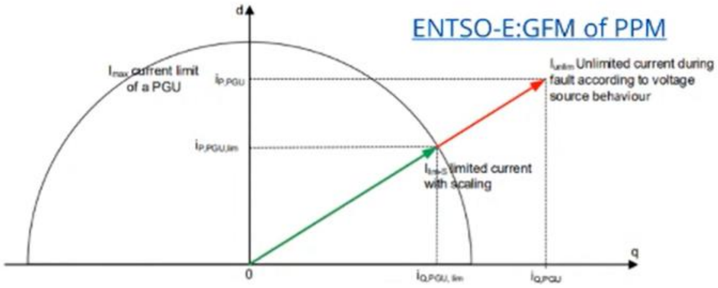
GFM example: Fluence

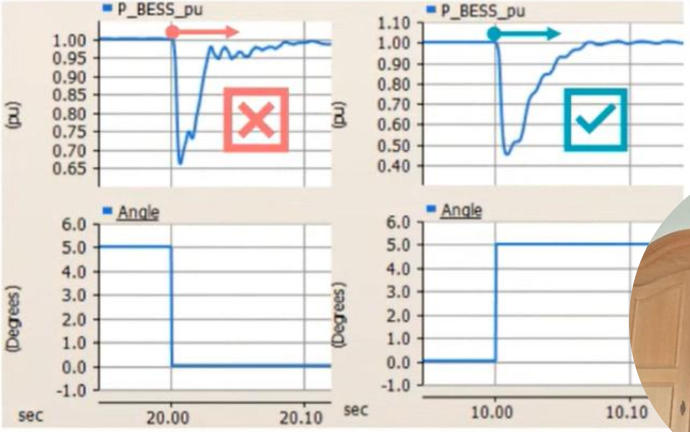
Short Overload is Obligatory

Even if not explicitly required per code, de-facto for stable controls

Inconsistent Control Response w/o >>I

- OEM Controls often fail on
  - Asymmetric conditions
  - Non-Prioritization of Current
  - Edge of Current Capability Curve → -δ° at 1p.u.
- Many GFM Codes do not:
  - Prescribe asymmetric fault tests
  - Detail prioritization of current
  - Prescribe testing at current limits





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Inertia Limits

Higher RoCoFs and/or higher Inertia Constants (H) drive higher plant overload requirements.

Methods for Reserving Power Overhead

- ΔP Powers must be reserved on top of steady state business cases to ensure revenue
- German TSOs check your average 15min power yearly and adapt availability and payment
- Double-bidding with FCR and VR is allowed in Germany and NESO
- NESO requires 5s duration (not H) at 1Hz/s
- Germany requires 1s duration at 2Hz/s

Parameterization of Controls

ΔP:RoCoF	H=3.125s	H=6.25s	H=9,375s	H=12.5s
0.1 Hz/s	1.3%	2.5%	3.8%	5%
0.5 Hz/s	6.3%	12.5%	18.8%	25%
1 Hz/s	12.5%	25%	37.5%	50%
1.5 Hz/s	18.8%	37.5%	56.3%	75%
2 Hz/s	25%	50%	75%	100%

TSO Design Requirement

Hardware Capabil

Quiz

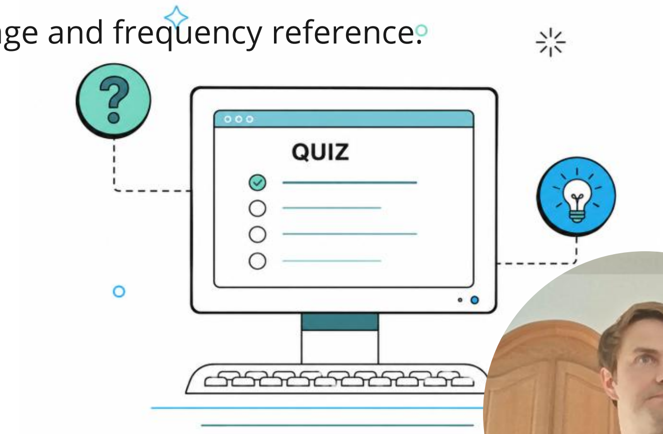
Can an electrical grid operate with 100% Grid-Following inverter-based resources?

A. Yes, provided there is sufficient battery capacity and renewable generation.

B. No, because Grid-Following inverters cannot contribute to system frequency.

A. No, because at least one source must establish the voltage and frequency reference.

B. Yes, if the transmission system is strong enough.



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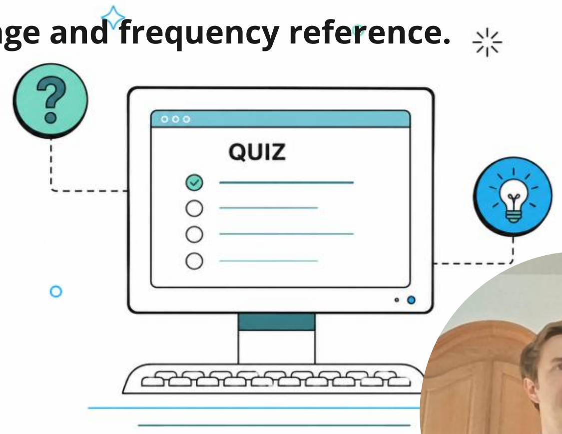
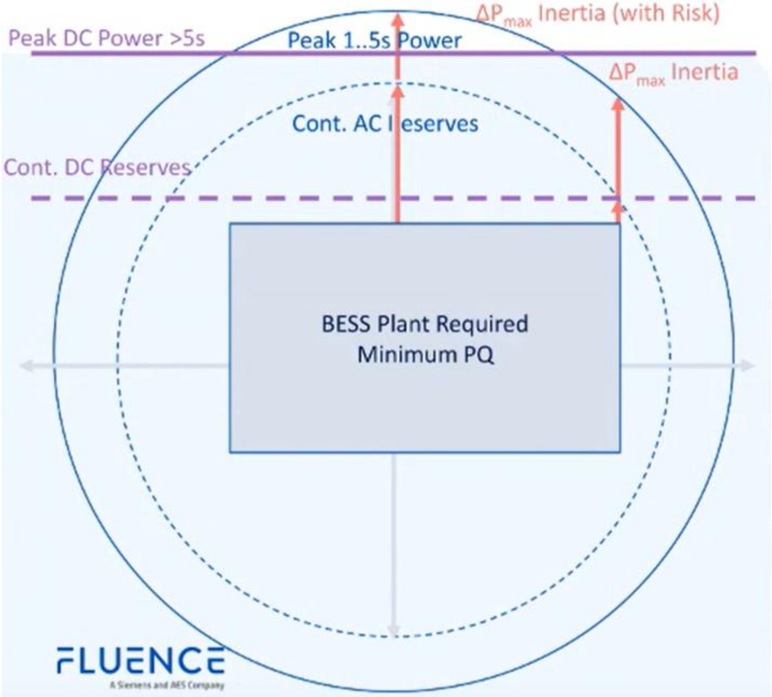


