# Synchronous Condensers as Enablers of Renewable Integration and Grid Stability: Lessons from the Island of Madeira

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PCIC Energy Europe 2026 | Copenhagen | June 2026

# Objectives

- **By the end of this tutorial, you will be able to:**
  - Explain why high IBR (inverter-based resource) penetration creates dynamic security gaps that energy storage alone cannot close.
  - Describe how a flywheel-assisted SynCon (synchronous condenser) provides real inertia, fault current, and voltage anchoring simultaneously.
  - Interpret EEM's phased grid-reinforcement strategy and how to apply the same decision logic to your systems.
  - Identify the commissioning risks specific to a weak-grid and the mitigations that resolve them.

# Tutorial Summary

1. **Why this topic matters** — how island grids become fragile
2. **Technical background** — why SynCon solves what BESS cannot
3. **Case study: Madeira Island** — EEM’s four-phase programme, 1994–2025
4. **SynCon design** — every spec choice justified by a system requirement
5. **Commissioning process** — what the datasheet does not tell you
6. **Grid results** — early operational signals from 2025
7. **What to bring home** — three questions for your own system

**~ 60 min presentation**

# Why This Topic Matters

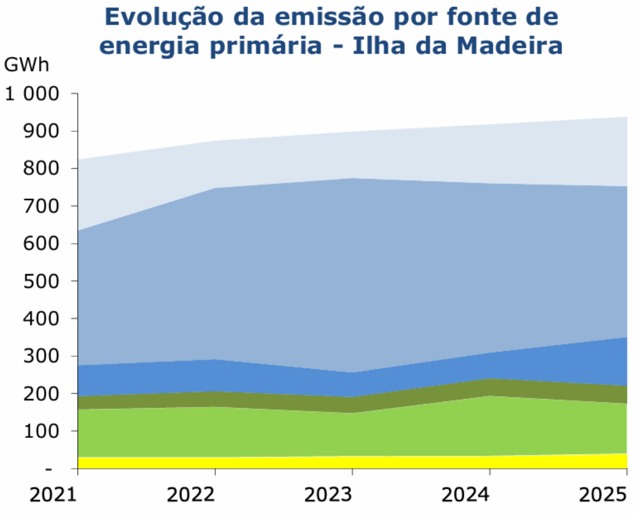
*The problem that forced a different approach*

# Why It Matters — Madeira as a High-IBR Island System

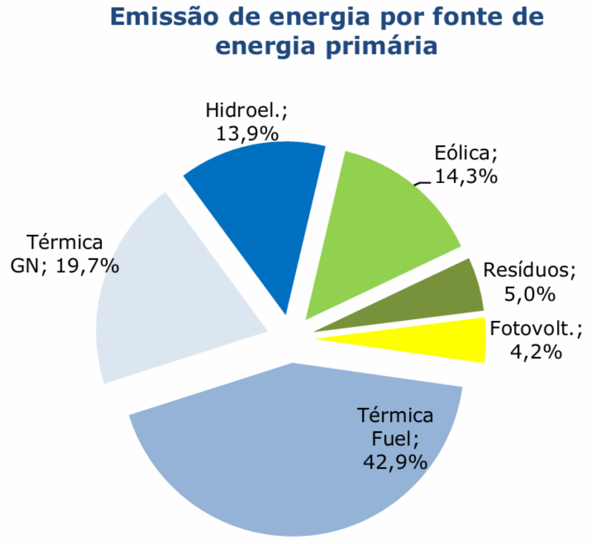
- Madeira Island: isolated grid — **no** synchronous interconnection.

- **2025 grid emission:**
  - 933.84 GWh
  - Peak demand 168.39 MW
  - Non-fossil generation share: 37.4%

- **2025 generation mix:**
  - Thermal fuel oil 42.9%
  - Thermal gas 19.7%
  - Wind 14.3%
  - Hydro 13.9%
  - Waste-to-energy 5.0%
  - Solar PV 4.2%.



