Benefits of Grid Forming Battery Energy Storage Systems

Project Findings and Recommendations

Ryan Quint,[1] Farhad Yahyaie,[1] Andrew Isaacs,[2] Lukas Unruh[2]

Elevate Energy Consulting,[1] Electranix Corporation[2]

ENERGY SYSTEMS INTEGRATION GROUP

February 4, 2025

Additional support provided by:

Today's Presenters

Ryan Quint, PhD, PE
President and CEO
Elevate Energy Consulting

Andrew Isaacs
Vice President
Electranix Corporation

Farhad Yahyaie, PhD, PEng
Head, Power System Studies and Modeling
Elevate Energy Consulting

Lukas Unruh
Engineering Manager
Electranix Corporation

ESIG Benefits of GFM BESS Project Team

- **Monthly ESIG Project Team Meetings**
  - Report-outs on modeling and study progress
  - Technical discussions regarding GFM technology
  - Presentations and discussions of GFM experience from industry experts and practitioners around the world

- **Core Modeling and Study Team Efforts**
  - Coordinated modeling and studies efforts
  - ATC, Elevate, Electranix, ESIG

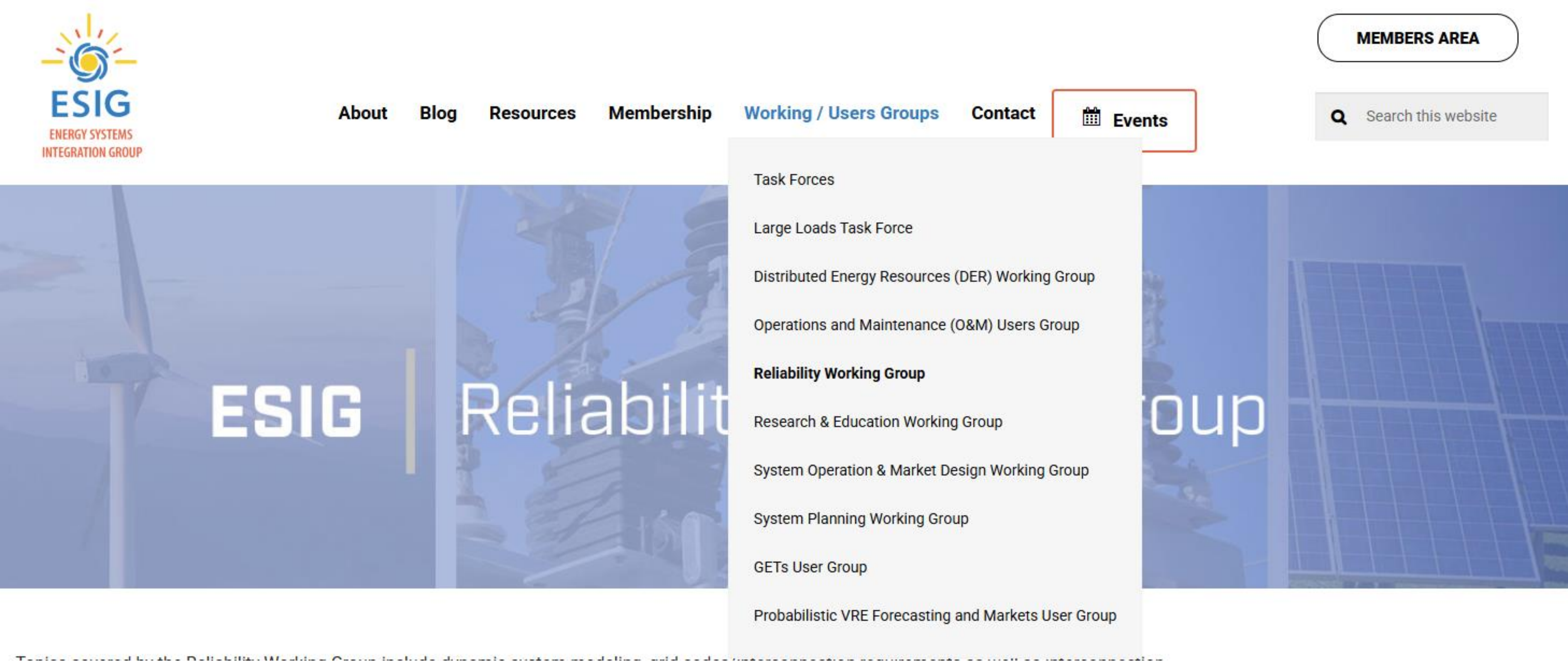
- **Deliverables**
  - Informational webinar today
  - Upcoming brief for decision makers, policymakers, and regulators
  - Outreach to key stakeholders

Project Team Meetings

- **April:** Kickoff and Project Introduction, Ryan Quint, Elevate
- **May:** Project Updates and Scope, Ryan Quint, Elevate
- **June:** GFM Functional Spec Testing, Farhad Yahyaie, Elevate; GFM Studies Update, Lukas Unruh, Electranix
- **July:** GFM Modeling Update, Farhad Yahyaie, Elevate; GB Grid Forming Development, Xiaoyao Zhou, NGESO
- **August:** GFM in Australia, Nilesh Modi
- **September:** History of BESS (and IBRs) in Alaska, Nick Miller, HickoryLedge
- **October:** GFM BESS in MISO, Patrick Dalton, MISO; Tesla GFM BESS Experience, Askhat Tullegen, Tesla
- **November:** ERCOT GFM Adoption, Yunzhi Cheng, ERCOT
- **December:** SMA GFM BESS Technology and Experience, Frank Berring, SMA
- **January:** GFM BESS Effective Inertia Contribution Measurements, Jiangkai Peng, NREL

**Most presentations posted publicly on the ESIG webpage*

Materials Posted



https://www.esig.energy/reliability-working-group/

Materials Posted

Benefits of GFM BESS Project Team

Objective: The Benefits of GFM BESS Project Team conducted detailed electromagnetic transient (EMT) studies on a real-world, interconnected power system to explore the benefits, opportunities, challenges, and considerations of adopting grid-forming (GFM) battery energy storage systems (BESS) at-scale. The studies explored, using an actual network with real models from original equipment manufacturers (OEMs), the following core questions:

- Is GFM BESS a "do no harm" solution option that provides grid-stabilizing benefits to both weak and strong areas of the grid?
- What are the benefits or challenges of adopting GFM BESS on a widespread basis?
- Will there be any notable interactions or interoperability challenges with GFM BESS technologies across multiple OEMs?
- Can GFM BESS help defer more costly solution options and lead to increased integration or less curtailment of renewables?

Approach: EMT studies were conducted with a partner utility, American Transmission Co. (ATC), using their actual network and scenarios loosely based on their interconnection studies. The study team developed scenarios and sensitivities in different zones of the ATC system to explore the questions described above. The studies were held confidentially among the core study team; however, results were shared in a genericized and anonymized manner with the broader project team to help guide the study, discuss key findings, explore additional sensitivities or scenarios, and to help craft the key messages regarding findings and recommendations from this work. The project team met periodically to hold informational meetings, hear from a wide array of stakeholders, and share lessons learned.

Deliverables: Deliverables include a public informationa
project team is developing and publishing a high-level p
briefings to key entities at the conclusion of the work.

Project Team Lead: **Ryan Quint**, Elevate Energy Consulti
Ryan Quint is the Founder and CEO of Elevate Energy Cor
over 20 years experience leading EMT studies and tacklir

Deliverables: Deliverables include a public informational webinar on February 4, 2025 to highlight the key findings, takeaways, and recommendations from the studies conducted. Additionally, the project team is developing and publishing a high-level policy brief intended for decision makers, policymakers, and regulatory bodies. The project team is also conducting educational outreach and briefings to key entities at the conclusion of the work.

Supporting Presentations:

July 2, 2024: GB Grid Forming Development, National Grid ESO
August 2, 2024: GFM in Australia, AEMO
September 5, 2024: History of BESS (and IBRs) in Alaska, HickoryLedge
October 3, 2024: Grid-Forming Battery Energy Storage Systems, MISO
November 7, 2024: ERCOT AGS-ESR Adoption and Proposed Requirements, ERCOT
December 5, 2024: SMA Large Scale Grid Forming Solutions, SMA

https://www.esig.energy/benefits-of-gfm-bess-project-team/

Why GFM in BESS, Specifically?

Attribute	BESS	Solar PV	Wind	STATCOM
Energy Buffer	Readily available	Curtailment or hardware upgrade	Maybe be available, to limited extent; hardware or curtailment may be needed	Limited available inherently; short-term can be added by supercapacitor
Mechanical Stress	None	None	Yes	None
Hardware vs. Software	Software	Software (and maybe hardware) with curtailment; hardware without	Software (and maybe hardware) with curtailment; hardware without	Software
Technology Readiness	Yes	In development	In development	Yes
Cost	Relatively low – “Free”	More costly	Expensive	Based on storage size (need)


Source: Tesla

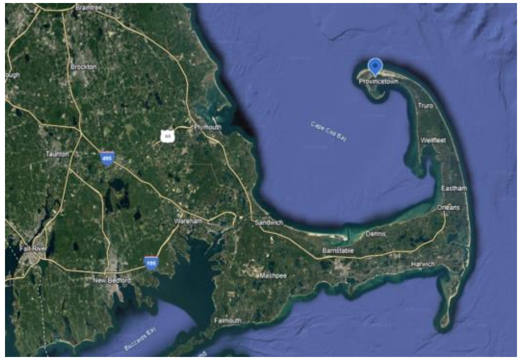

Source: Hitachi Energy

Examples of Existing GFM Projects in the Continental US

Mackinac HVDC

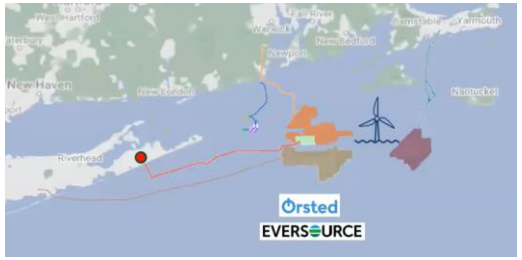
Source: B&V

Cape Code GFM BESS



Source: Eversource

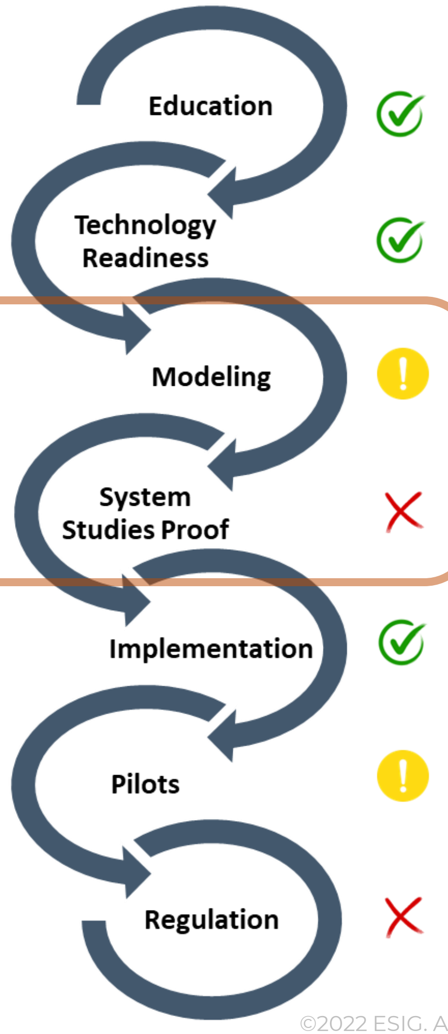
South Fork Offshore Wind GFM STATCOM



Source: Eversource

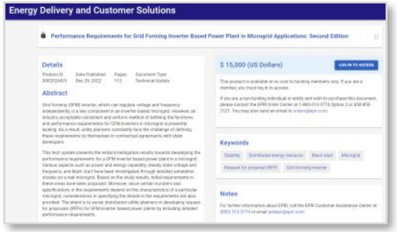
Pathway to Widespread Adoption

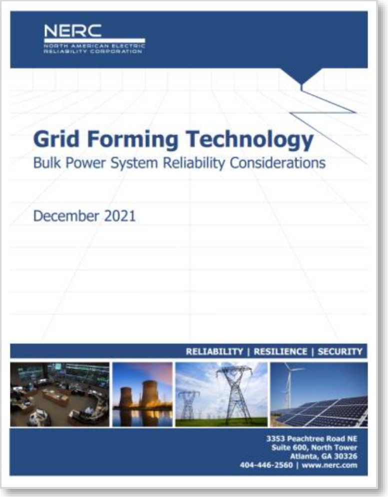
Education	*Trust that we sufficiently understand the technology*
Technology Readiness	*Trust that the technology is commercially available*
Modeling	*Trust that we can accurately represent the equipment in studies*
System Studies	*Trust that the technology will work in the larger interconnected system*
Implementation	*Trust that we know how to integrate the technology*
Pilots	*Trust that early adopters had success*
Regulation	*Trust that regulatory action is just, cost-effective, and reasonable*

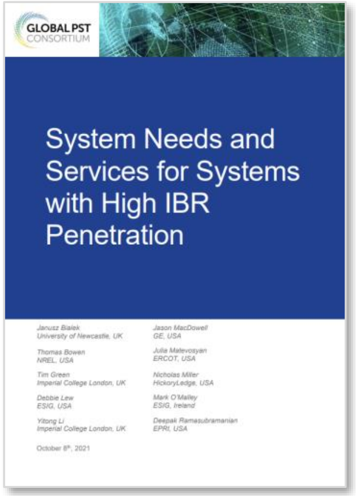


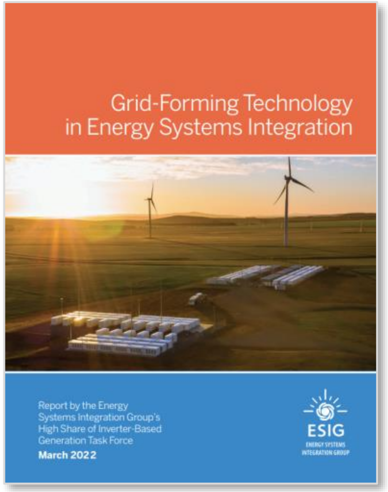
Lots of Past Work
Turning Momentum into Reality