PCS overview – Fluence example

Function/Attribute	DC Block + Central PCS from:		Smartstack AC Block
	Supplier A	Supplier B	
De-rating to run GFM	10%	0%	0%
Hardware Required?	Yes, AC Filter	No	No
Over-load Capability (Inertia)	0%	120%	125..130%
Over-Current Capability (SCL)	TBD	125 %	~130%
Overbuild Impact	Increased footprint, extra MV trafo and RMUs		Internal PCS Exp[illegible]
Controls Validation	Failing	Passing	Passing
Grid-Restoration Capable	No	Yes	Yes

Interia Sizing

"MWs" are not energy for Inertia, rather a historical proxy for inherent P(RoCoF) from machines



Key Points to Consider

- Inherent Capabilities vs. Design Overbuild
  - Every BESS has spare PCS power MVA
  - Some PCS have inherent overload(1..5s) as well
  - Some customers may pay for even more!
- Max Inertia is limited by various factors:
  - Controls – e.g. H=1(stability) to 12.5s(market)
  - AC power reserves: $\Delta P_{max} = \frac{2 \times H \times RoCoF_{max} \times P_{nom}}{50\ Hz}$
  - DC power limits to serve max AC power
  - Both AC&DC power reserves must be provided for full time duration (e.g. 1..5s)
- Payment on $MWs = H[s] \times P_{nom}[MW]$

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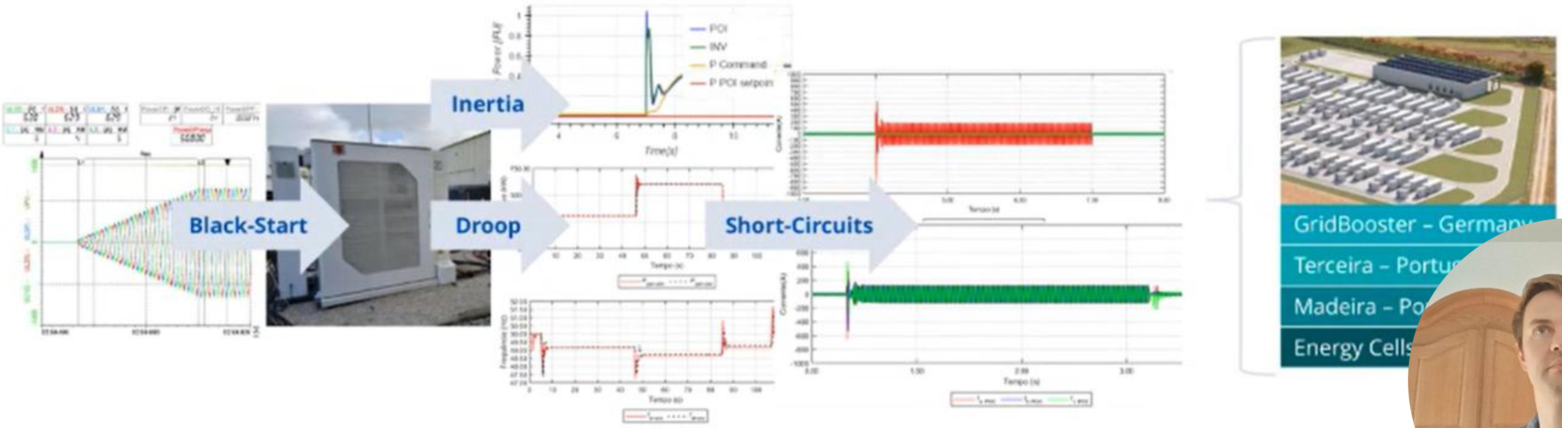
Qualification and Integration

Picking Apart the PCS

- **Documentation Diligence.**
- **EMT Simulations:** (PSCAD, PF, PSSE, HiL)
- **Factory Witnessed Tests:** Direct Controls/Sequences, Accuracy, Speed, CMV, Black-Start, Short-time >>I

- **Core Lab(s):** Simulation & Validation Fluence PPC/Cube, 1..2xPCS, MV Trafo, Grid and/or Grid Emulators, Load banks
- **Power Plant Controls (PPC)** Adaption & Tuning in EMT
- **Project Execution**

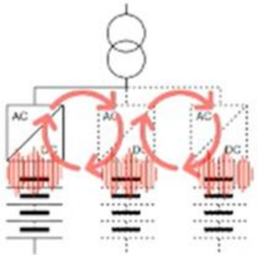


GFM Topology

Common Mode Voltage (CMV) Circulating Current (CC)