**Evolução da emissão por fonte de energia primária - Ilha da Madeira**



**Emissão de energia por fonte de energia primária**

# Why It Matters — Operational Evidence That Triggered Reinforcement

- Instantaneous renewable penetration frequently exceeded **70%** during off-peak hours.
- Specific events produced RoCoF close to **1.5 Hz/s**, frequency nadirs approaching 48.0 Hz, and conditions with low short-circuit current — including potential full blackout scenarios.
- These events confirmed the grid had crossed a threshold where dynamic performance — not capacity — was the binding constraint.
- **This is not an isolated case!**

# Why It Matters — The Remaining Gap

- **The issues with a high-IBR grid:**
  - Low sustained high fault current for protection coordination.
  - Lack of stiff voltage support simultaneously with inertia delivery.
  - Weakened dedicated synchronous source.
- Madeira targets ≥ 55% renewable share by 2030. And they are not the only one.
- Like it or not, renewables are here to stay, and the dynamic gap can only close with dedicated synchronous support.
- **A flywheel-assisted SynCon is a great solution for this context.**

# Technical Background

*What physics drives the requirement for synchronous machines*

# Technical Background — The Real Bottleneck Is Dynamic Security

- The big issue: operating limit **shifts** from annual energy adequacy to dynamic security as IBR share grows.

- **Three constraints bind simultaneously — not independently:**
  - Frequency security: sufficient inertia to limit RoCoF and arrest the nadir above load-shedding thresholds
  - Fault current: minimum short-circuit level for protection grading and relay selectivity
  - Voltage stiffness: capacity to absorb reactive power disturbances without exceeding the permissible voltage band

- No single converter-connected asset addresses all three in a single equipment.

# Technical Background — Real vs. Synthetic Inertia

- **Real inertia** (SynCon + flywheel) is kinetic energy in rotating mass — released instantly as frequency deviates
  → physics-driven → zero control latency.

- **Synthetic inertia** (BESS): emulated via power electronics — effective but bounded by:
  - Measurement and control delay (typically 20-100 ms)
  - State of charge — a depleted battery delivers nothing
  - Converter current limits — cannot surge beyond rated current

- Adding a flywheel to a SynCon raises H without enlarging the electrical machine — the most cost-efficient path to a high inertia constant.

# Technical Background — Fault Current: Why Converters Cannot Replicate It

- A synchronous machine delivers a natural short-circuit surge driven by its internal EMF and sub-transient reactance X''d
  - → physics, not software
  - → First-cycle magnitude: 5-8 p.u.

- Converters are current-limited: typically, 1.0-1.2 p.u. maximum, constrained by semiconductor ratings.

- **Low fault current from IBR-dominated grids causes:**
  - Protection relays failing to pick up
  - Reduced discrimination between faulted and healthy feeders
  - Narrower stability margins and harder voltage recovery after a fault

# Technical Background — Voltage Anchoring in Weak Grids

- A SynCon operates as a strong voltage source with low impedance
  - → it anchors the local busbar
  - → Its AVR (automatic voltage regulator) has a sub-cycle correction

- In weak grids (low SCR), voltage deviations are larger — the SynCon reduces the excursion.

- IBR converters in grid-following mode need a voltage reference – the SynCon provides that reference.

# Technical Background — Why BESS Alone Is Not Enough

- **BESS excels at:**
  - Fast active-power frequency response (sub-second)
  - Energy arbitrage and peak shaving
  - Synthetic inertia emulation — within limits