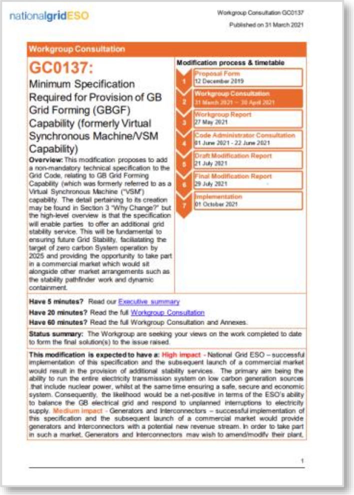
ESIG

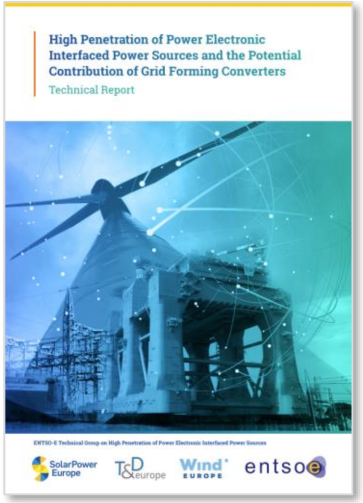


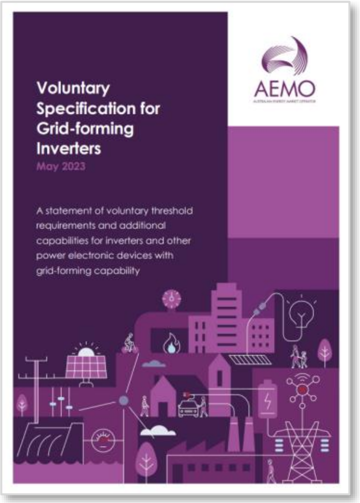


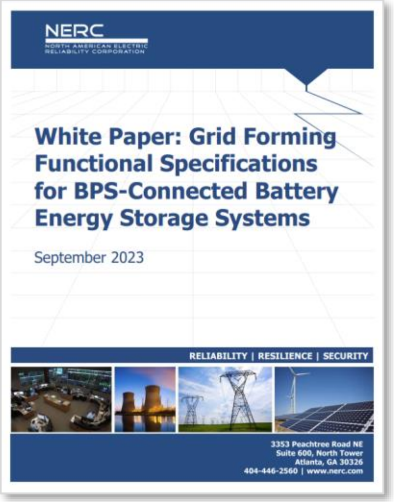


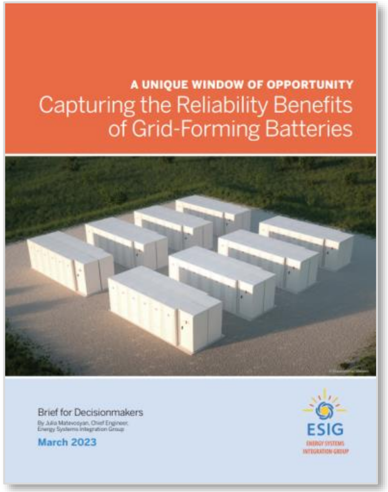


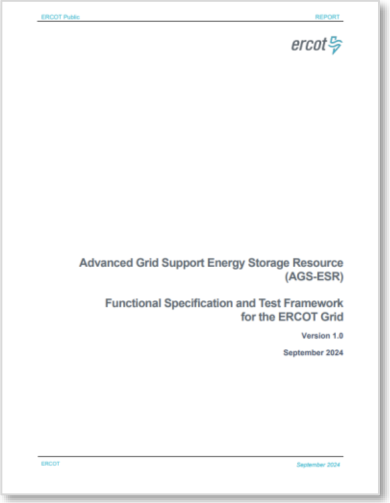


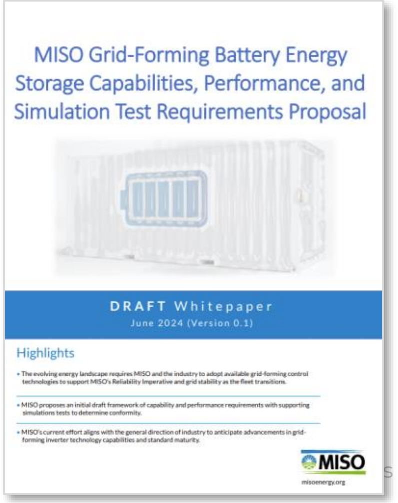






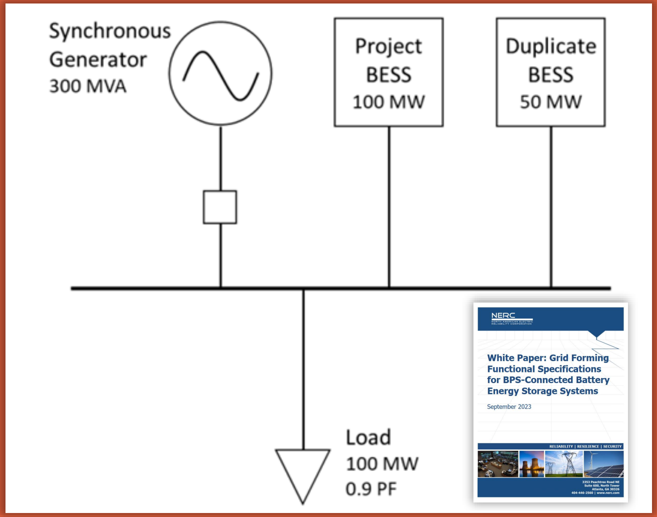




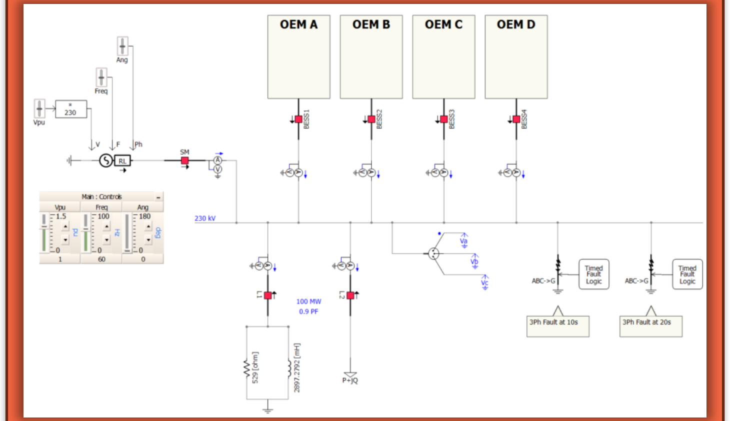


Topics to Cover Today

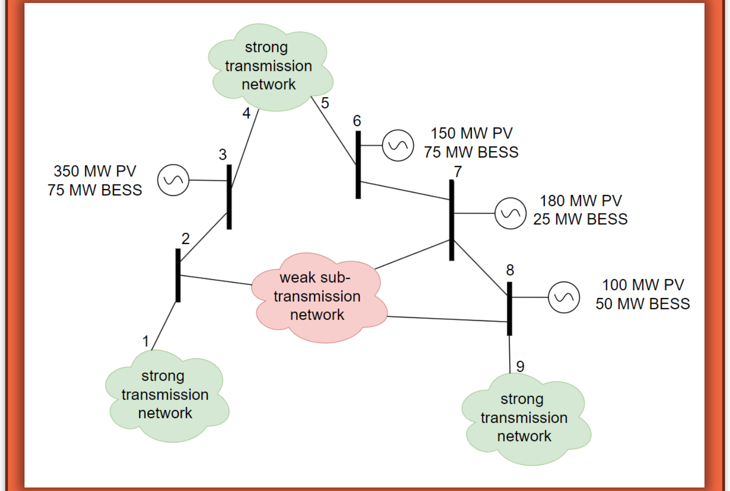
NERC GFM Functional Specification and Test Procedures



GFM BESS Microcosm System Tests



Near-Actual System Studies



Exploring the system level benefits of GFM BESS with "real-world" modeling and studies

Objective of This Work

- Do no harm solution
- GFM and GFL interoperability
- GFM in weak and strong grids
- GFM BESS across multiple OEMs
- Significant growth of GFM BESS
- GFM to defer other options
- Recommendations to OEMs

GFM BESS Model Testing

NERC GFM BESS Functional Specification and Simulation Test Procedures

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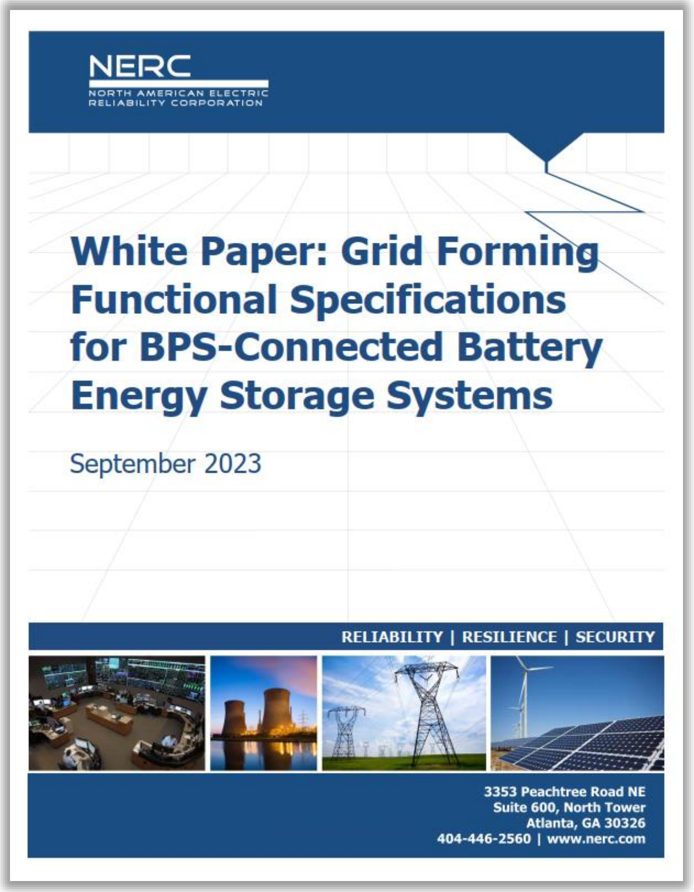
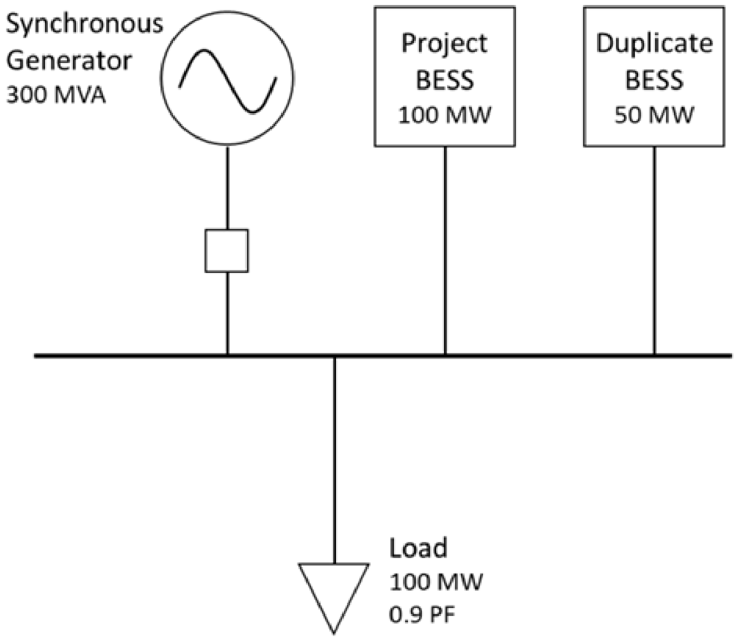
Model Assessment Objectives

- Test GFM and GFL PSCAD models provided by OEMs against the **NERC GFM Functional Specification for BPS-Connected BESS**
- Provide **feedback and findings** to OEMs based on testing
- Summarize and share **findings and conclusions** in a genericized manner.
- Only GFM models that pass the tests will be considered in subsequent studies



GFM BESS Simulation Tests

- **Test 1:** BESS initially discharging and ends at higher level of discharging
- **Test 2:** BESS initially charging and ends up discharging
- **Test 3:** BESS GFM performance at maximum active power



Summary of Test Results

Test #	OEM "A"		OEM "B"		OEM "C"*		OEM "D"		OEM "E"	
	GFM	GFL	GFM	GFL	GFM	GFL	GFM	GFL	GFM	GFL
Test 1	Pass	Fail	Pass	Fail	Pass	Fail	Pass	X	X	X
Test 2	Pass	Fail	Pass	Fail	Pass	Fail	Pass	X	X	X
Test 3	Pass	Fail	Pass	Fail	Pass	Fail	Pass	X	X	X

* OEM "C" did not provide a power plant controller (PPC). A generic PPC based on REPC_A is used.
X = Modeling issue could not be addressed with OEM.

Conclusion: All GFM BESS models pass and all GFL BESS models fail the NERC Functional Specifications; IBR facilities still need to pass the other performance checks.