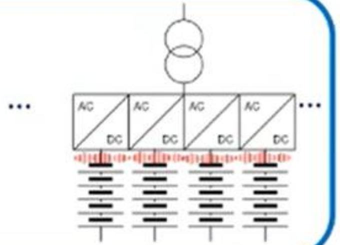
GFM Hardware Topology Issues

- Shared Winding
- Multi GFM Controller
- Multi-PCS-No-Synch
- Multi-DC-Bus



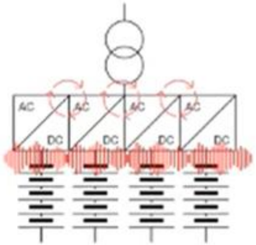
Smartstack Configuration

- String PCS (250..500kVA)
- >>Switching Frequency
- Increased Decoupling
- 1-2+ Battery String/DC-Bus



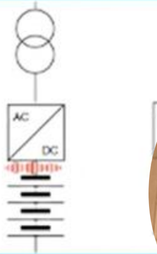
GFM Hardware Topology Issues

- Single Winding
- Single GFM Controller
- Multi-Synched-Stack
- Multi-DC-Bus



Gridstack Pro Configuration

- Single/Multi Winding
- Single GFM Controller
- Multi-Synched-Stack
- Single-DC-Bus



Application of utility scale inverters

FFR: Fast Frequency Response
IBR: Inverter Based Resources

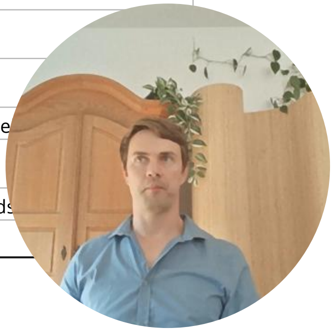
Service/capability	Grid-following inverter system	Grid-forming inverter system	Synchronous machines
Can contribute to system strength		✓	✓[A]
Can have positive disturbance withstand (active power oscillation damping)		✓	✓
Can have positive disturbance withstand (fault ride-through capability)	✓	✓	✓
Can contribute to system inertia		✓[B]	✓
Can contribute to FFR	✓	✓	
Can contribute to primary frequency response	✓	✓	✓
Can support a power system island with supply balancing and secondary frequency response	✓	✓	[illegible]
Can initiate or support system restoration	✓[C]	✓	[illegible]

A. Synchronous machines can usually contribute to system strength much more than IBR due to their higher over
B. A grid-forming inverter system requires energy storage to deliver inertia.
C. Grid-following inverters can support but not initiate system restoration.

Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

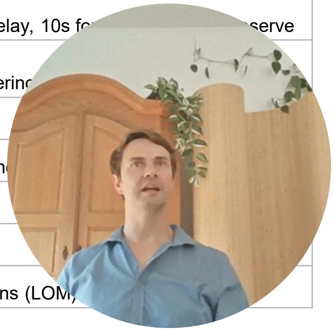
GFL vs GFM general specifications

Parameter	Common GFL Requirement	Common GFM Requirement	Comment
Control topology	Current source control (PLL-based)	Voltage source control (internal oscillator)	
Frequency setpoint range	47.5 – 51.5 Hz	45 – 55 Hz	GFM wider for islanding
Frequency droop (P–f)	Not required	2% – 5% configurable	Mandatory for load sharing
Voltage regulation accuracy	±1% steady-state	±1% steady-state	
Frequency regulation accuracy	Follows grid	±0.01 Hz internal accuracy	Only GFM defines frequency
Synthetic inertia response time	Not supported	≤50 ms activation	
Short circuit current	≤1.2 pu for ≤50 ms	≥2.0 pu for ≥100 ms (configurable up to 3 pu)	
Short Circuit Ratio capability	Minimum SCR ≥3.0	Stable at SCR ≥1.0 (target down to 0.5)	Weak grid operability
THD (voltage / current)	≤3% current THD	≤3% voltage THD	
Black start	Not supported	Can be supported, but not always included.	Key requirement
Islanded operation duration	Not supported	Continuous	
Grid reconnection time	Standard sync ≤60 s	≤5 s seamless synchronisation	
Overload capability (10-60s)	1.1 – 1.2 p.u.	1.1 – 1.2 p.u.	
High overload capability (1-2s)	1.5 p.u.	1.2 – 1.3 p.u.	Differentiator, he
Parallel operation coordination	Parallel operation coordination	Needs coordinated droop-based sharing	
Transition (grid ↔ island)	Not supported	<20 ms	NB for microgrids