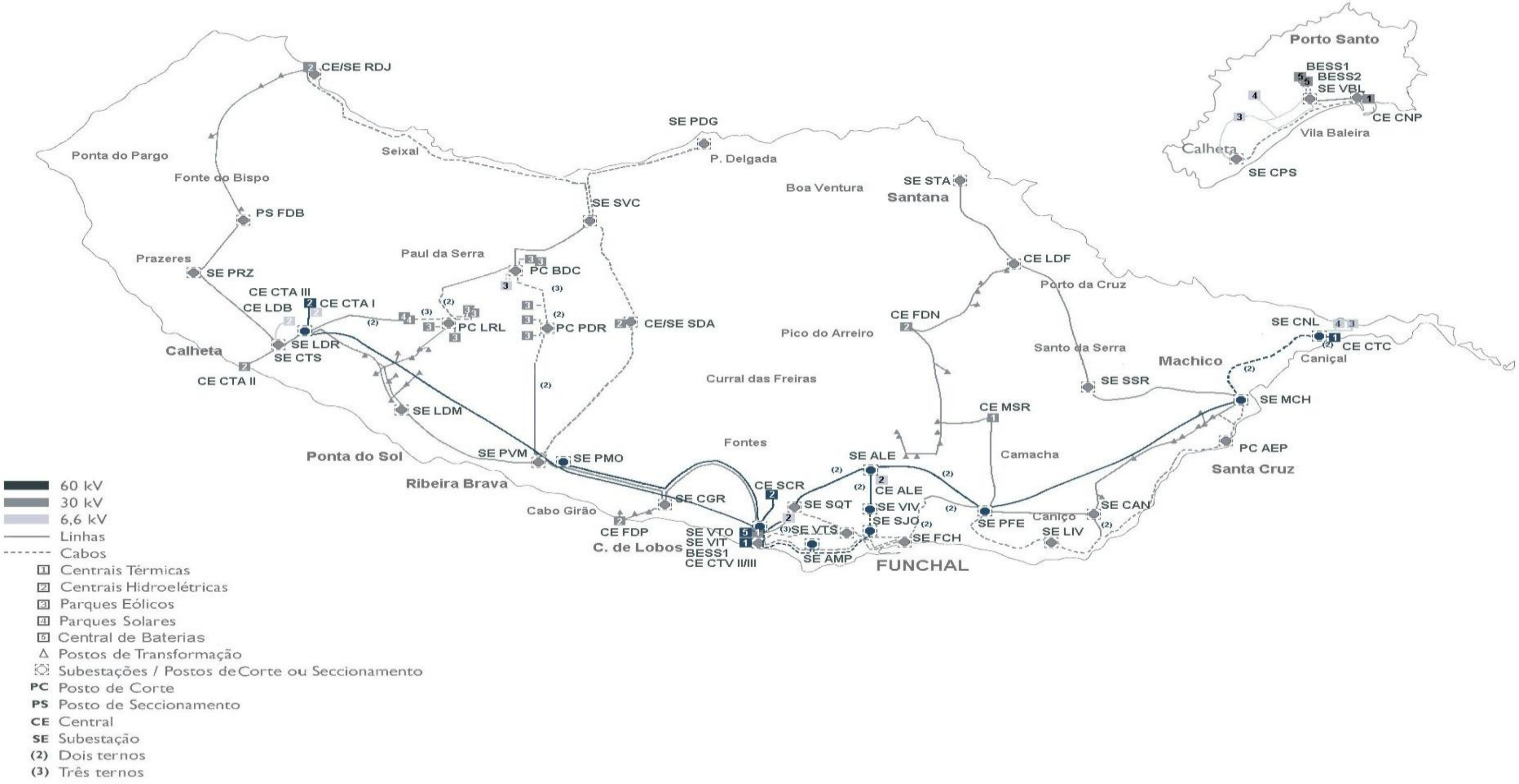
- **BESS does not inherently provide:**
  - Fault current above converter limits
  - A stiff voltage source — converters follow, not anchor, the grid
  - Physical inertia independent of state of charge

- The grid-strength foundation on which BESS controls operate must itself be maintained — **that is the SynCon's role.**

# Case Study: Island of Madeira

*EEM's reinforcement programme 1994–2025*

# Island of Madeira: Interconnecting grid



# Case Study — EEM's Four-Phase Reinforcement Strategy

- **Phase I:** Hydro units converted to synchronous condenser mode
  - ➢ Reactive power support + base inertia at near-zero marginal cost.

- **Phase II:** BESS nodes installed at Vitória and Caniçal
  - ➢ fast-frequency response and RoCoF mitigation.

- **Phase III:** AGC platform coordinating BESS, solar, wind, and hydro for real-time optimal dispatch
  - ➢ EEM internal development – Improving control before adding more assets.