✓

Learnings from GFM Model Testing

- Four OEMs' GFM models **pass** NERC GFM BESS functional specification tests
- Test 3 results are *interesting* among OEMs that pass
  - Output of Unit 2 for OEM "A" **reduces** after the trip.
  - Output of Unit 2 for OEM "B" **increases** above the max limit after the trip.
  - Output of Unit 2 for OEM "C" **increases** above the max limit after the trip.
- Two OEM models **did not pass** additional model quality tests
  - OEM "D" failed initialization.
  - OEM "E" models are not dispatchable as a GFM resource.

Working with OEMs is essential in resolving modeling and performance issues.

Microcosm System Testing

Extracting Useful Fundamental Takeaways

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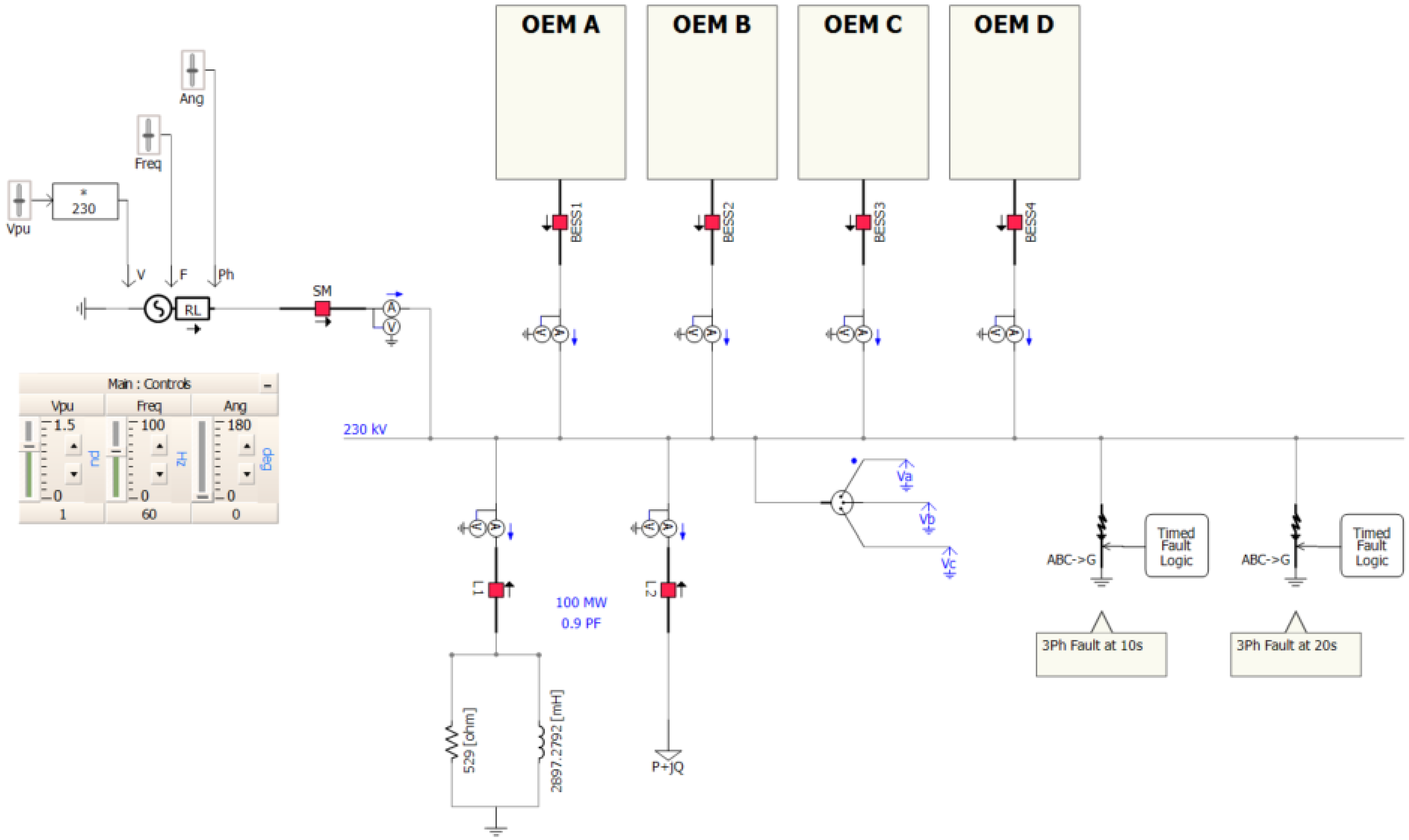
Multiple OEMs Microcosm Test

- Four passing and usable GFM BESS OEM models
- Use a **configurable voltage source** to represent system conditions
- **Scenarios:**
  - Change load level
  - Apply faults
  - Change system strength
- Evaluate **interoperability** of different OEMs:
  - Dynamic performance
  - Control stability
  - Interactions



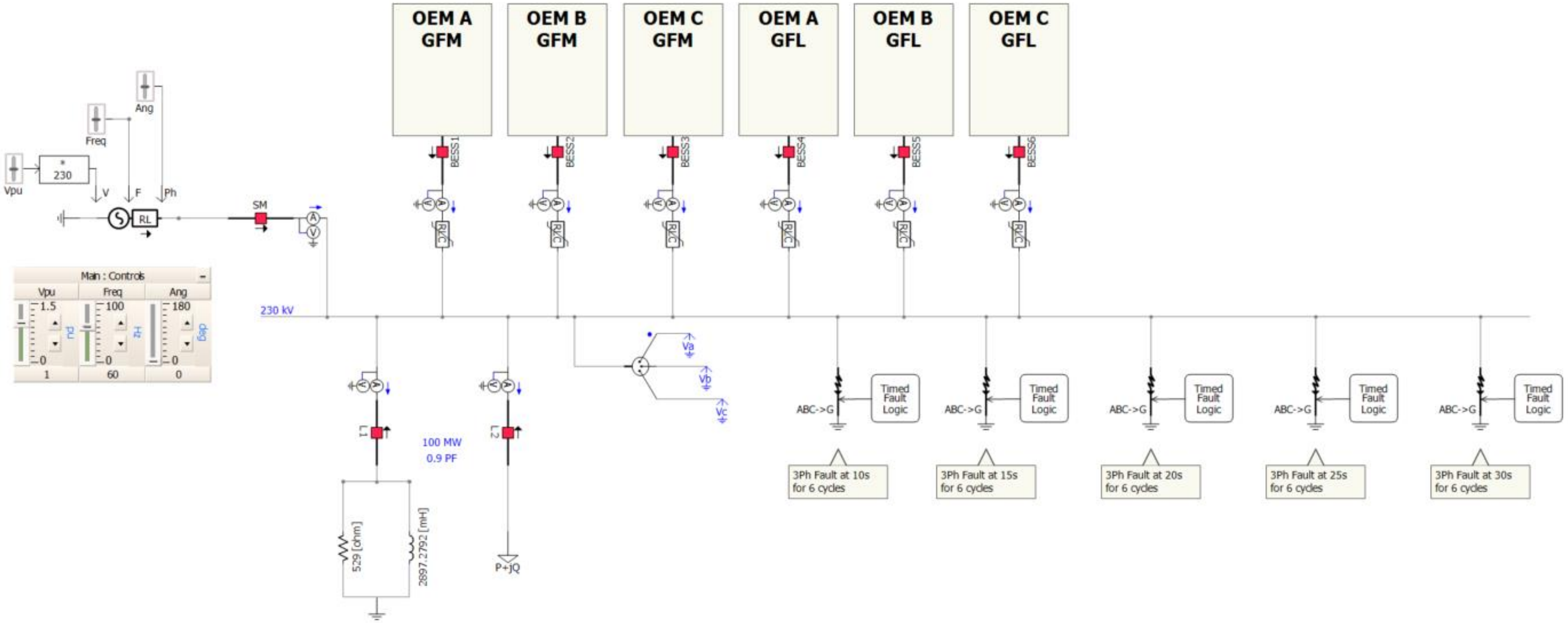
Tests and Key Findings

Test	Description	Key Findings
1	Stable transition to a system with very high IBR penetration	Stable with acceptable performance
2	Load step change in a system with very high IBR penetration	Stable with acceptable performance
3	FRT test in a system with very high IBR penetration (strong connection)	Stable with acceptable performance
4	FRT test in a system with very high IBR penetration (weak connection)	Stable with acceptable performance

* The system was comprised of only GFM BESS units (i.e., from 4 OEMs)

GFL + GFM Interoperability

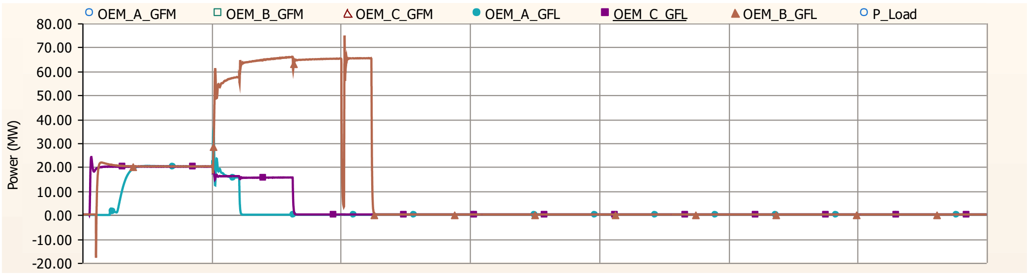
- Explore the combination of GFM and GFL resources working in tandem to support the grid.



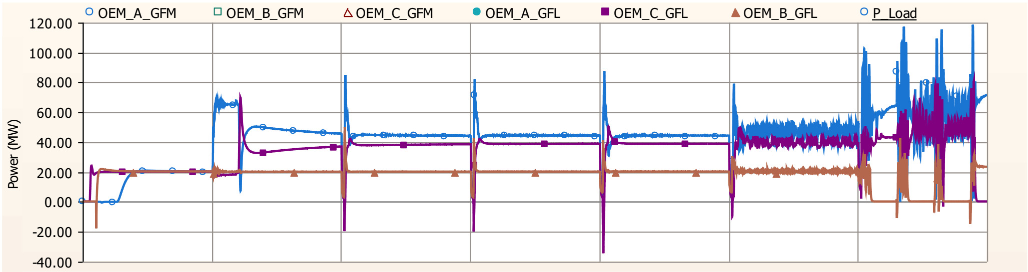
Transition of GFM:GFL Ratio

Increasing GFM:GFL Ratio

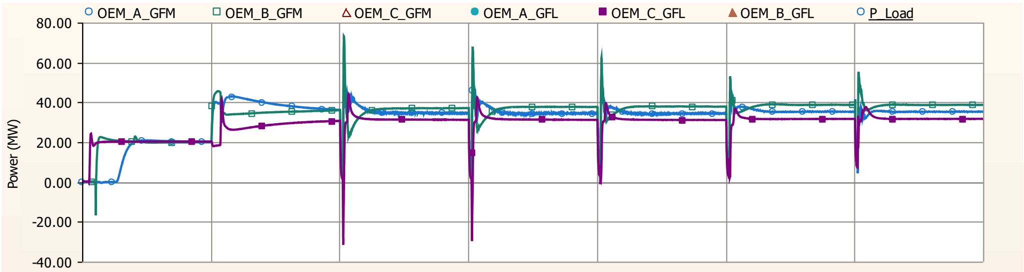
3 GFLs, 0 GFMs



2 GFLs, 1 GFMs



1 GFLs, 2 GFMs

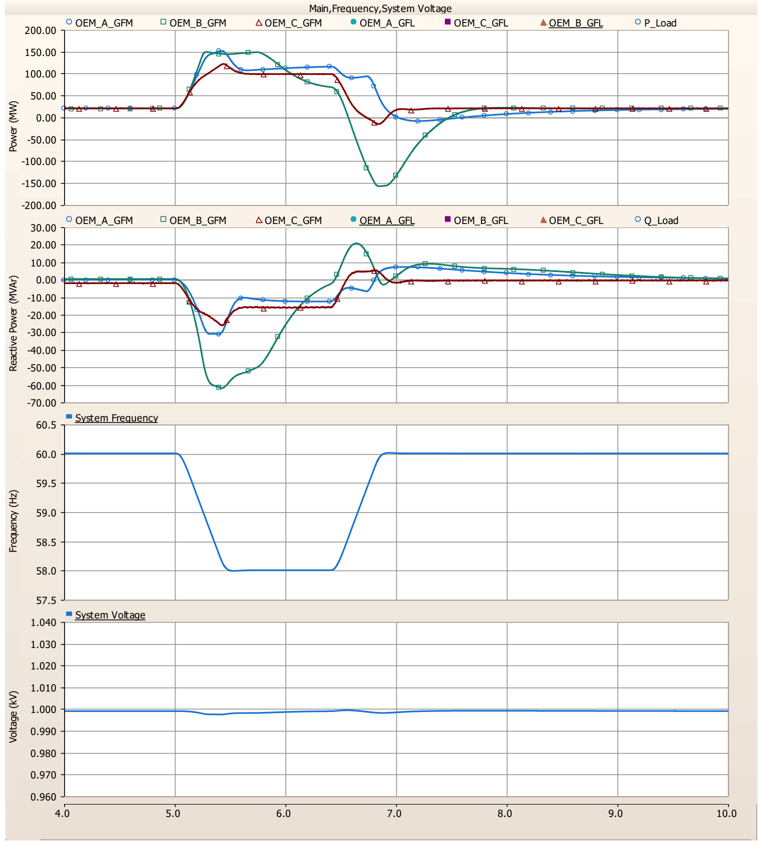


- Increasing % of GFM BESS improved system stability
- More pronounced for weaker conditions with resources spread out
  - 100% IBR system test

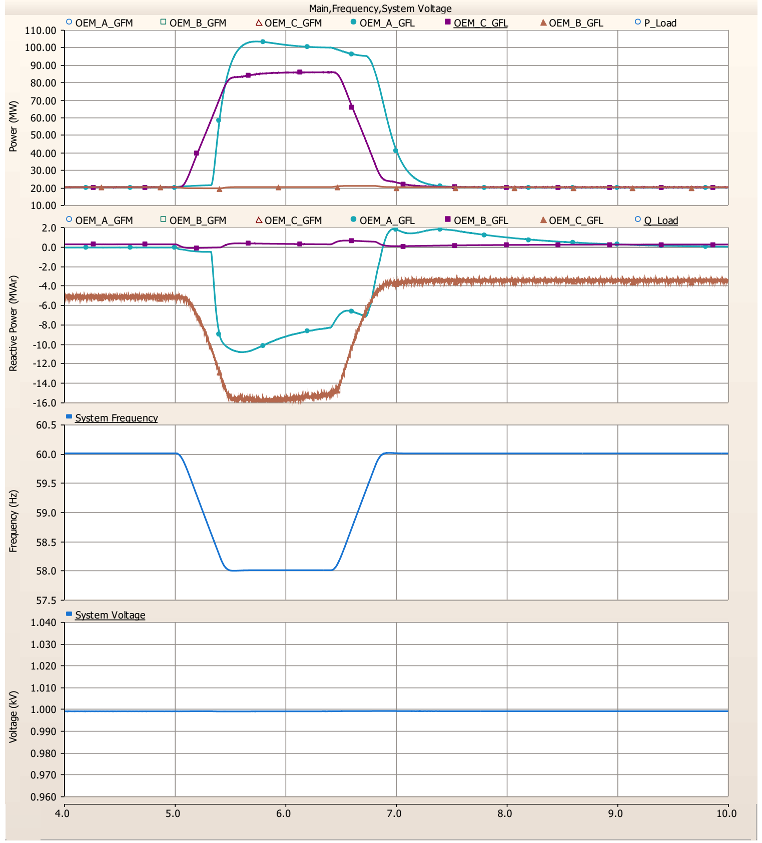
ROCOF Performance

- Both GFM and GFL ride-through a ROCOF of 5 Hz/s. GFM provided a more aggressive response to the change.