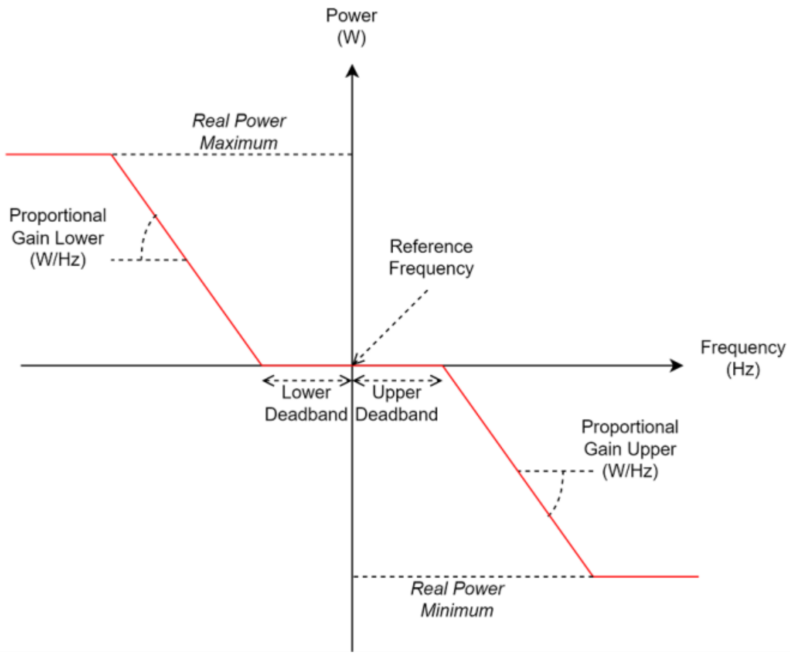


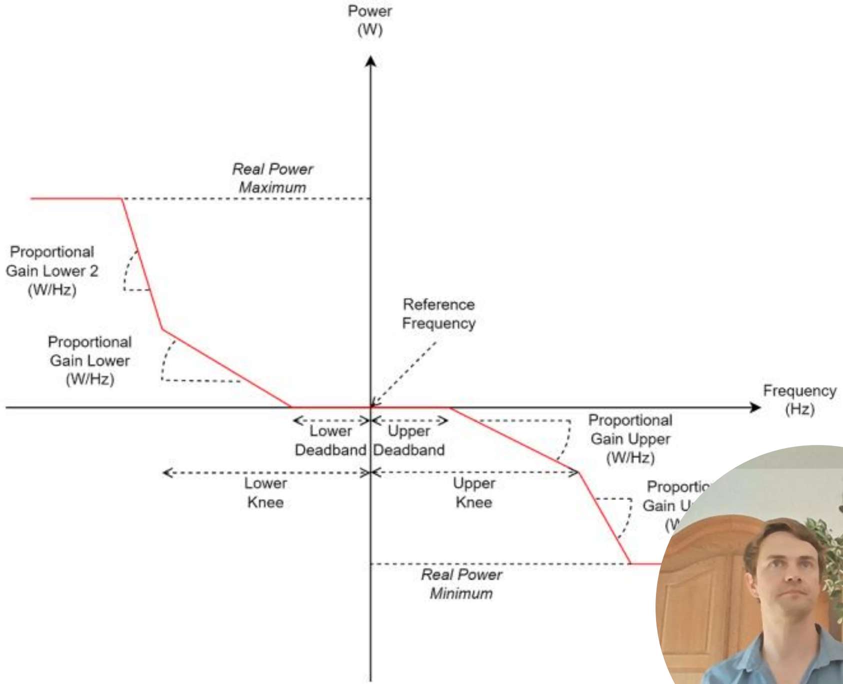
SA BESF code vs GFL vs GFM

Requirement (Category C)	SA BESF Grid Code	Typical GFL	Typical GFM	Notes
Control hierarchy	Not specified	Current-controlled	Voltage-controlled	
Synchronisation method	Not specified	PLL-based	Internal voltage source based	
Minimum SCR	Not specified, prescribed by studies	SCR >2 or (1.8 when tuned)	1 - 1.5 (0.8 when tuned)	
Zero-voltage ride-through	150 ms @ 0 p.u.	50-150 ms @ 0 pu (250 ms+ when tuned)	150-500 ms @ 0 pu (1000 ms+ when tuned)	
Voltage ride-through recovery	Within 500 ms (≥90% recovery)	500 ms - 2000 ms	50 ms - 200 ms	OEM-dependent
Reactive current response	±20% accuracy within 60 ms	±10% to ±20% in 40 - 150 ms	±5% to ±15% in 5 - 50 ms	GFM faster due to voltage-source behavior
Fault current contribution	Not specified	1.0–1.2 pu	1.2–2.5 pu	Synchronous machines (3–6 pu)
RoCoF tolerance	Up to ±2.5 Hz/s	1 - 3 Hz/s	3–10+ Hz/s	
Phase jump tolerance	20°	10–20°	20–60° (>90° possible when tuned)	
Inertia capability	Not specified	Synthetic inertia	Virtual synchronous inertia	
Frequency response latency	Not specified directly, but 1 s/10 s	50 - 300 ms delay	5 - 100 ms delay (1 - 5 ms possible)	1s comm delay, 10s fo... serve
Frequency measurement accuracy	±10 mHz	±5 - 20 mHz	±1 - 10 mHz	Mostly meterin...
Black start (Grid restoration)	Not specified	Unavailable	Often available extra	
Islanded operation mode	Not permitted	Unavailable	Available and controllable	GFM design...
Reactive power capability	PF ±0.95	PF ±0.95	PF ±0.95	
Ramp rate control	1 - 20%/min configurable	100%/s configurable	100%/s configurable	
Protection coordination	LOM shut-down within 2 s	Configurable 0.1-2s	Configurable 0.1-2s	Loss of Mains (LOM)