- **Phase IV:** Dedicated flywheel-assisted SynCon at Caniçal
  - ➢ Closes the residual gaps

# Case Study — Asset Commissioning Timeline 1994–2025

- SCR 30 MVA hydro-CS (1994)
- CTA2 8.6 MVA hydro-CS (1996)
- CTA3 37.5 MVA hydro-CS (2021)
- SDA 13.8 MVA hydro-CS (2024)

Total Hydro-Condenser fleet: 89.9MVA

- CBM1 BESS 16.4 MW Vitória (2022)
- CBM2 BESS 20.5 MW Caniçal (2025)

Total BESS fleet: 36.9MW

- AGC-Hydro (2023)
- CNL SynCon+flywheel 15 MVA Caniçal (2025).

Control & 15MVAr SynCon

# Case Study — Phases I and II in Practice

- **Phase I — Hydro in SynCon mode:**
  - Machines declutched from turbines; rotate synchronously, absorbing or injecting reactive power – Inertia contribution modest — machines with low H values.
  - Result: voltage support improved; fault current supplemented; no additional cost

- **Phase II — BESS installation:**
  - Fast-frequency response (FFR): active power injection within <200 ms of frequency deviation
  - Result: wind curtailment dropped to <1%; pumped-hydro units freed from continuous frequency-response standby.

- Both phases necessary but not sufficient — protection coordination requirements remained unmet at high IBR levels.

# Case Study — Phases III and IV: AGC and the Dedicated SynCon

- **Phase III — AGC coordination:**
  - Coordinated setpoint control across BESS, wind, solar, and hydro condensers
  - Enabled higher instantaneous IBR penetration through real-time reserve management.
  - Hydro unit ramps from 0 to 100% in 15 seconds in CS
  - BESS switches between Grid-Forming (high-IBR periods) and Grid-Following (normal) to maintain system stability across operating modes.

- **Phase IV — Canical SynCon:**
  - Eastern zone — the area previously without a dedicated synchronous source
  - Closes the three remaining gaps simultaneously: fault current floor, sustained inertia, and voltage anchoring

# Case Study — A Transferable Planning Framework

- EEM's logic applies to any high-IBR island or weakly-connected grid:
  - **Step 1 — Measure:**
  - **Step 2 — Identify the binding constraint:**
  - **Step 3 — Phase the response:**
  - **Step 4 — Place strategically:**
- Key insight: work backwards from the grid limit — not forward from the asset you own.

# SynCon Design

*Technical choices, trade-offs, and constraints*

# SynCon Design — Project Objectives: Three System-Driven Requirements

- **Design driven by three system requirements — not by machine convention:**
  - Maximum fault current to maintain protection grading at high IBR dispatch levels.
  - Maximum inertia constant H within an acceptable machine size and cost envelope.
  - Thermal reliability for sustained operation through repeated grid disturbances.

- Each requirement maps directly to a grid failure mode identified in the operational evidence. No spec was chosen by convention.

# SynCon Design — Site Selection: Why Caniçal?

- Caniçal is in the eastern zone —previously without any dedicated synchronous source.
- Protection relays in this zone faced the worst-case deficit under high-IBR, light-load conditions.
- The eastern zone hosts the Madeira Free Trade Zone and the Maritime Port — together the largest industrial load concentration on the island.
- Placing the SynCon at Caniçal maximises the fault-current and voltage benefit precisely where load density and network weakness coincide.

# SynCon Design — The Machine: Rating and Inertia

- **Rating:**
- +/- 15 MVA at 60 kV connection point through a 12% transformer.

- **Inertia & Mechanical Construction:**
- H = 10.4s (J = 8490 kgm2) which lead to ~100 MWs:
  - Machine H = 4.6 s (rotor mass) → J = 3755 kgm2
  - Flywheel H = 5.8 s (shaft extension, carbon steel construction) → J = 4735 kgm2
  - Critical speed margins verified for both SynCon-only and combined SynCon + inertia booster → > 15% separation.

