General Summary Full Session

Grid Forming Technology and System Stability

The industry is rapidly advancing toward integrating grid forming technology as a core solution to manage high shares of inverter-based resources (IBRs) and ensure system stability.

- **Grid forming technology is crucial to enable systems to operate safely at up to 100% IBR penetration**, as highlighted by one of the expert speakers who noted some systems already operate at **75–80%** inverter-based share
    - Grid forming allows inverters to maintain voltage and frequency stability rapidly after disturbances, supporting services like fault current injection, damping, and black start.
    - The technical requirements are evolving from regional and national codes toward more harmonized regulations, but **lack of harmonization across countries creates complexity and cost**, as emphasized by two of the expert speakers.
    - Manufacturers stressed the importance of clear, precise requirements and validation methods like envelope curves and EMT simulations to ensure reliable grid forming performance.
    - The **RFG 2.0 code is expected by early 2026** and will require upgrades to current national codes to reflect new system realities, emphasizing the need for faster implementation to keep pace with grid changes.
- **Market-based and technical requirements are both essential to procure grid forming capabilities effectively**, with examples like Germany's inertia market launching by January 2026 and the UK's Pathfinder tenders showing how procurement mechanisms can incentivize adoption.
    - Germany's inertia market uses a **fixed price** system with a split between basic and premium products based on availability.
    - The UK experience shows that **market tenders with clear performance specs can accelerate deployment** and allow batteries to compete with synchronous condensers, increasing technology diversity.

    - There remains a challenge in balancing mandatory grid code requirements with market incentives to avoid overburdening developers and to encourage cost-effective grid forming deployments.

- **System operators face challenges in managing grid stability with increased IBR penetration and must enhance monitoring, modeling, and quality assurance**
    - One system operator plans to introduce grid forming battery storage and Statcoms by 2029 as part of grid restoration strategies.
    - Real-time monitoring tools and improved EMT simulations are critical to verify asset behavior and avoid instability during system events.
    - The Iberian blackout in April 2023, involving a **55 GW system outage lasting up to 12 hours**, highlighted the urgent need to evolve grid codes and operational practices to handle voltage and frequency challenges under high renewables.

- **Manufacturers express concern about the risk of mandating immature or overly prescriptive grid forming requirements**, urging flexibility and technology-neutral approaches to enable innovation and cost control
    - Manufacturer: warned that **no reliable grid forming wind turbine technology is fully proven yet**, making broad mandates risky.
    - Manufacturer: emphasized the need for **precise and harmonized definitions and test protocols** to avoid ambiguous requirements that could delay projects or increase costs.
    - OEMs prefer a market-based approach to finance long-term investments with clear revenue streams for grid forming services to reduce risk and encourage adoption.

Regulatory Framework and Implementation

The evolving regulatory landscape is attempting to keep pace with technology and system needs but faces delays and fragmentation that slow harmonization and deployment.

- **The European RFG 2.0 code and related network codes are central to defining mandatory grid forming requirements but face complex implementation across member states**
    - Technical and regulatory bodies are driving amendments to the grid connection codes, targeting adoption by 2026, but national implementation will vary in timing and scope.

    - Implementation guidelines following code adoption can be accelerated by member states if urgency dictates, but manufacturers require stable, detailed specs before mass production can begin.
    - The codes separate mandatory requirements (non-negotiable) from non-mandatory aspects subject to TSO discretion, and remuneration is not prescribed in codes but is handled by market or national mechanisms.
- **Fragmentation remains a challenge with over 27 EU member states potentially adopting varied flavors of grid forming regulations**, risking increased complexity and costs for manufacturers and slowing progress.
    - It was pointed out that **harmonization efforts exist but member states often implement variants tailored to their local system needs**.
    - Connection codes separate generation and demand requirements due to different operational roles and visibility, but allow flexibility at local connection points for combined assets such as hybrid PV plus storage.
    - The need for precise, aligned definitions of key concepts like voltage and fault responses is critical to reducing ambiguity and easing compliance.
- **Regulatory approaches combine grid code mandates, market mechanisms, and network component deployments to ensure system stability while balancing cost and feasibility**
    - Germany's System Stability Roadmap integrates all three pillars with milestones through 2030, including compulsory grid forming for new battery connections at transmission level and market-based inertia procurement.
    - Panelists agreed that no single approach suffices; a dynamic combination tailored by region and service type is required to deliver secure, cost-effective grids.
    - Some expressed concern that too stringent or overly detailed mandates risk excluding technologies or delaying deployment, favoring performance-based, technology-neutral requirements incentivized by markets.
- **Existing installed assets lacking grid forming capabilities present a significant challenge for transition**, with options including retroactive requirements, voluntary market participation upgrades, or continued reliance on synchronous machines.
    - Regulatory frameworks allow for gradual retroactive application, but cost-benefit and technical feasibility analyses are needed for existing plants.

  - Germany and other countries are considering how to incentivize upgrades or compensate existing assets to avoid abrupt losses in system stability.
  - OEMs note that retrofitting synchronous machines for grid forming or synchronous condenser operation is expensive and technically challenging, making long-term solutions reliant on new inverter-based assets.

Data Centers and Large Loads as Grid Forming Resources

The rapid growth of large AI data centers and other flexible loads offers both challenges and opportunities for grid stability and flexibility services.