Frequency droop





SA BESF

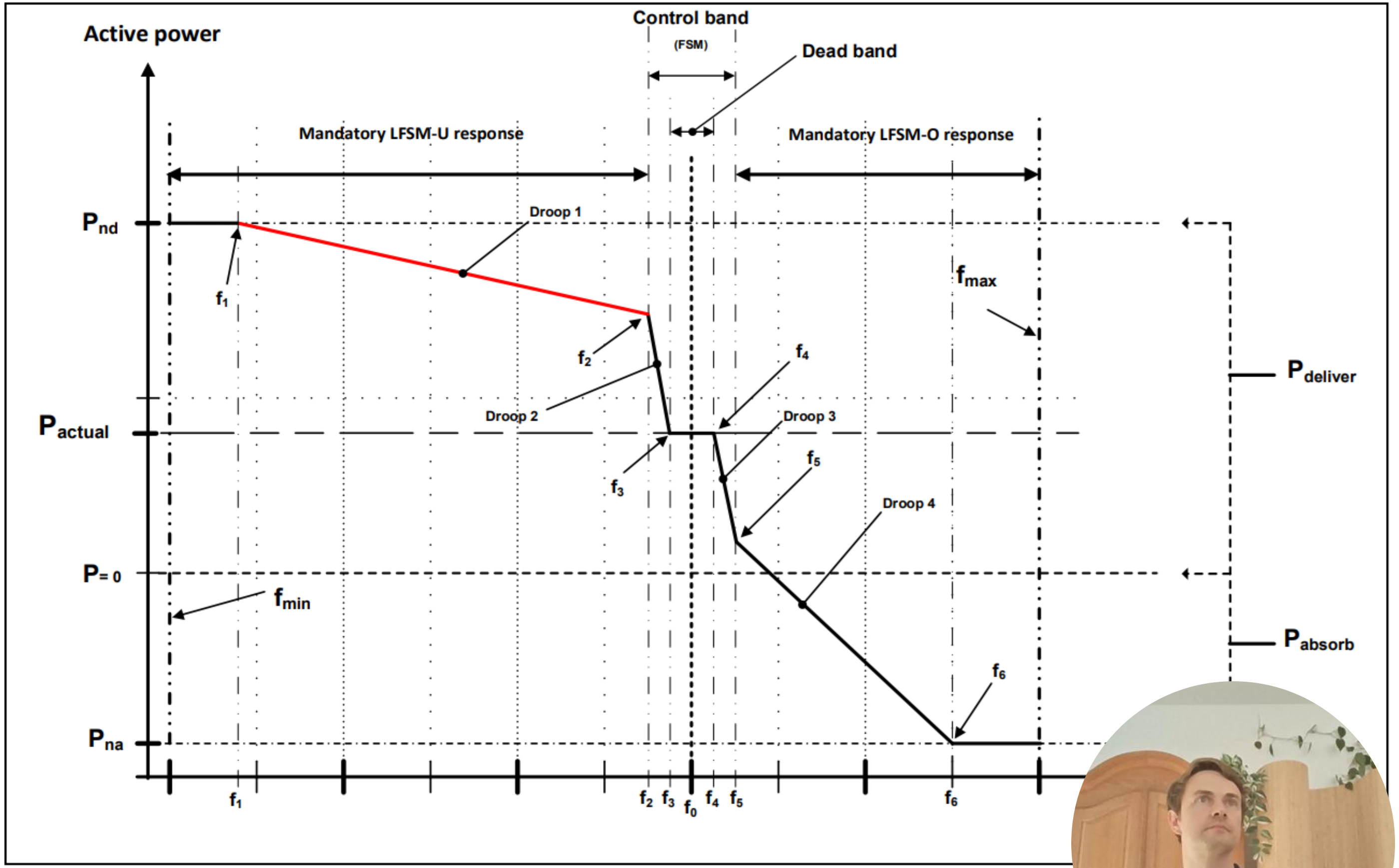
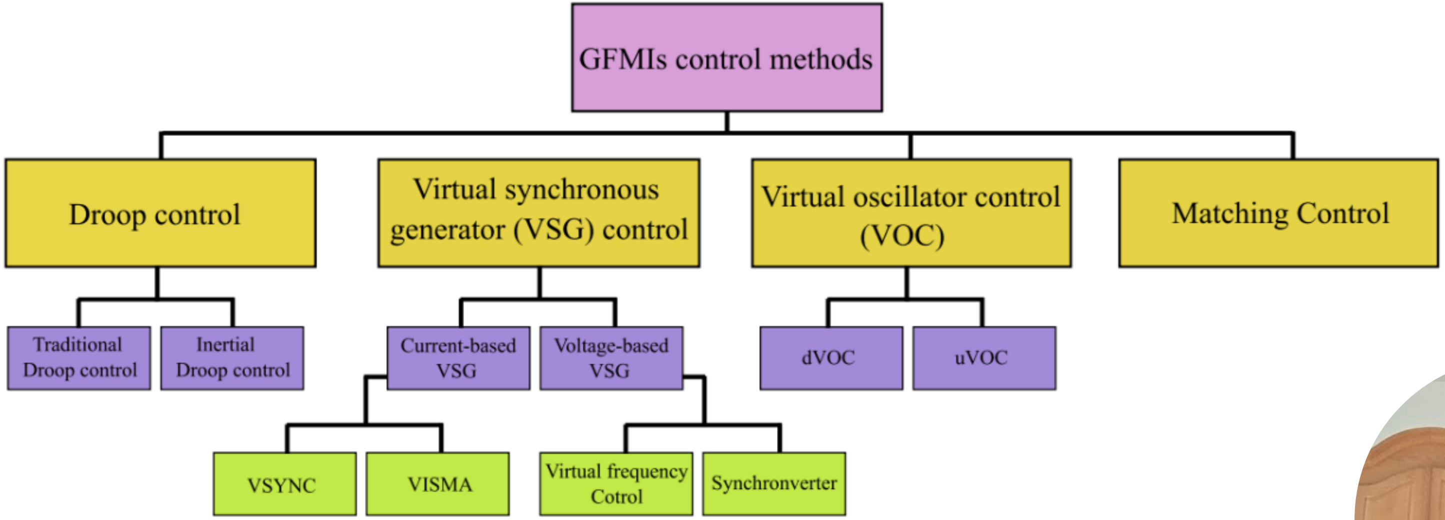