- **System study basis:** Frequency variation of 5% and 10% voltage variation

# SynCon Design — Excitation and Thermal Philosophy

- **Excitation: PMG (permanent magnet generator) shaft-mounted.**
  - PMG excitation is self-sustaining.
  - Critical in island systems where auxiliary bus voltage may collapse during a fault.

- **Insulation class — Class F rated, operated at Class B limits:**
  - Class F insulation (155 °C rated) with Class B operating limit (130 °C).
  - Enables sustained repetitive dynamic overloads up to 2.0 p.u. for 10 s without insulation degradation.

- Thermal margin is a reliability requirement, not a comfort factor — a SynCon in a weak grid faces repeated large MVAr swings.

# SynCon Design — Fault Current Contribution

- Standard factory configuration: 2.0 kA symmetrical short-circuit current.
- Project specification: 2.6 kA symmetrical — a 30% uplift.
- How: reduced sub-transient reactance X''d by modifying stator winding geometry and slot shape.

- **Machine fault current envelope:**
  - Nominal stator current: 787.3 A
  - PMG sustains field current through voltage dips — fault current maintained

- Protection implication: higher fault current restores the relay sensitivity lost when IBR units are dispatched.

# SynCon Design — Starting Architecture: LV-VSD & Pony Motor

- **Starting**:
  - 800 kW LV-VSD (low-voltage variable speed drive) + Pony Motor.
  - VSD ramps the machine progressively to near-synchronous speed before synchronization.
- **Why not direct-on-line?** DOL inrush would exceed fault-level margins.
- **Flying-start:**
  - Re-engages without a full coast-down — restart time from >90 min to <5 min.
- **Pony motor additional perk**:
  - small auxiliary motor support slow-speed turning during outages.

# SynCon Design — Control and Dispatch Architecture

- **AVR**
  - operating modes: constant voltage / constant reactive power / power factor.
  - Dual-redundant with 60 kV bus voltage feedback.
  - PSS (Power System Stabilizer): included.

- **Dispatch**: Modbus TCP/IP protocol.

- **Limiters**: OEL (over-excitation), UEL (under-excitation), active current limiter.

- **The entire control chain is treated as one coherent architecture.**

# Commissioning Process

*Validation under real island conditions*

# Commissioning — Validation, Not Handover

- **What made Madeira different from standard commissioning:**
  - Grid frequency and voltage fluctuate continuously
  - No other large synchronous source in the eastern zone
  - Each test changes the grid state

- Approach: commissioning treated as validation plus tuning — tests designed to excite the system modes that matter in service.

*[FIGURE: Commissioning test sequence overview — phase 1 (rotation validation), phase 2 (grid connection), phase 3 (AVR/PSS tuning), phase 4 (redundancy tests). Source: WEG commissioning report]*

# Commissioning — Weak-Grid Synchronisation

- **Phase 1**: rotation validation – without grid coupling.

- **Phase 2**: controlled grid connection — synchronization.

- **Challenge**: synchronization window is narrow and time-varying.
- **Solution**: synchronization logic tuned with tighter phase and voltage thresholds.

- **Result**: more than 50% completed in under 4 minutes from standstill.
- **Lesson**: synchronization algorithms designed for stiff grids must be re-tuned for island conditions — factory defaults are not adequate.

  *[FIGURE: Synchronisation event recording — VSD speed ramp, synchrocheck window, breaker close. Overlay: Madeira grid frequency variation during the synchronisation sequence.]*

# Commissioning — VSD Flying-Start

- **Challenge**: VSD must identify rotor speed and phase angle of the spinning machine before engaging — without reliable mechanical sensors at all speeds.
- **Flywheel effect**: the larger combined J slows speed decay, but the VSD speed-identification algorithm must account for the higher inertia.
- Standard drive firmware was tuned specifically for the machine + flywheel inertia constant — do not use generic settings.