GFM



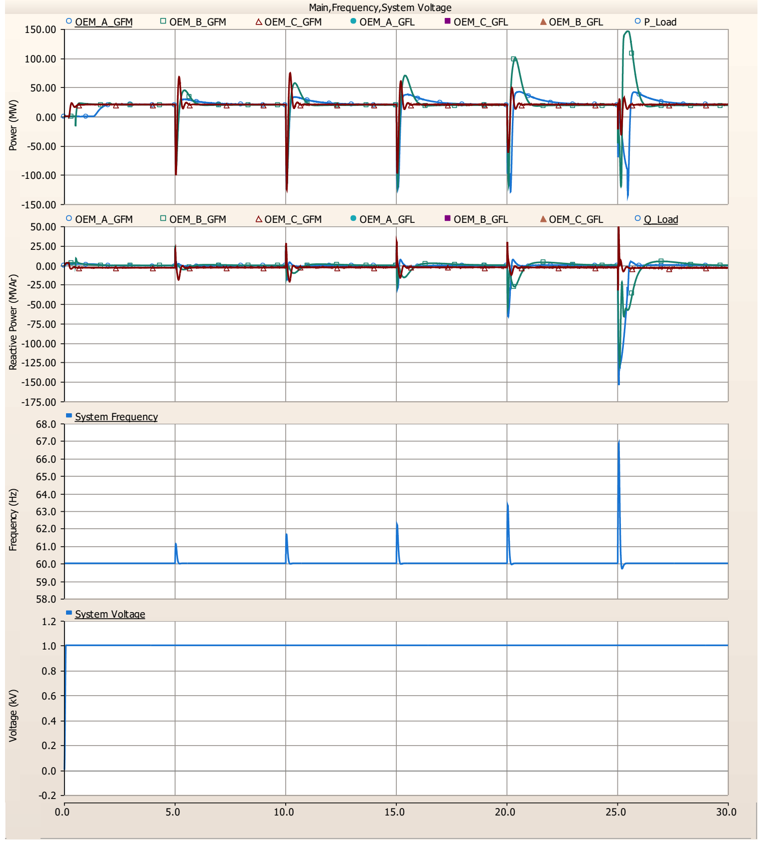
GFL



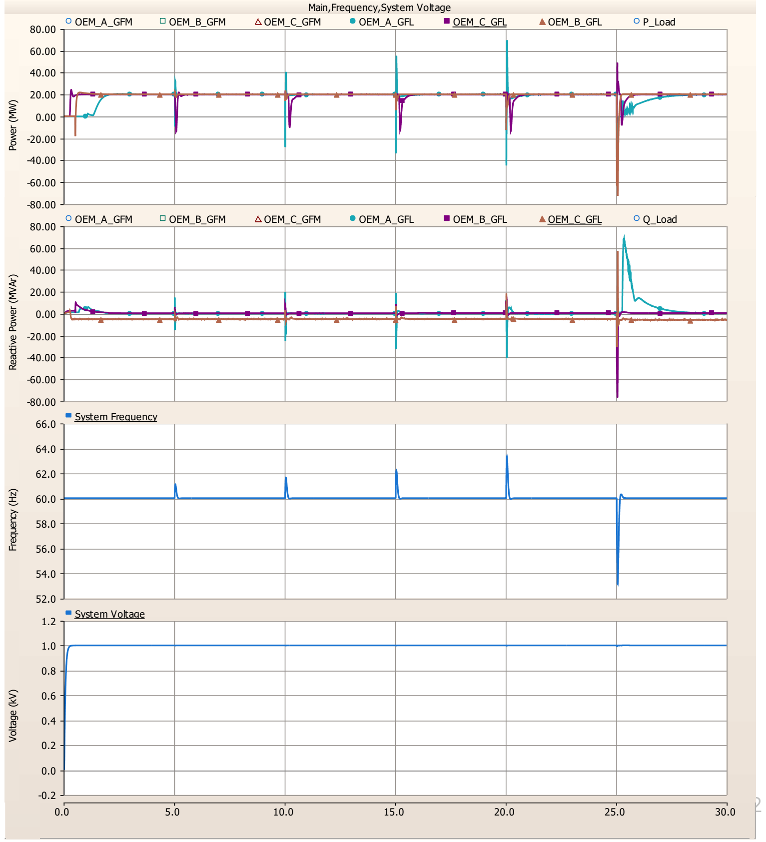
Phase Angle Jump Performance

- Both GFM and GFL ride through phase angle jumps of up to 180°.

GFM



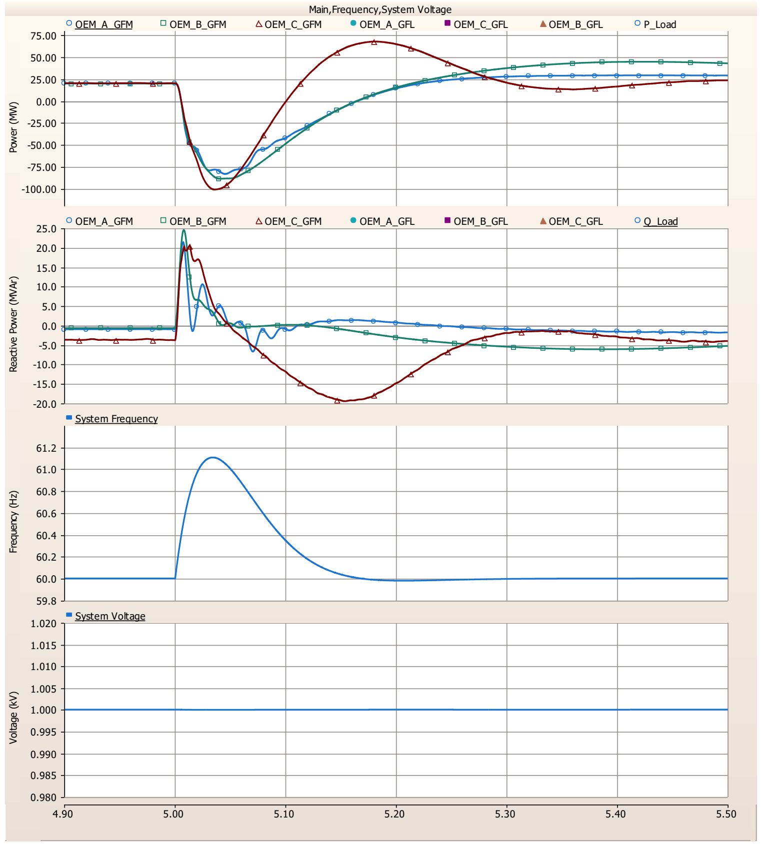
GFL



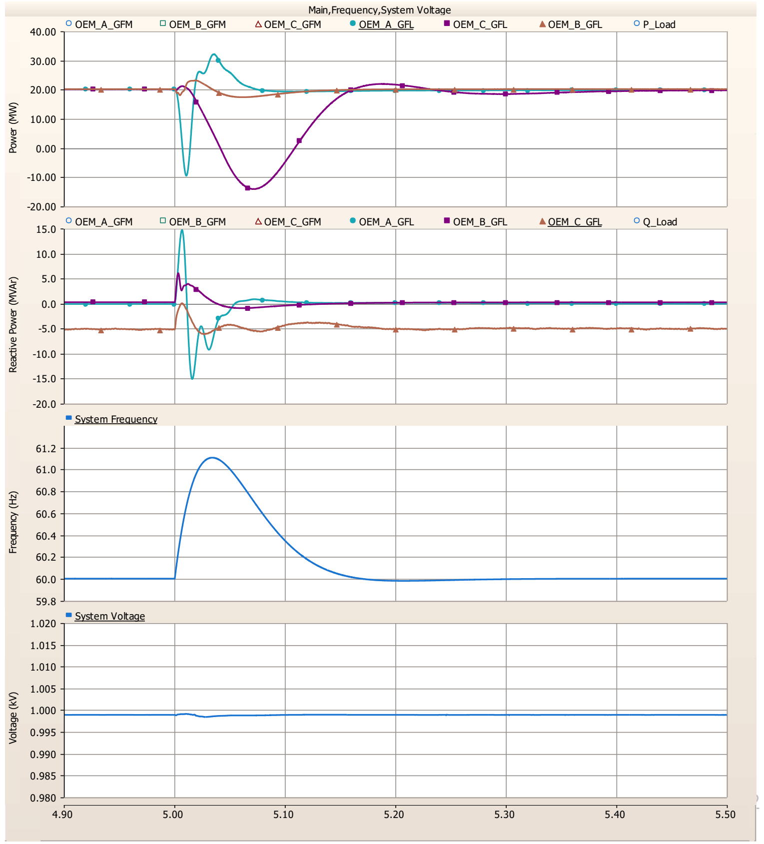
Phase Angle Jump Performance

- GFM provided a fast and substantial response to phase angle jumps while operating within its current limits (confirms the voltage source behavior).

GFM

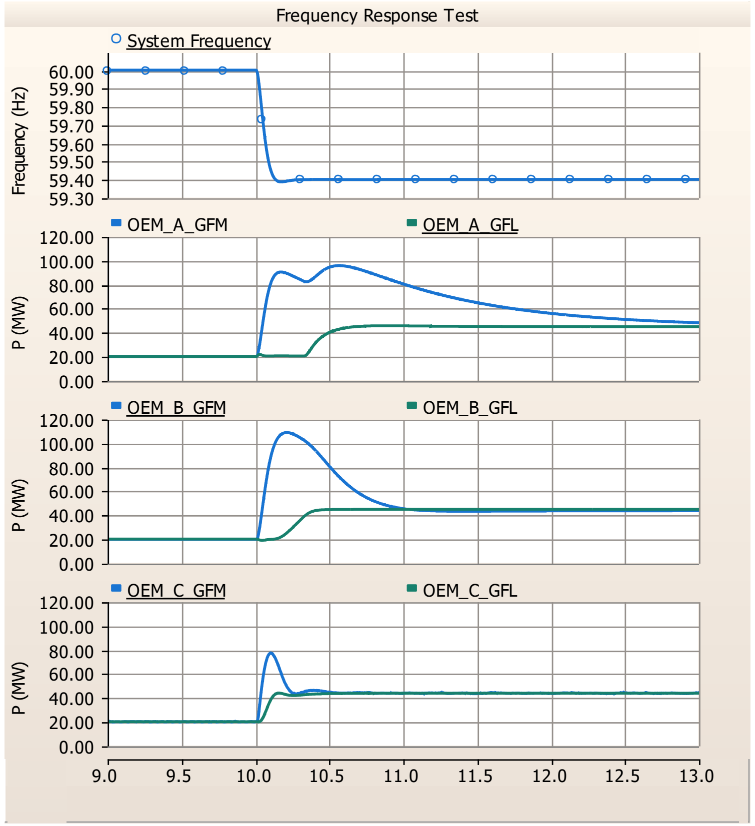


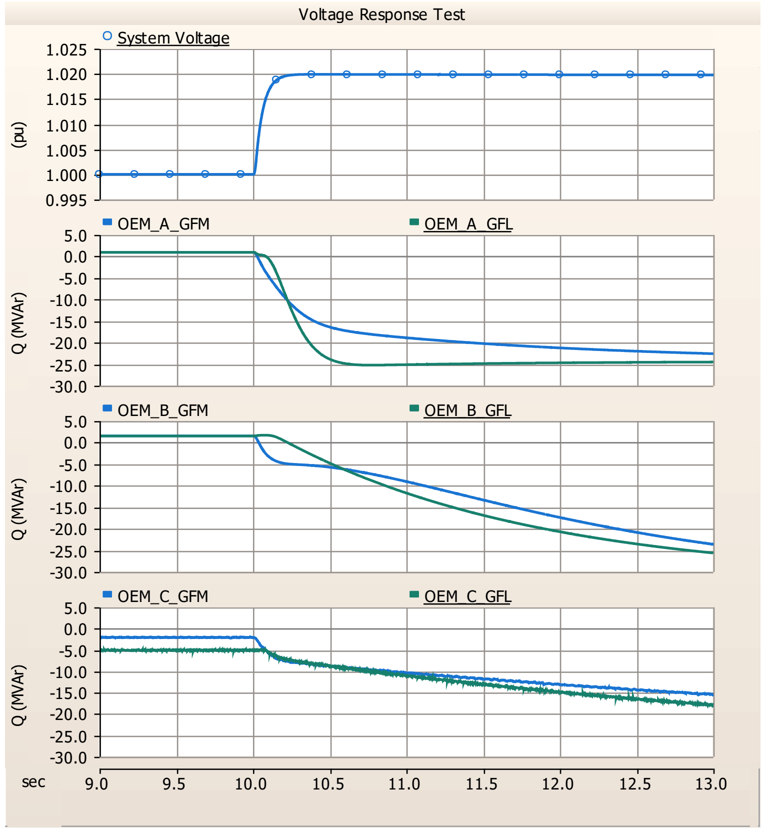
GFL



Speed of Response

- Response to frequency changes is generally faster and more substantial in GFMs than GFLs.
- Response to voltage changes varies among GFMs and GFLs from different OEMs.