Figure 5 - Power response during low frequency

Control loops

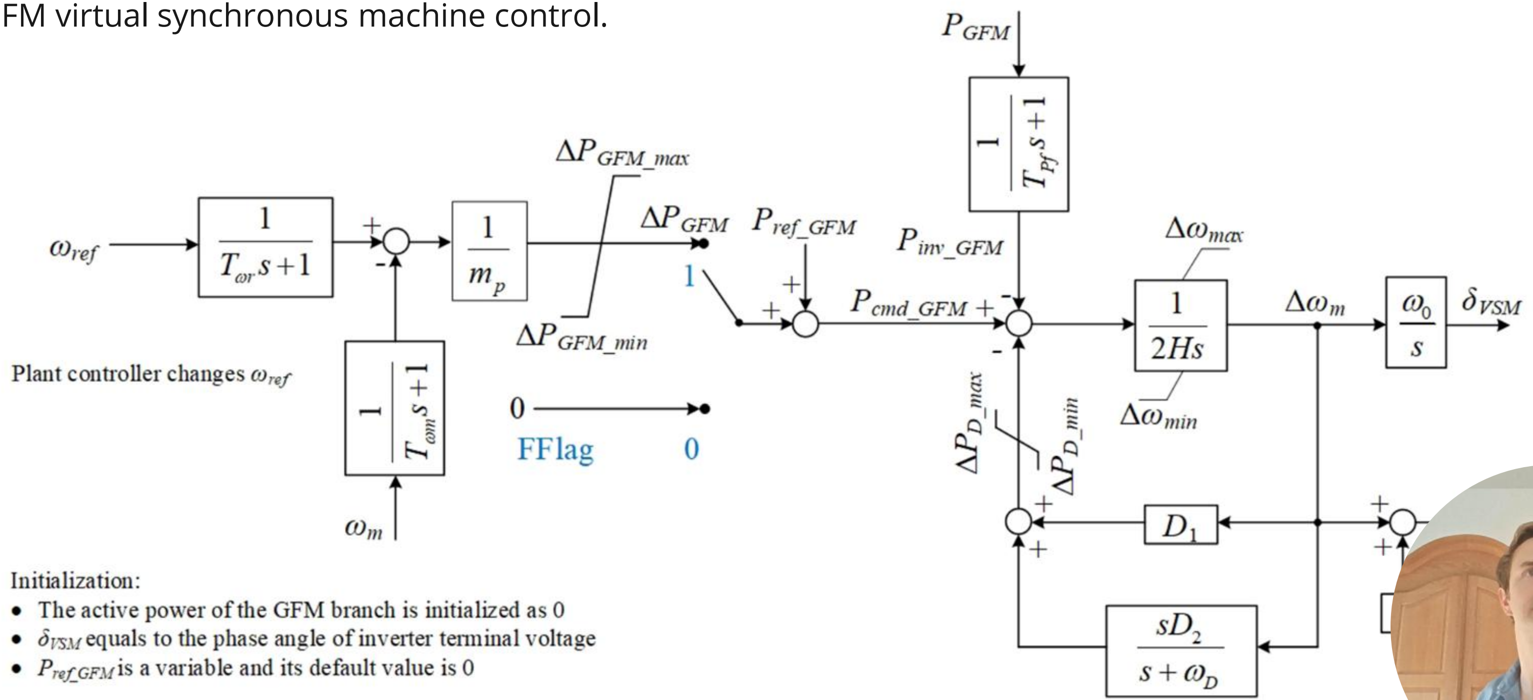
GFMIs conventional control methodologies.



Ref: Advanced control and protection strategies for grid-forming inverters in microgrids—A review, International Journal of Electrical Power and Energy Systems, 202

Control loops

GFM virtual synchronous machine control.



Ref: Standard Library Grid-Forming Hybrid Control Inverter-Based Resource Model Specification, Unify consortium, USA, 2025

Control loops

PGM: Power-generating module

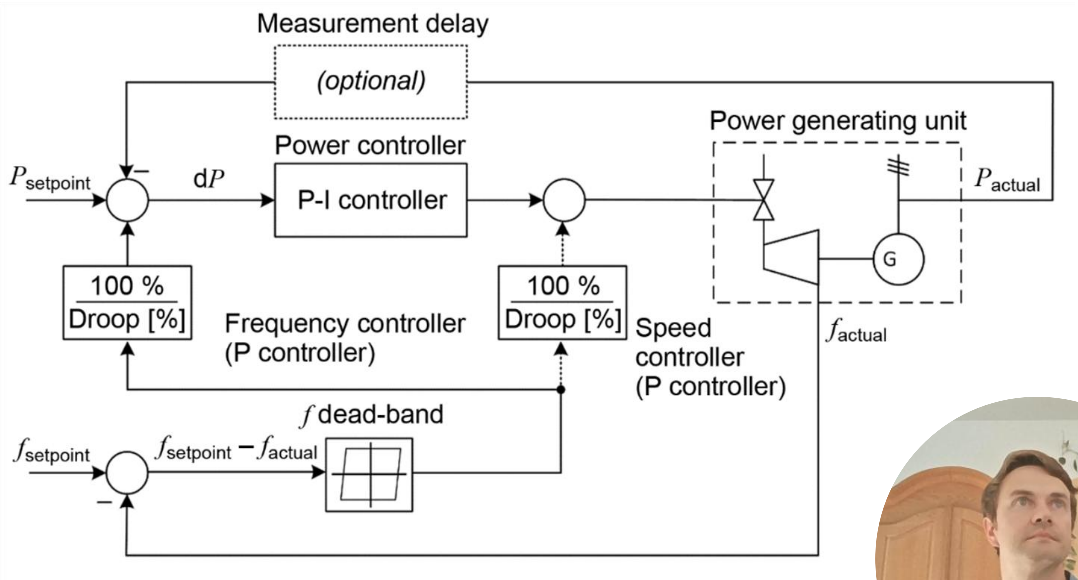


Figure 14 - Schematic structure of power controllers in PGM

Ref: Technical requirements for grid-forming capabilities including provision of inertia, VDE, Germany, October 2025

Section 4: FAQs & Takeaways

PSCAD models

Comparing simulation based inertia response of syncon, existing grid-forming battery, and modified settings battery under RoCoF of 0.5 Hz/s

Model	Function	Inertia constant	Damping	Reactance	Proportional band
Synchronous condenser	Uses a PSCAD generic library model based on the Davenport synchronous condenser parameters, scaled down to 77.16 MVA to match the size of compared battery.	8.655	0.0 damping based on ElectraNet's publication via the OPDMS case	N/A	N/A
Grid-forming battery with settings from an operational asset	The specific customer requested Tesla to reduce the grid-forming inertia as much as possible, requiring these settings.	1.0	0.9	0.2	0.5 Hz
Grid-forming battery with high inertia settings	For comparison, the same plant was modelled with adjusted grid-forming settings.	5.0	2.0	0.04	0.8 Hz

Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

FAQ

When do I need GFM instead of GFL?