- **Data centers represent a growing share of system peak load, with some regions having data center capacity equal to 15% of peak demand, e.g., Dublin with about 1000 MW on a 6000 MW system**
  - ERCOT's queue shows potential for **up to 100 GW of data center capacity by 2030** on an 85 GW peak system, illustrating rapid growth and the challenge of integrating large, fluctuating loads.
  - Regulatory efforts in the US include special rate categories and demand response programs targeting data center load flexibility, including machine learning workload shifting.
  - The panel discussed the potential for data centers to provide grid forming-like services, but the definition and technical requirements remain unclear given their fluctuating, mostly load-based nature.
- **Panelists highlighted innovative concepts such as treating data centers as microgrids with local generation and storage, decoupled from the public grid by back-to-back converters to manage fluctuations more effectively**
  - This approach could reduce grid connection constraints and enable smoother integration but requires economic viability and technical validation.
  - TSO: data centers have strong business incentives to implement grid forming capabilities, possibly accelerating grid forming deployment at distribution levels faster than renewables alone.
  - Some US data centers already employ grid forming synchronous machine contracts, but concerns remain about equipment wear from load fluctuations and the long-term sustainability of this approach.

System Operations, Monitoring, and Modeling

Real-time monitoring, advanced modeling, and quality assurance are critical enablers for safe operation of grids with high shares of grid forming devices.

- **TSOs emphasize the need for improved simulation tools, such as EMT simulations and SCADA upgrades, to manage asset switching sequences and prevent instability during restoration or faults**
    - Proof of concept models show how switching order of assets like batteries and Statcoms affects system stability and oscillations.
    - Real-time observability and individual asset behavior monitoring are essential to enforce compliance and reliability as grid forming technology proliferates.
- **Industry-wide data and model quality remain a significant bottleneck to accurate dynamic grid analysis and planning**, as multiple panelists highlighted poor data quality and inconsistent model standards across Europe
    - This hinders reliability assessments and increases risks of unexpected behavior from new grid forming assets.
    - Efforts to improve data sharing, develop better validated models, and organize coordinated testing across countries are underway but require acceleration.

Strategic and Process Insights

Stakeholders agree the energy transition demands rapid, collaborative action with flexible strategies reflecting system diversity and evolving knowledge.

- **The transition to a grid dominated by IBRs and grid forming technology is unprecedented in speed and scale, requiring regulatory and market frameworks to adapt quickly or risk instability**
    - The Iberian blackout serves as a stark reminder of vulnerabilities, underscoring the need to respect grid physics and operational realities rather than rely solely on market or technology optimism.
    - A top-down approach is advocated: define future system scenarios, identify stability requirements, assess economic procurement options, then develop codes and market rules accordingly.
    - The complexity of European grids with many TSOs and DSOs complicates coordination, requiring improved governance, transparency, and possibly consolidation or cooperation frameworks.

- **Collaboration and knowledge sharing between countries, system operators, manufacturers, and regulators is vital to accelerate learning and avoid reinvention**
    - Pilot projects, sandboxes, and cross-border studies are essential to reduce risks and improve confidence in grid forming deployments.
    - Experience from the UK's Pathfinder tenders and South Africa's load shedding management offer valuable lessons on market design and demand-side flexibility.
    - Industry participants emphasize that no single technology will solve all challenges; all sectors must contribute and coordinate to achieve a stable, sustainable energy system.
- **Manufacturers caution against overly prescriptive or premature mandates that could stifle innovation or render technologies uneconomic, urging balanced, flexible approaches with clear incentives.**
    - The need for long-term revenue certainty, performance-based requirements, and recognition of differing technology capabilities is essential to accelerate deployment without compromising system needs.
- **System stability must be viewed holistically, integrating grid code mandates, market mechanisms, and direct network assets to meet diverse and evolving reliability needs cost-effectively**.
- **DSOs are a critical but often overlooked part of the stability challenge, requiring increased capabilities and coordination with TSOs to manage distributed grid forming resources and islanding risks**.
    - While their capabilities vary widely, steps toward consolidation, technical upgrades, and clearer obligations are underway in Germany and other countries.
- **Time is of the essence: Industry and regulators must balance urgent deployment with realistic technology maturity and economic feasibility to avoid destabilizing the transition**.
- **Key takeaway consensus is to act decisively, share knowledge, and pragmatically combine technical and market tools to ensure the energy transition succeeds without compromising grid stability**.

Action items

System Operators and Regulators

- Develop modeling and analysis methodologies to better quantify grid stability needs and inertia requirements, aiming for improved forecasts by 2027
- Expedite adoption and implementation of updated grid codes (RFG 2.0), potentially shortening regulatory timelines where feasible
- Enhance monitoring systems for real-time grid forming performance validation post-deployment
- Continue stakeholder engagement with manufacturers and grid users to refine technology-neutral but system-specific requirements

Manufacturers

- Coordinate with TSOs early in development to align on grid forming envelope curves and validation criteria
- Accelerate certification processes for grid forming resources while balancing cost and technological feasibility

Market Designers and Regulators

- Design long-term markets providing stable revenue streams for grid forming capabilities, especially for battery storage and flexible loads
- Reform connection queue management to prioritize realistic project deployments and align with system planning

DSOs

- Prepare capability improvements for managing inverter-heavy distribution networks, including dealing with unintended islanding and grid support services
- Explore collaboration or consolidation models to augment technical and operational competencies

Workshop Organizers

- Facilitate continued knowledge sharing on best practices, pilot projects, and regulatory innovations internationally