GFM BESS System Studies

Exploratory EMT Studies on the ATC System

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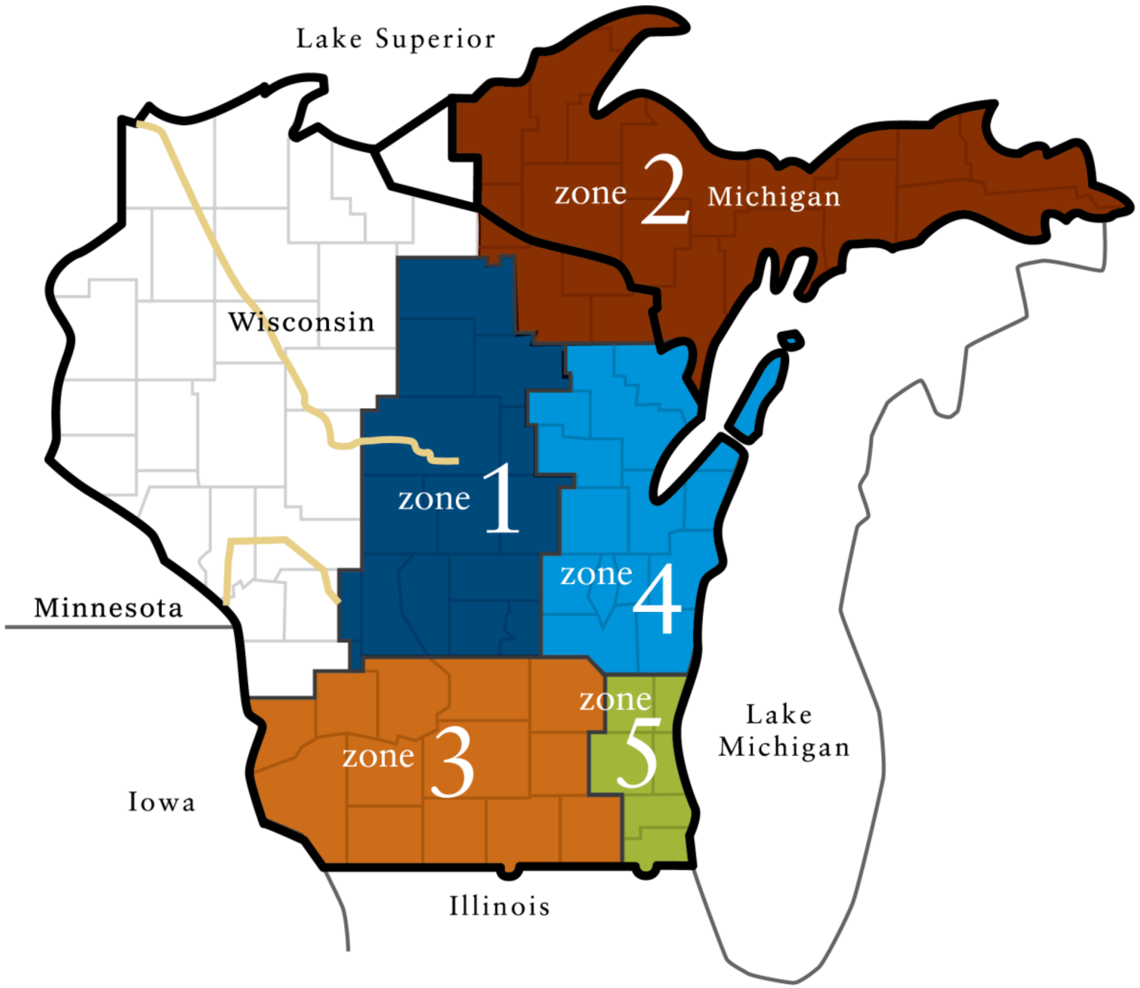
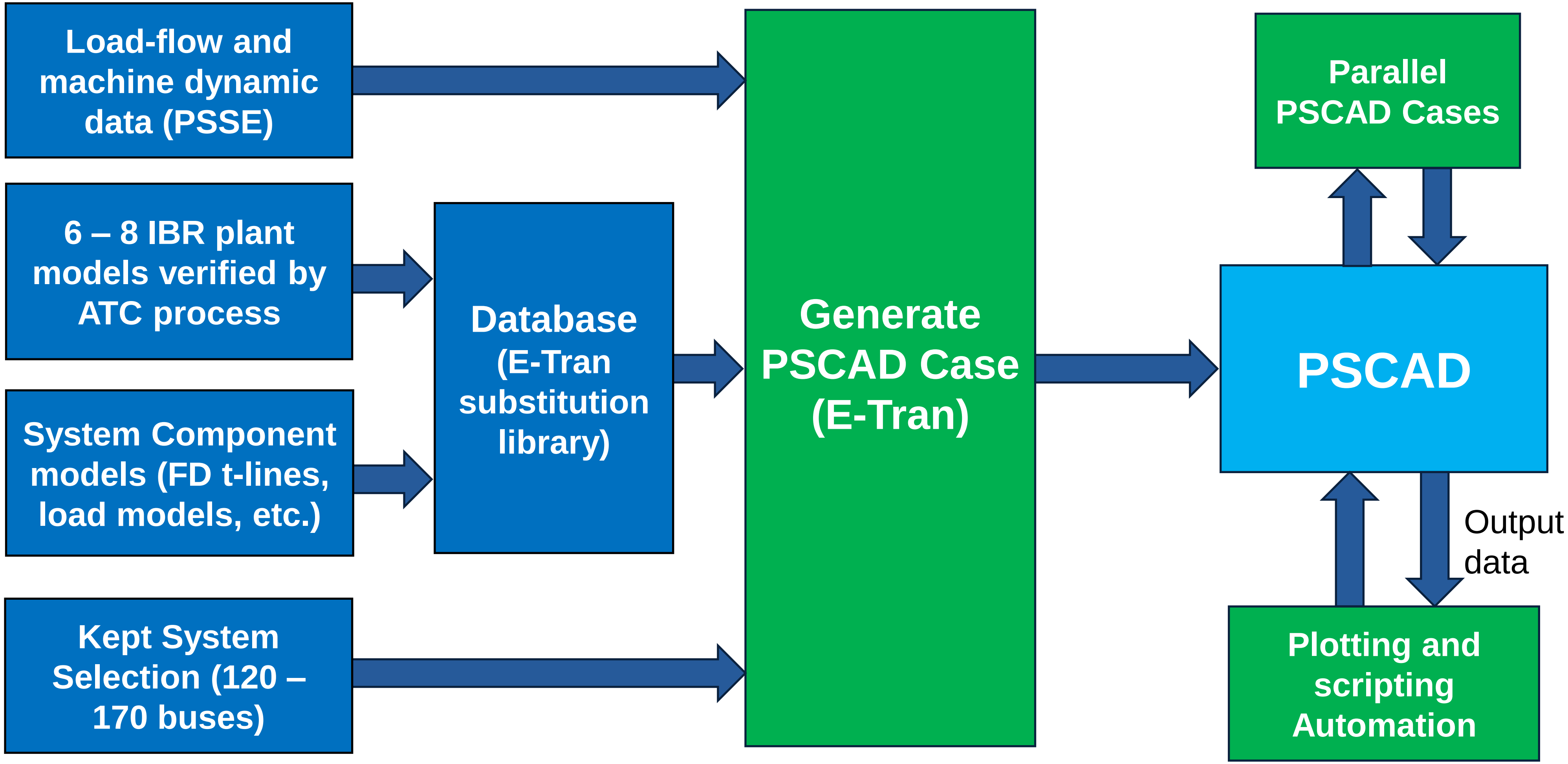
Utility Partner – ATC



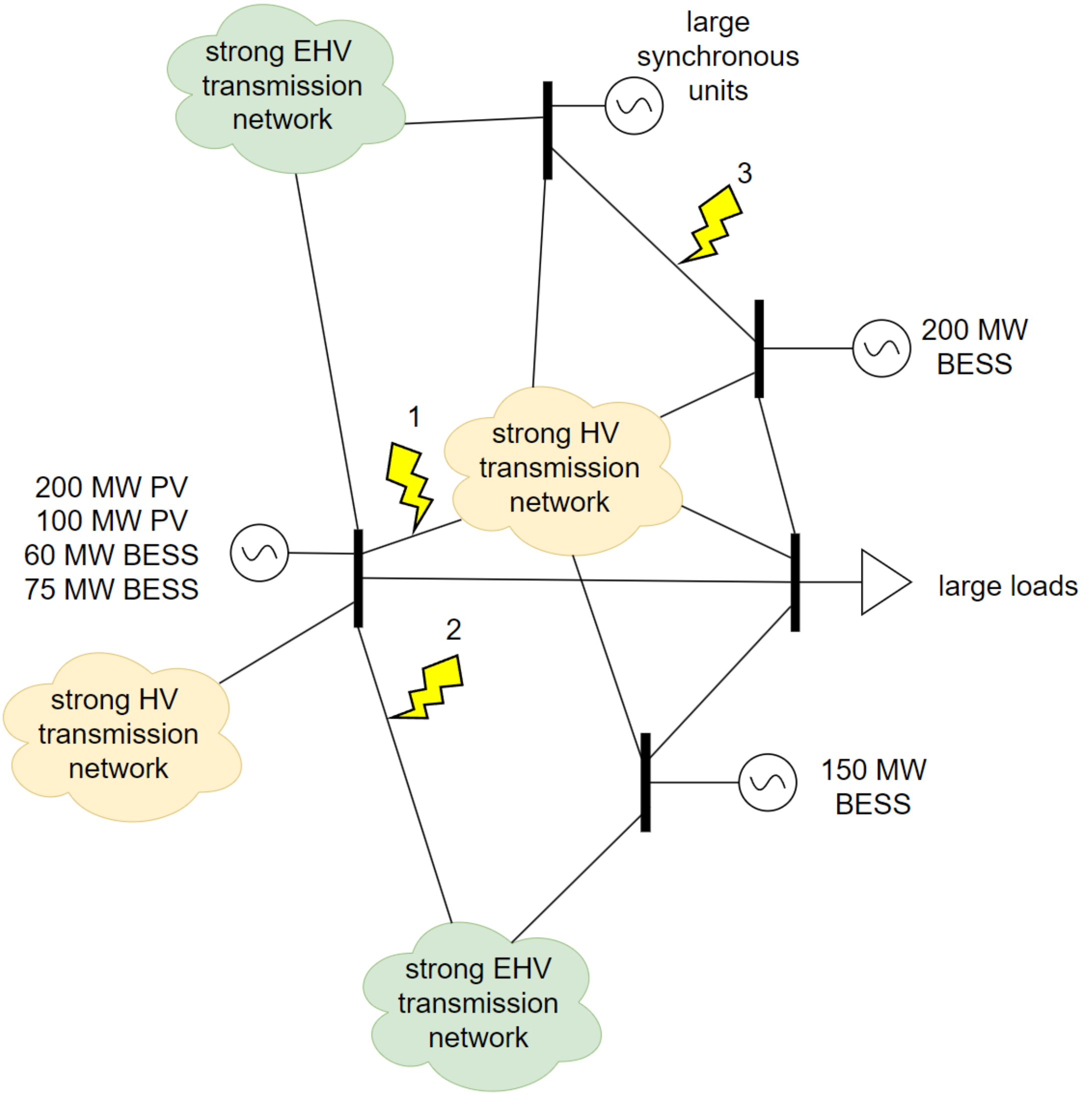
- 5 million electric consumers
- Over 10,000 miles of transmission
- Over 580 substations
- Summer peak load ~13 GW
- Part of Eastern Interconnection
- Diverse Planning Zones – Zones 1 to 5
  - Load pockets – strong system
  - Sparse pockets – weak system
  - IBR-dense pockets – stability issues