1. SCR (Short Circuit Ratio) is low. Eg:
   SCR > 5, GFL usually acceptable.
   SCR ~3–5, situation dependent.
   SCR < 3 GFM often required.
2. High renewable penetration + Low inertia (e.g. Microgrids)
3. Grid code compliance requirement
4. Additional revenue stream e.g. for BESS business case
5. Black start

FAQ

Black start and Grid forming the same things?

No. Grid forming does not automatically mean you can do black start. But typically you would require GFM for black start.

For black start, you typically also require:

- Protection coordination
- Restoration procedures
- Auxiliary supply strategy
- Utility approval/testing

FAQ

Does GFM provide real inertia?

No. Grid-Forming (GFM) inverters do not provide true synchronous inertia because they have no directly coupled rotating mass.

Inertia Type	Typical Source	Response Time	Description
Real (Synchronous) Inertia	Synchronous generators, turbines, synchronous condensers	Instantaneous	Physical kinetic energy directly coupled to grid frequency
Synthetic Inertia	GFL or GFM.	~20–500 ms	Fast active power injection based on measured RoCoF/frequency
Virtual Inertia	GFM inverters	~5–50 ms	Emulated synchronous machine behav Virtual Synchronous Machine controls

A company at Smarter-E Conference (Intersolar) announced 2 µs response time!

FAQ

Are residential backup systems faster at islanding than grid-scale GFM inverters?

Yes, typically.
Residential backup systems usually island in ~5–20 ms, while typical grid-scale GFM systems are ~20–100 ms.

Why the gap:

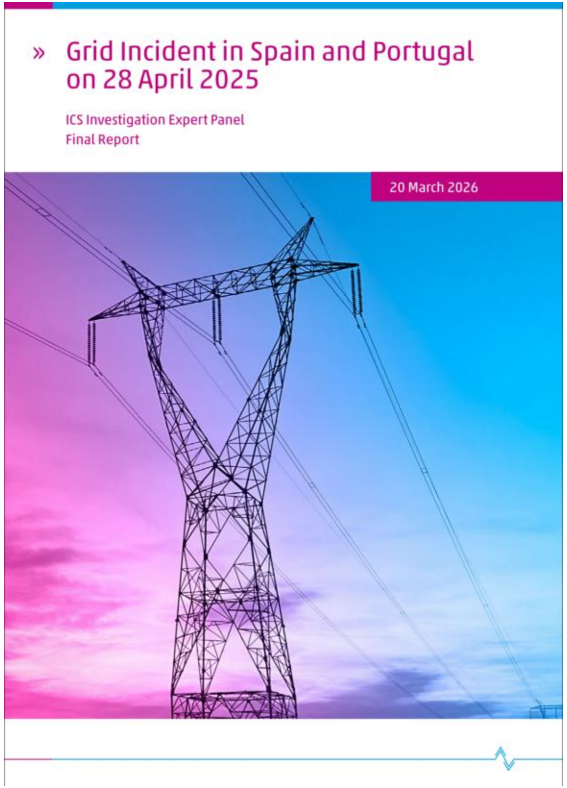
Residential: single inverter + internal transfer switch, minimal protection, no coordination, thus very fast.
Grid-scale: MV breakers, protection relays, multiple PCS, transformer/network transients, and grid-code constraints, adds delays.

Note: the inverter control is similar; the difference stems from system-level protection and coordination and not the power electronics.

FAQ

Sequence of events:

1. High renewable generation and exports created an electrically stressed system.
2. Two oscillation events (0.63 Hz and 0.2 Hz) occurred during the preceding 30 minutes.
3. TSOs took actions to damp the oscillations, but these measures also increased system voltage.
4. Around 12:32, voltages began rising rapidly.
5. Renewable generators reduced active power or disconnected, reducing reactive power absorption.
6. Overvoltage caused more generators to trip.
7. This created a cascading loss of generation (>2.5 GW in seconds).
8. Spain and Portugal lost synchronism with Continental Europe.
9. The Iberian Peninsula separated electrically and collapsed into blackout.



Root Cause Analysis:

1. Insufficient reactive power absorption during rapidly rising voltage.
2. Some renewable plants operating at fixed power factor, meaning they did not dynamically support voltage.
3. Manual rather than automatic switching of shunt reactors (i.e. slow reduction of overvoltage).
4. Some conventional generators not providing the expected reactive power.
5. Certain generator protection settings tripping before network voltage limits were reached.
6. High renewable concentr southwest Spain prod northward power tra
7. Small rooftop PV dis further worsened th

FAQ

What needs to be tuned for the GFM for grid compliance?

Main things to be tuned:

1. Droop control settings (P–f, Q–V)
2. Dynamic response (inertia, damping, loop bandwidths)
3. Limits and priorities (current, ramps, protection interaction)

Starting points

1. P–f droop: 3–5%
2. Q–V droop: 3–5% (weaker grids could be slightly “softer”, e.g. 5–7%)
3. Deadbands: small but nonzero (around 0.2–0.5%)
4. Damping: to avoid oscillations (0.2–2 Hz modes)

Validate with PSCAD (or similar) at target SCR and network impedance.

Common Misconceptions of GFM BESS

Myth	Reality
① "Grid-forming batteries can't provide inertia like traditional synchronous generators as they lack physical spinning mass or is slower to respond to disturbances."	Grid-forming batteries can provide synthetic inertia by emulating a voltage source behind an impedance and the swing equations of synchronous machines. Unlike grid-following inverters, they don't rely on frequency measurements to respond. Instead, their response is intrinsic to their control architecture, delivering a fast, stabilising response in milliseconds comparable to physical inertia.
② "Synthetic inertia is less reliable than traditional inertia because it is software driven and not mechanical."	Synthetic inertia offers similar response speeds and is more reliable than traditional inertia. Grid-forming batteries are a more reliable source of inertia due to the modular nature of batteries, with the average availability rate of batteries in ERCOT (Texas) at 97.7% in 2023. In contrast, a small mechanical issue in a synchronous ma can cause the entire plant to go offline.

Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

Common Misconceptions of GFM BESS

③ "Syncons are a commercially superior option to grid-forming batteries as networks can directly procure a syncon with lower capex and therefore expand their network asset base at lower cost to consumers."

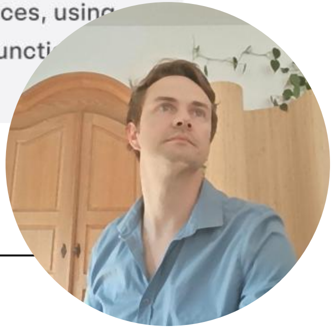
Grid-forming batteries are multi-use assets that can value stack across a range of market services such as energy, frequency, bilateral contracts, as well as inertial and system strength contributions. Unlike single-use assets, they can recover their cost through other market-facing activities while still providing reliable inertia contributions when needed. Grid-forming batteries are also able to be flexible based on market signals and can evolve their services as system needs change.

As battery installs scale, capital costs continue to drop, and deployment timeframes are accelerating. In contrast, syncons face increasing lead times and costs. New syncons face a lead time of greater than 30 months for delivery and installation, around 12-18 months to add a clutch to existing generator if no foundation modification, and up to 48 months for larger units to add a flywhee excluding connection. Retrofitting existing generators as syncor further significantly higher opex than a purpose built syncon.[14]

Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

Common Misconceptions of GFM BESS

Myth	Reality
④ **"Inertia from inverters requires constant energy draw, reducing battery efficiency."**	Grid-forming batteries provide small inertial responses during normal conditions, with immaterial impact on efficiency. Frequency disturbances in typical operations tend to have low Rates of Change of Frequency (RoCoF) and short duration, so the associated energy loss is minimal. While large disturbances can have a greater impact on battery operation, such events are infrequent and do not affect day-to-day performance. This is demonstrated in HPR, where the batteries operate in "inertia mode" for mere seconds during disturbances, using a reserved power margin that doesn't disrupt their primary functi such as energy dispatch.



Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

Common Misconceptions of GFM BESS

⑤ **"Grid-forming batteries are limited in providing inertia due to the need to reserve energy headroom."**

The need to reserve energy headroom to provide inertia service is a commercial consideration that can be optimised rather than a technical limitation. A relatively minor amount of battery energy is consumed to provide because of inertial responses. While inverters in grid-forming do draw more switching losses than grid-following inverters that could be inactive, these losses can be offset from the grid via control modes that maintain battery energy, reducing throughput, but at some cost to the owner.

Batteries typically avoid reaching minimum state of charge (SOC) for commercial reasons and spend limited time at their active power limit, and this behaviour is not representative of their usual cycling patterns, maintaining energy headroom. Energy reserves are not always fully utilised, and in cases of positive RoCoF, adjustments can be made based on operator requirements, indicating that this is more of an operational decision than a technical constraint. Operators hav the flexibility to manage the balance between inertia and reserve o site-by-site basis and have the option to adjust the inverter's overload capability.

Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

Common Misconceptions of GFM BESS

Myth	Reality
⑥ **"Synchronous condensers have a much better overload capability, making them a better provider of inertia."**	In the NEM, syncons have a 3 – 5 p.u. overload capability, whereas grid-forming batteries are currently around 1.2 p.u.. However, if there is a market or actual need for such characteristics grid-forming battery facilities can have more inverters installed to increase the fault current as required.

Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

Common Misconceptions of GFM BESS

⑦ "Grid-forming batteries cannot provide fault current, which is a requirement for providing network support services (system strength)."

Historically, fault current was used as a proxy for system strength because it was directly tied to the physical characteristics of synchronous machines. These machines inherently produced large amounts of fault current due to their rotating mass and electromagnetic design, which also made them capable of maintaining voltage and frequency stability. Because fault current and system strength came from the same source, one was used to infer the other. However, this relationship no longer holds with grid-forming batteries, which can provide system strength without needing to produce high fault currents. As a result, fault current is no longer a necessary metric for providing network support services. Tesla's position is that new technologies should aim to replace the functional outcomes of le systems, not replicate their underlying characteristics.

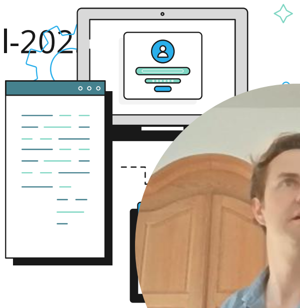
Ref: tesla-energy-the-role-of-grid-forming-inverters-in-providing-inertia-white-paper, Tesla, USA, 2025

Final Takeaways

- To go 100% renewable, Grid Forming BESS is a practical option for (virtual) inertia.
- Future grid codes are very likely to require Grid-Forming capability for more utility-scale projects.
- For now, every project should evaluate whether Grid-Forming delivers technical, regulatory, and commercial value on a case by case basis.

Resources

- Siemens Energy, Grid-forming converters, White paper, Germany, 2024
- NERSA BESF code https://www.nersa.org.za/files/files/2024/08/BESF_Code_Version_5.3.pdf
- Modo Energy, https://modoenergy.com/research
- Rocky Mountain Institute - The Economics of BESS, https://rmi.org/app/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf
- Fluence Energy, https://fluenceenergy.com/energy-storage-technology/
- Energy Storage News, https://www.energy-storage.news/
- Tesla, The role of grid forming inverters in providing inertia, White paper, USA, 2025
- Advanced control and protection strategies for grid-forming inverters in microgrids—A review, International Journal of Electrical Power and Energy Systems, 2025
- ENTSOE, Iberian blackout, https://www.entsoe.eu/publications/blackout/28-april-202 blackout/



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