*[FIGURE T — RIGHT SIDE: Flying-start speed-time profile — machine speed decay after disconnection, VSD re-engagement point, ramp to synchronous speed. Compare: cold start timeline vs flying-start timeline.]*

# Commissioning — The 1 h 30 min Coast-Down: What It Revealed

- **Coast-down testing revealed:**
  - PMG auxiliary power remains available throughout the full deceleration curve
  - Bearing lubrication effective down to ~5% rated speed — no forced standstill lubrication required during normal coast
  - Vibration profile crosses two critical speeds during deceleration — both remain within lateral analysis limits

- **Operational asset**: a long coast-down allows controlled shutdown while supporting auxiliaries throughout.

*[FIGURE U — RIGHT SIDE: Coast-down speed-time curve with annotated critical speeds and auxiliary power availability. Source: WEG commissioning test record]*

# Commissioning — Redundancy and Auxiliary Resilience

- **Redundancy architecture:**
  - Dual AVR channels with automatic bumpless transfer on failure
  - Dual protection relays (main + backup) — independent measurement chains
  - Auxiliary cooling fans: N+1 configuration
  - Lube oil: AC pump + DC emergency pump on battery backup

- **Commissioning test**: manual auxiliary failures introduced; machine remained in service through all tested failures without tripping.

*[FIGURE V — RIGHT SIDE: Redundancy architecture diagram — dual AVR, dual protection relays, N+1 cooling fans, AC/DC lube oil pump configuration. Source: WEG engineering documentation]*

# Commissioning — Four Lessons for Weak-Grid Projects

- **1. Re-tune synchronization algorithms for island conditions with weak-grids where phase slips and frequency varys.**

- **2. Treat redundancy and auxiliary continuity as engineering requirements.**

- **3. Tune AVR and PSS against the real grid — not against a model.**

- **4. Fine-tune AVR + VSD (voltage & frequency) coordination with a flywheel-system for starting and synchronization – easier to accelerate than to deaccelerate.**

# Grid Results

*Early operational signals — 2025 data*

# Grid Results — Operational Data: An Important Caveat

- **What can be stated with confidence:**
  - The machine is in commercial service, dispatched as a grid-support asset by EEM
  - Early operational signals confirm the design intent across all three service categories
  - No grid-security events in the eastern zone attributable to low fault level or insufficient inertia have occurred since commissioning

- Quantitative performance data will be presented in future publications as the operational dataset matures.

# Grid Results — Voltage Support and Frequency Response

- **Voltage support**: the SynCon actively regulates Caniçal busbar voltage.
- **Frequency response**: inertial contribution is qualitatively consistent with simulation predictions.
- **Complementarity with BESS**: BESS handles the fast millisecond-scale active-power response; the SynCon provides the sustained physical inertia floor and fault level.
- **The two technologies are complementary, not competing.**

# Grid Results — Dispatch Flexibility and Short-Circuit Power

- **Dispatch flexibility**: the installation reduces the need to keep hydro units synchronized purely for frequency response.

- **Short-circuit power**: with SynCon online and 60 kV ring closure, average SCL increased +3% and SCL increased +12% when compared with 2024 figures across key nodes.

- **The SCL gain is the operationally critical figure** — it lifts the minimum fault level that protection relays see under light-load, high-IBR conditions.

- **Headline result: in 2025 the Madeira grid operated with a single thermal unit online during off-peak high-renewable windows.**

# What to Bring Home & Conclusions

*Three questions for your own system*

# What to Bring Home — Three Framework Questions for Your System

- Before specifying a SynCon or any grid-support asset, answer these three questions:
  - **1. What is your binding dynamic constraint, and at what IBR penetration does it bite?**
  - **2. Does your grid need one service or three simultaneously?**
  - **3. Where in your network topology does dynamic support deliver the most leverage?**

- **Takeaways from this tutorial:**
  - Island grids require simultaneous treatment constraints.
  - A flywheel-assisted SynCon is powerful precisely because it couples electromechanical support in one asset.

# Conclusions

- High IBR penetration creates constraints.
- A flywheel-assisted SynCon couples three services in one asset.
- Commissioning quality determines service value.
- Madeira 2025: proof of concept at grid scale.

# OBRIGADO!

*The floor is open — what did this raise for your own system?*