ATC PSCAD Model Development



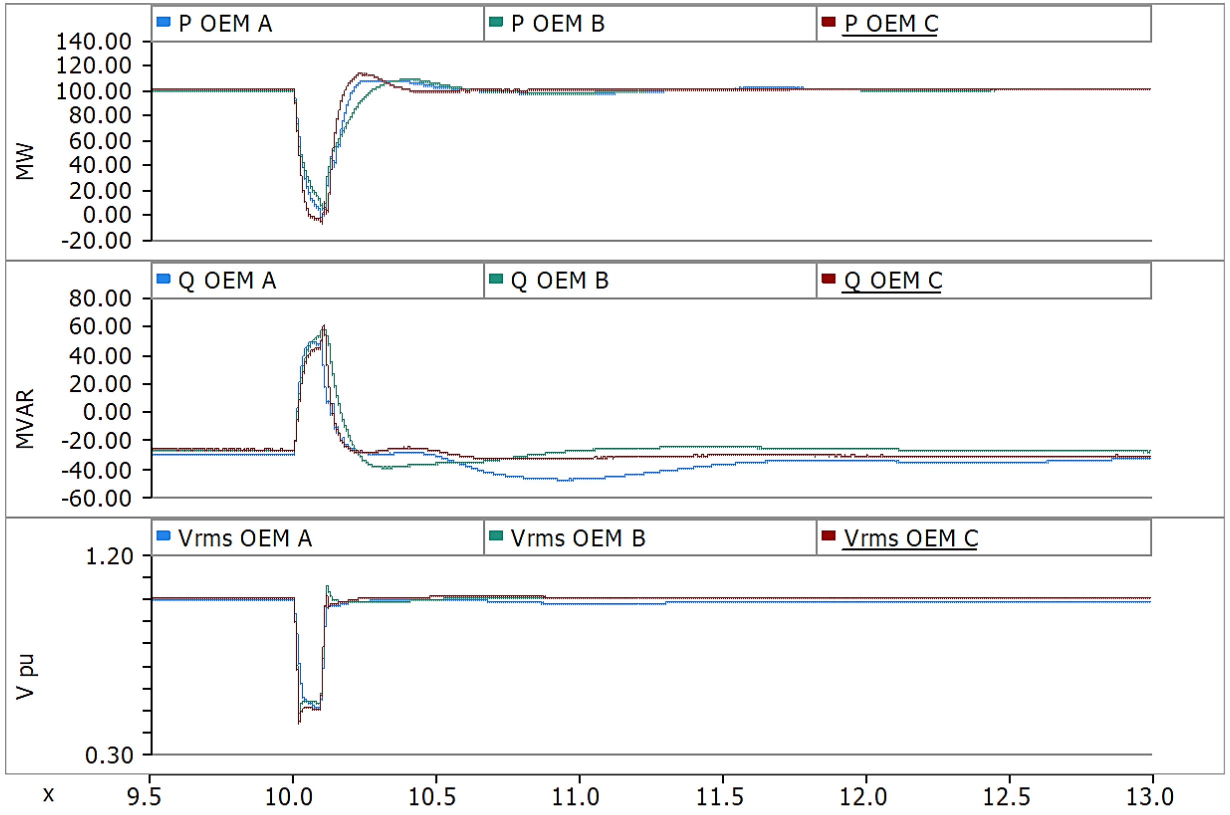
Scenario 1: Strong System Study (Zone 5)

- Very strong, looped 345 kV network outside Milwaukee (SCR > 50)
- Load center with large power electronic loads
- IBR penetration presently low and concentrated
- GFL BESS in service today, added more BESS to network
- Studied 3 N-1 faults:
  - 3 fault locations
  - GFL and GFM BESS scenarios
  - Charging and discharging
- Looking for any harmful system impact by GFM BESS

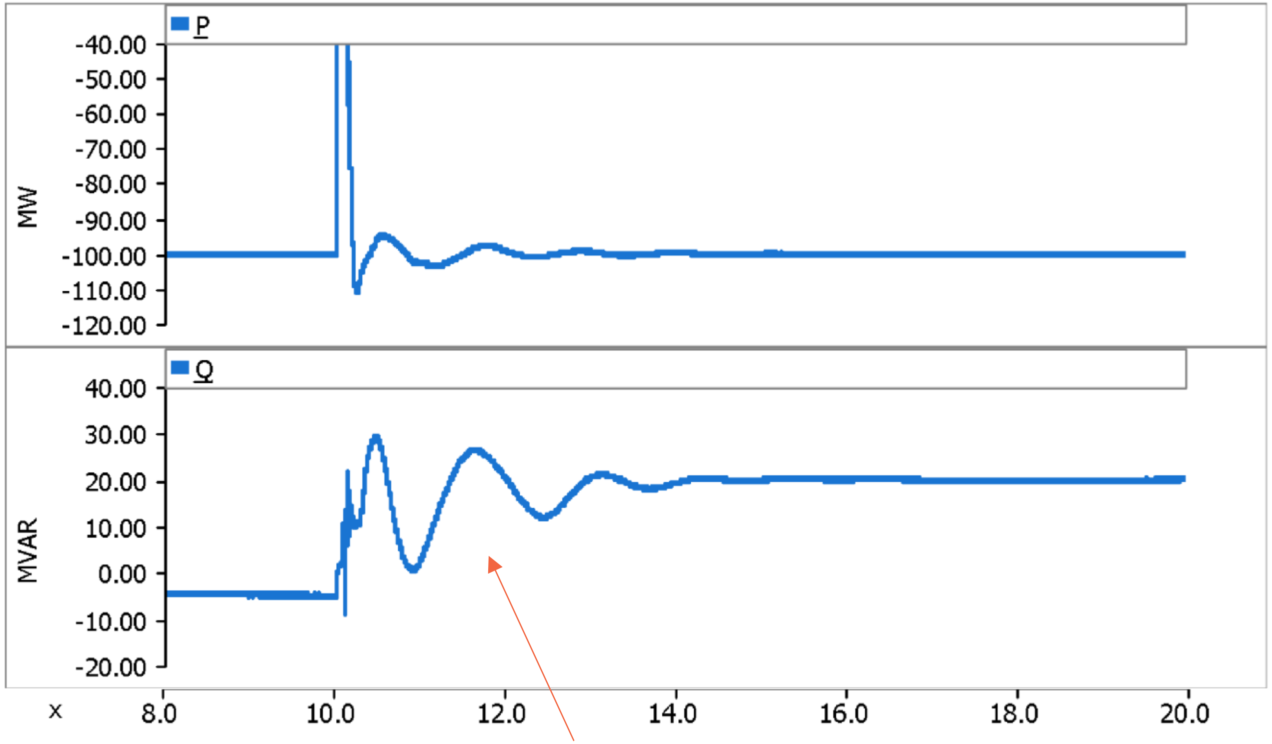


Scenario 1: Strong System Study

Example of multi-OEM plant response



Least damped GFM response



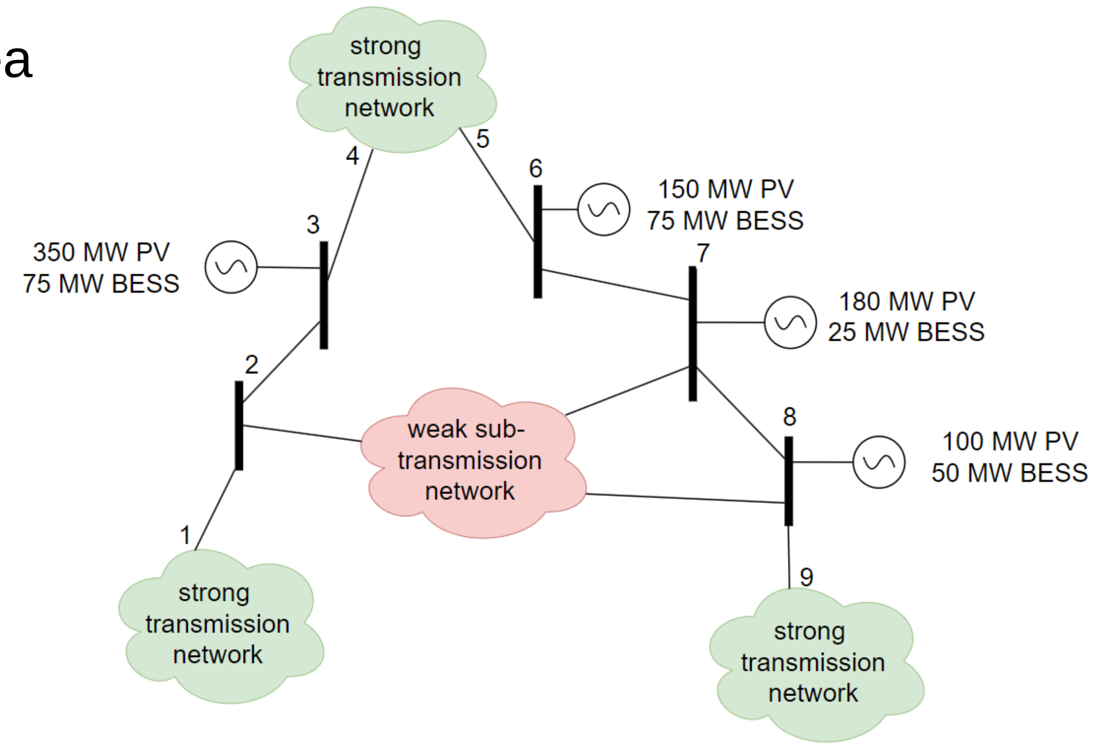
Some machine-like swings (VSM mode GFM) but relatively damped

Scenario 1: Strong System Study Objectives

- ✓ *Demonstrate GFM BESS as a “do no harm” solution*
- ✓ *Demonstrate that multiple GFM BESS from different OEMs operate reliably together*
- ✓ *Identify possible issues integrating significant GFM BESS in a local strong network*

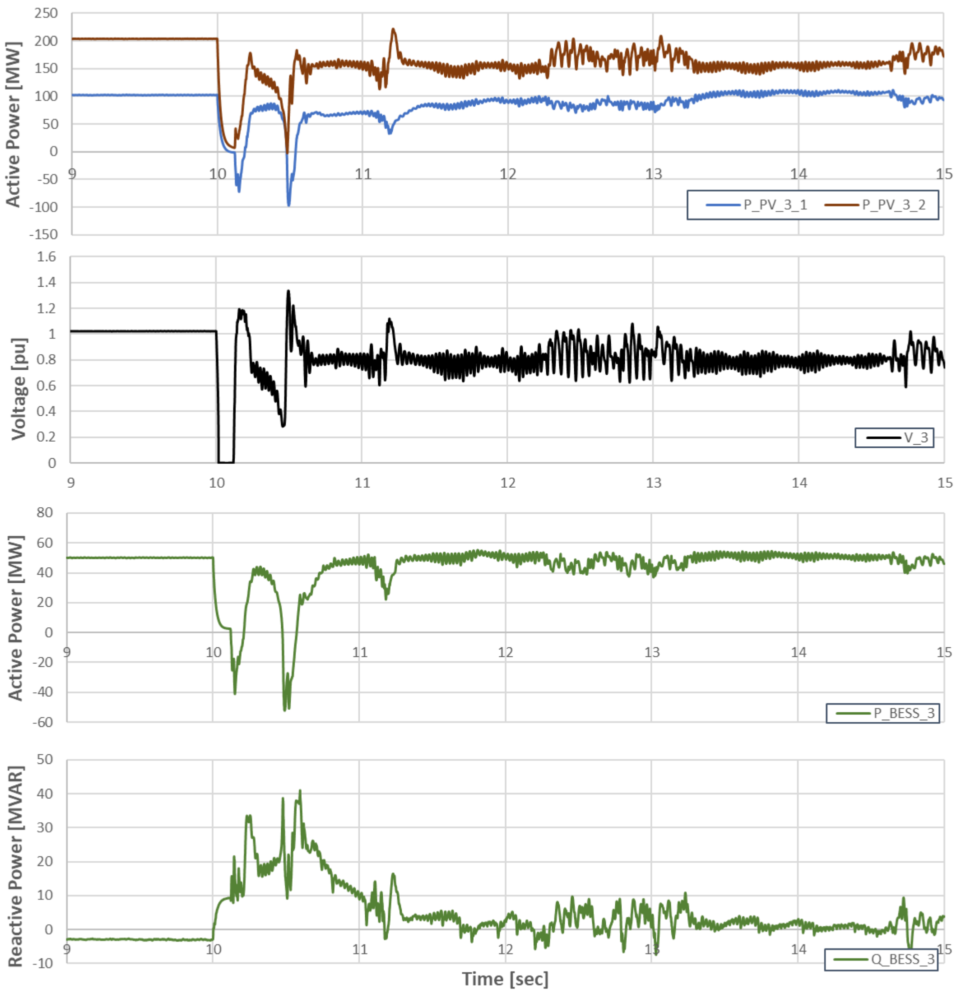
Scenario 2: Weak System Stabilization

- IBR-saturated region
- Strong surrounding transmission network, weak local area with limited transmission
- Studied N-1 *and* N-1-1 faults
- Scenarios aimed at separating the IBRs from the strong sources to create the weakest grid conditions possible
- BESS studied as GFL and GFM
- Questions:
  - Does GFM BESS improve local stability?
  - Does GFM BESS enable more IBR integration?
  - Does GFM BESS avoid operational curtailment?

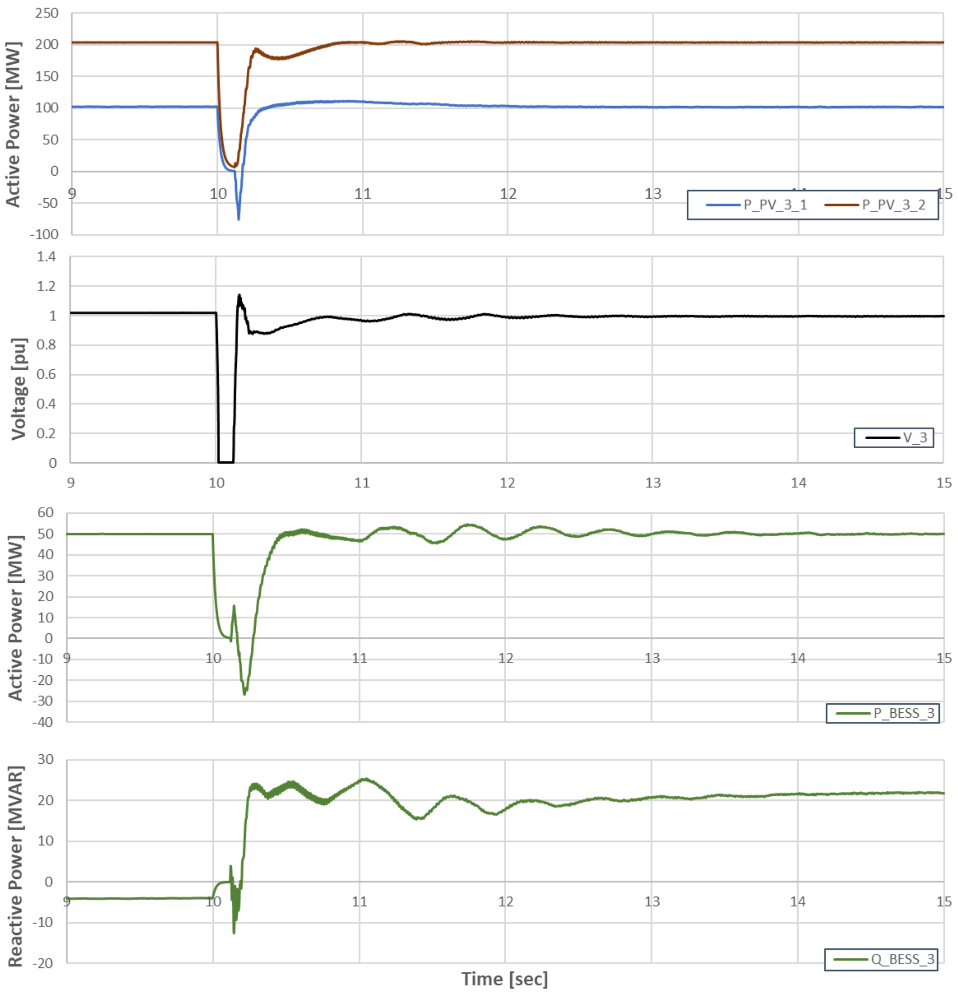


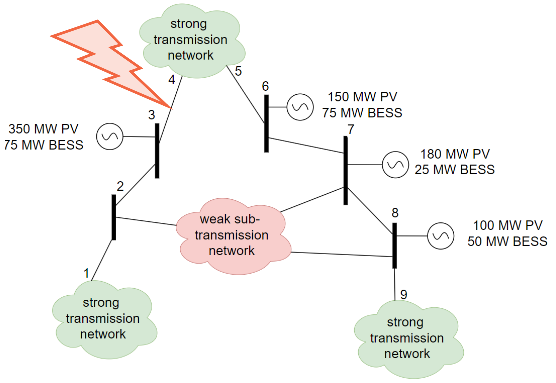
Fault on Line 3-4, No Prior Outage

BESS in GFL Mode



BESS in GFM Mode



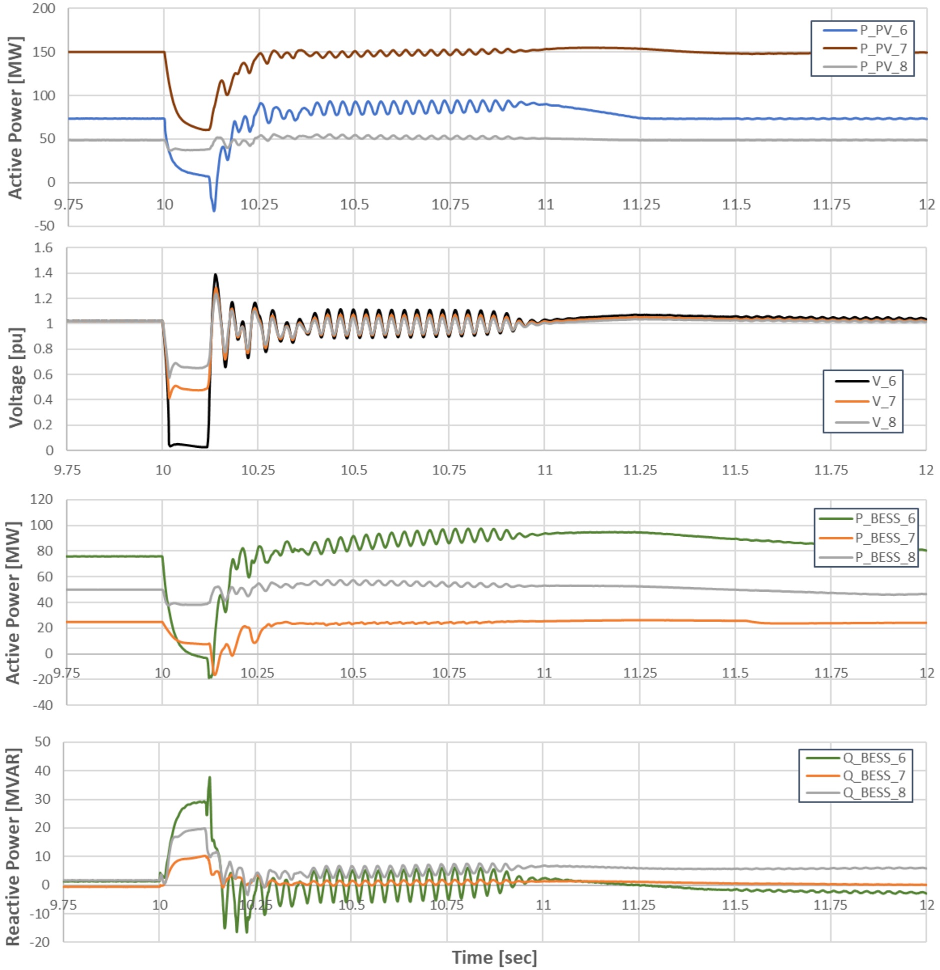


Findings:

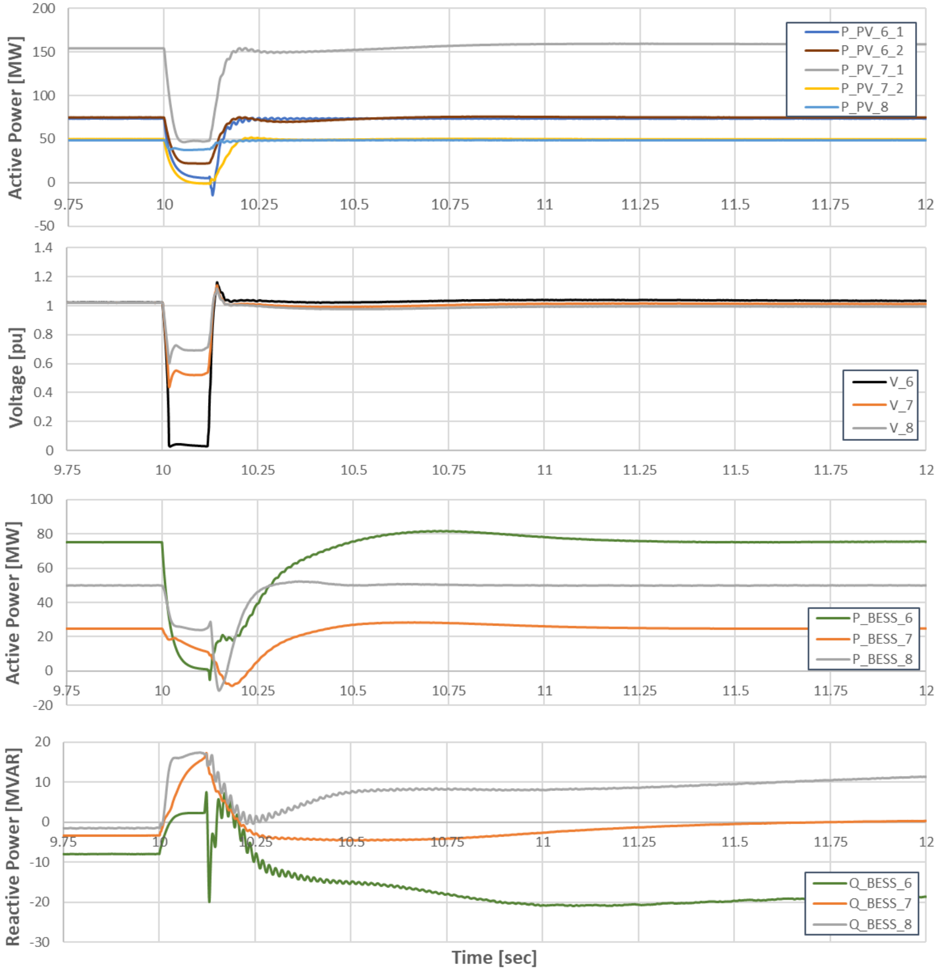
- **SCR < 1.3 under N-1**
- **GFL BESS scenario is unstable**
- **GFM BESS scenario is stable**

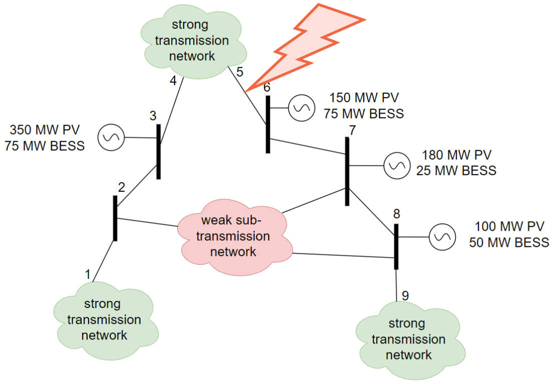
Fault on Line 5-6, No Prior Outage

BESS in GFL Mode



BESS in GFM Mode, 125 MW More PV

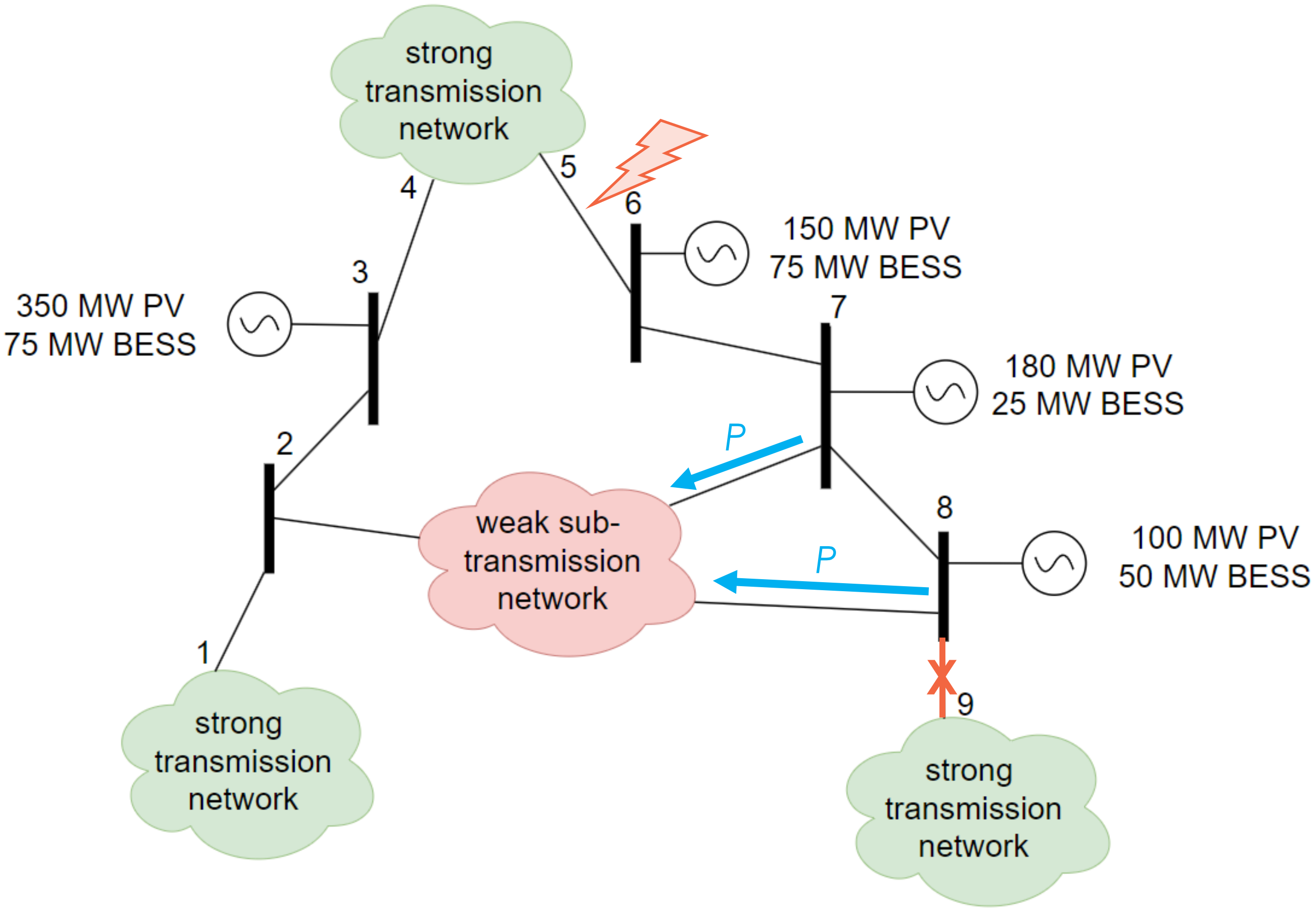




Findings:

- WSCR < 1.6 under N-1
- GFL BESS scenario is marginally stable
- GFM BESS scenario is stable even with 125 MW additional solar PV

Fault on Line 5-6, Prior Outage of Line 8-9

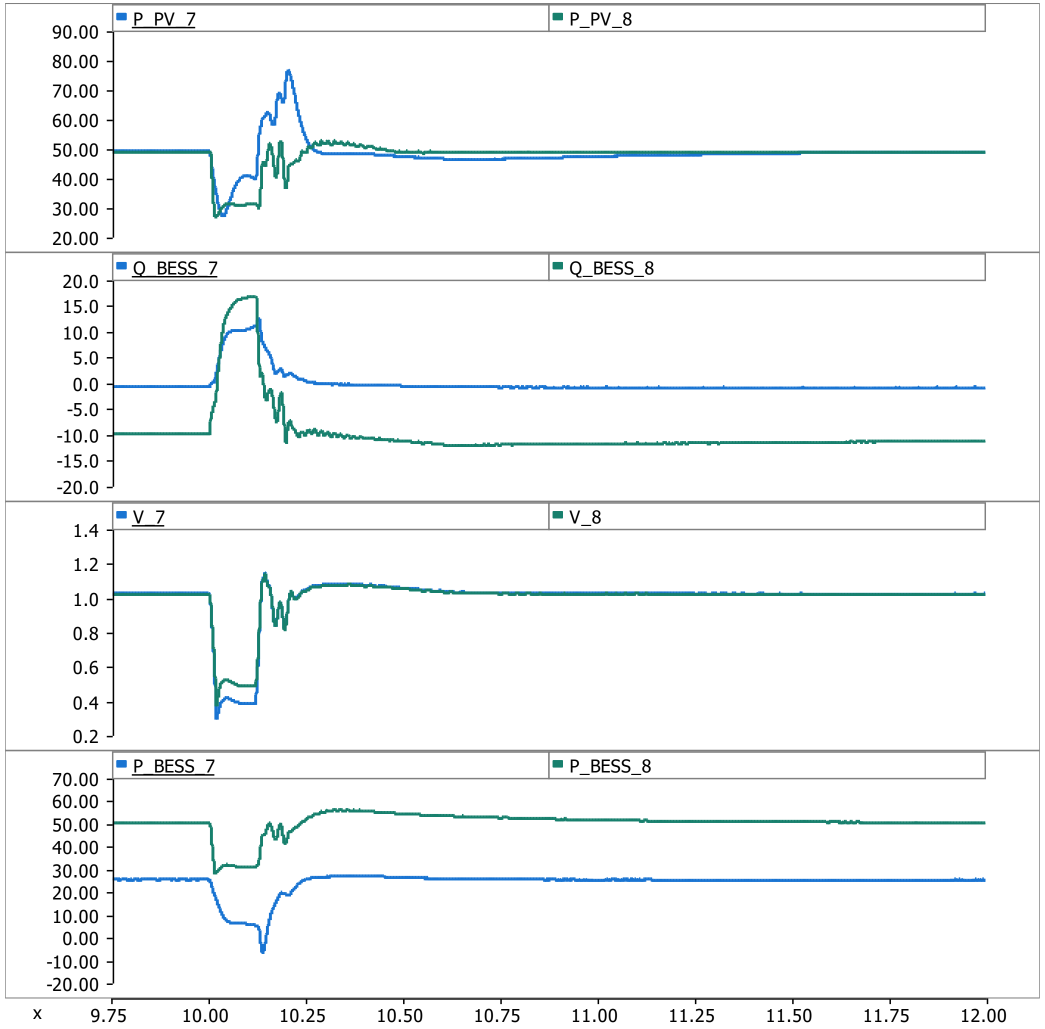


Findings:

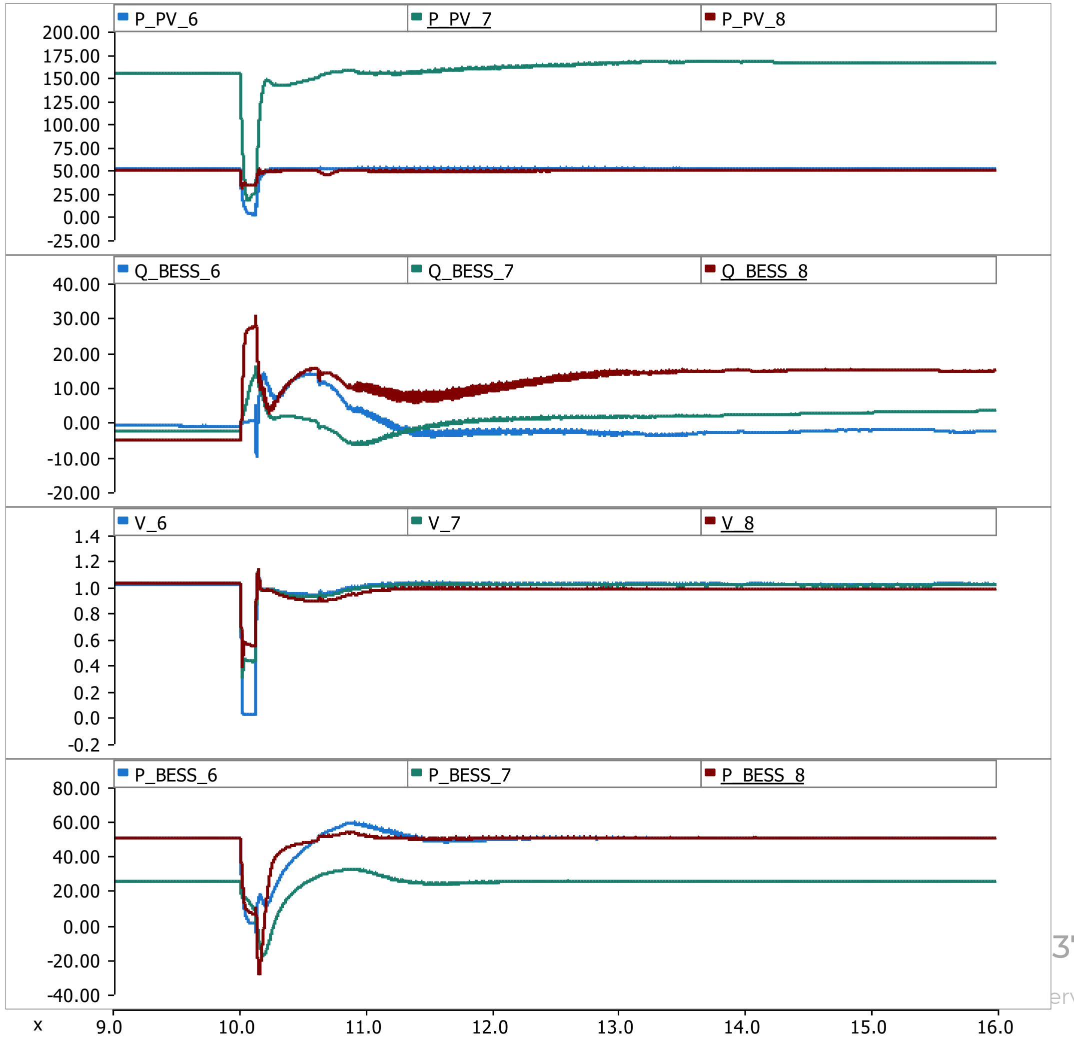
- **With Line 8-9 out of service, fault at Line 5-6 creates significant IBR penetration connected through weak sub-transmission network**
- **Very low WSCR under N-1-1 conditions**
- **Curtailment required in both GFL and GFM BESS scenarios**
  - **Curtailment with GFL BESS = 250 MW**
  - **Curtailment with GFM BESS = 50 MW**

Fault on Line 5-6, Prior Outage of Line 8-9

BESS in GFL mode, 250 MW Curtailment



BESS in GFM mode, 50 MW Curtailment



Scenario 2: Weak System Objectives

- ✓ *Demonstrate GFM BESS as a "do no harm" solution*
- ✓ *Demonstrate that multiple GFM BESS from different OEMs operate reliably together*
- ✓ *Identify possible grid-stabilizing benefits of adopting significant GFM BESS in a weak network*
  - Reduced need for stability-driven network upgrade
  - Reduced IBR curtailment for outage conditions
  - Increased IBR hosting capacity

** Studies involved GFM BESS operating at Pmax. Further benefit may be derived if additional dynamic headroom is available – more studies are needed to demonstrate this.*

Key Findings, Recommendations, and Future Work

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Key Findings, Based on the Work Done...

- Is GFM BESS a “Do No Harm” solution? Yes.
- Do the GFM BESS Functional Specifications and Test Procedures hold up? Yes.
- Will growth of GFM BESS cause reliability challenges? No.
- Does GFM BESS provide specific stability benefits in weaker grids? Yes.
- Does GFM BESS operate stably and reliably in strong grids? Yes.
- Are GFM BESS interoperable across OEMs and with GFL? Yes.
- Could GFM BESS help defer other more costly solution options? Yes.
- Could GFM BESS serve as a bridge to long lead-time solutions? Yes.

Recommendations

- Develop models and conduct EMT studies to **quantify the benefits** of GFM BESS on your local system; understand the value it can bring
- Use GFM BESS as a **solution in your toolbox** to solve grid stability issues like weak grids, near series capacitors, etc.; consider even in strong grids to help stability
- Consider GFM BESS to maximize project value: **lower risk for new IBR interconnections, increase IBR hosting capacity, reduce curtailments,** and **minimize network upgrades**
- **Pilot** GFM BESS projects to gain operational experience
- Develop GFM BESS **technical requirements** and integration into facility interconnection requirements; incorporate into RFPs for new resources
- **Don’t wait** – take advantage of BESS interconnections today; retrofits are expensive

THANK YOU

Ryan Quint – ryan.quint@elevate.energy

Andrew Isaacs – ai@electranix.com

Julia Matevosyan – julia@esig.energy

Additional Materials

Key Findings – Modeling and GFM Testing

- **GFM BESS Modeling**
  - Coordination with OEMs was necessary, some modeling issues arose
  - GFM BESS models across OEMs implemented differently; requires careful attention
  - Off-the-shelf GFM BESS models worked stably, required no tuning for stable performance
- **NERC GFM BESS Functional Specification and Test Procedures**
  - All GFM BESS models tested passed the NERC tests; all GFL BESS models failed
  - Testing core GFM functionality could likely be simplified to one (1) test; others are rigor testing the GFM BESS across many operating conditions
- **GFM BESS as a Solution Option:**
  - Small incremental cost to GFL BESS when designed in up front
  - Retrofits require more systems integration work and costs
  - Dramatically lower cost than other solutions (e.g., synchronous condensers)

Key Findings – Microcosm System Testing

- **In a microcosm test system, GFM BESS…**
  - From multiple OEMs operating in close proximity (at same plant or nearby plants) did not introduce instability or oscillation risks (i.e., interoperability)
  - Stably operated for much more extreme contingencies (e.g., severe faults) with weak grid conditions
  - Stably operated in strong grid conditions
    - No unexpected controller instability or oscillations observed
  - Stably operated in weak grid conditions
    - Improved voltage and frequency performance – helps stabilize GFL resources
  - Required no controller tuning to achieve stable performance in strong vs. weak systems, less sensitivity compared with GFL
  - Greater ratio of GFM:GFL BESS resulted in improved stability overall

Key Findings - Studies

- **Studies in the ATC system showed that GFM BESS…**
  - Were interoperable across multiple OEMs at same plant and nearby plants
  - Reliably and stably operated in both **strong** (SCR > 50) and **weak** (WSCR < 1.3) grids
  - Provided grid-stabilizing support reliably and stably with **out-of-the-box controls**
  - Stably operated with **no interactions** between different OEM GFM controls
  - **Improved system performance** and dynamic response compared with GFL
  - Would require **fewer network upgrades** for stable operation of N-1 contingencies
  - Could **enable higher IBR hosting capacity** for future IBRs
  - Required **less curtailment** for N-1-1 contingencies
  - Could lead to **less complex stability planning studies** due to improved stability

Conclusion: GFM BESS provided quantifiable grid-stabilizing benefits in both weak and strong grid networks. GFM BESS is a valuable solution option to increase IBR hosting capacity, reduce stability-related curtailments, and avoid more costly network upgrades.

✓

Recommendations

- **Proactive Planning of High IBR Operating Conditions**
  - Conduct real-world exploratory simulations of GFM BESS to quantify the benefits it can bring to local transmission networks; results look rather promising
  - Use findings from these studies, as needed, to develop a GFM adoptions strategy within a specific system
- **Pilot GFM BESS Projects**
  - Identify key locations where GFM BESS bring value (qualitative or quantitative assessment)
  - Understand and gain experience with the grid-stabilizing benefits GFM BESS can provide
  - Focus on learning, modeling, studies, collaboration across utility/system operator, developer, OEMs, and third-parties
  - Focus on standalone BESS and co-located plants initially, if needed, to simplify controls (minimize newness risk)
- **Develop Technical Requirements Language**
  - Adopt/develop GFM BESS functional specifications (requirements) and simulation test procedures; a simplified version of the NERC tests can suffice, and additional details can be added as needed
  - Integrate language for RFPs for future BESS; link to requirements

Recommendations

- **GFM BESS as a Solution**
  - Leverage GFM BESS in areas of high IBR penetration (locally or regionally), weak grids, and locations prone to subsynchronous control interaction issues to minimize risk
  - Consider GFM BESS even in strong grid conditions to help stabilize current and future grid conditions
  - Consider adopting system-wide to improve stability and to maximize IBR hosting capacity
- **Future Industry and Regulatory Standards**
  - Consider developing industry standards that incorporate GFM technology (i.e., enhance or modify IEEE 2800-2022) to more explicitly account for GFM performance characteristics
  - Consider if standardizing adoption of GFM BESS may help harmonize industry standards and fully leverage the capabilities of modern IBR technology – don’t just minimize risk; extract maximum value
- **Continue Exploratory Studies, Pilots, and Information Sharing**
  - Share modeling, study, requirements development, and integration successes stories and challenges so others can learn from real-world experience, wins, and mistakes – continuous improvement
  - Start now; don’t wait