Storage-Enhanced Grid-Strength-Constrained UC

Wei Wang, Buxin She, Xue Lyu, and Di Wu

Pacific Northwest National Laboratory

PROJECT PROFILE
Topic: Grid Resilience & Reliability; Analytics Vertical: Grid Integration and Field Validation Strategic Pathway: Optimize Project start and finish: FY26-FY26

PROBLEM

The U.S. power system is undergoing profound changes

- **Rapidly growing demand** from electrification and large, dynamic digital loads (e.g., data centers)
- **Reduced physical inertia** due to increasing penetration of inverter-based resources (IBRs)

These trends create new operational challenges for maintaining frequency and voltage stability under weak-grid conditions and contingencies

Battery energy storage systems (BESS) is a promising solution as they can emulate **virtual inertia and damping** to support grid strength, but current practice is limited

- IBR control modes/parameters are often **preconfigured**
- BESS dynamic support may **not be co-optimized** with energy dispatch, leaving value and reliability benefits untapped

An operational framework that **co-optimizes dispatch and IBR controls** to maintain frequency and voltage stability cost-effectively is needed

APPROACH

Grid-Strength-Constrained Unit Commitment with Storage-Enhanced Voltage and Frequency Support

- BESSs in GFM mode allocate their capacity to provide **inertia and damping support**
- **Grid-strength constraints** are quantified by
  - GFM penetration level
  - Eigenvalue-based stability metrics
  - Frequency nadir and RoCoF limits
  - Low voltage ride through requirements
- Two types of **contingency events**
  - Data center **load spikes**: large increase of load
  - **N-1 generation trip**: simultaneous loss of generation capacity, physical inertia, and damping
- Decision variables
  - IBRs: control mode (GFL/GFM), virtual inertia and damping parameters, and required reserve
  - BESS: charge/discharge power and state of charge
  - Standard UC decision variables: status of synchronous generators, optimal power flow
- Nonlinear constraints are reformulated through piece-wise linear approximation and binary expansion to balance model accuracy and complexity
- **Joint optimization** of dynamic support and economic operation
- Minimize **generation and operation costs** subject to system load and reserve requirements
- A **two-stage solution framework** that achieves computational tractability and efficiency

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

Stage 1: Joint Scheduling

Min Generation + Operation Cost

s.t.
1) SOCP AC OPF
2) SG on/off status and generation constraints
3) BESS physical capabilities and dynamics
4) IBR GFL/GFM mode and reserve constraints
5) Frequency nadir and RoCoF constraints
6) GFL/GFM penetration level constraints
7) GFM IBR low voltage ride through constraints

$$\Theta = [\mathbf{p}, \mathbf{q}, \mathbf{r}, \mathbf{s}^{\mathrm{up}}, \mathbf{s}^{\mathrm{dn}}, \mathbf{x}, \mathbf{h}^{\mathrm{lm}}, \mathbf{h}^{\mathrm{ml}}, \mathbf{M}, \mathbf{D}]$$

Power and Reserve | Status and Mode (binary variables) | Inertia and Damping

Fixed reserve, mode, inertia, and damping that ensure small signal stability

Correction needed

Stage 2: Stability Evaluation and Correction

ANDES

sa.EIG.run()
sa.EIG.report()

Sensitivity-based Correction

$$r_k = \mathrm{Re}(\lambda_k(\boldsymbol{\theta}_0)), s_k^{(\mathrm{Re})} = \left[\frac{\partial \mathrm{Re}(\lambda_k)}{\partial \mathbf{M}} \quad \frac{\partial \mathrm{Re}(\lambda_k)}{\partial \mathbf{D}}\right]$$

$$\mathrm{Re}(\lambda_k^{+}) \approx r_k + s_k^{(\mathrm{Re})}\Delta\boldsymbol{\theta} < -\epsilon$$

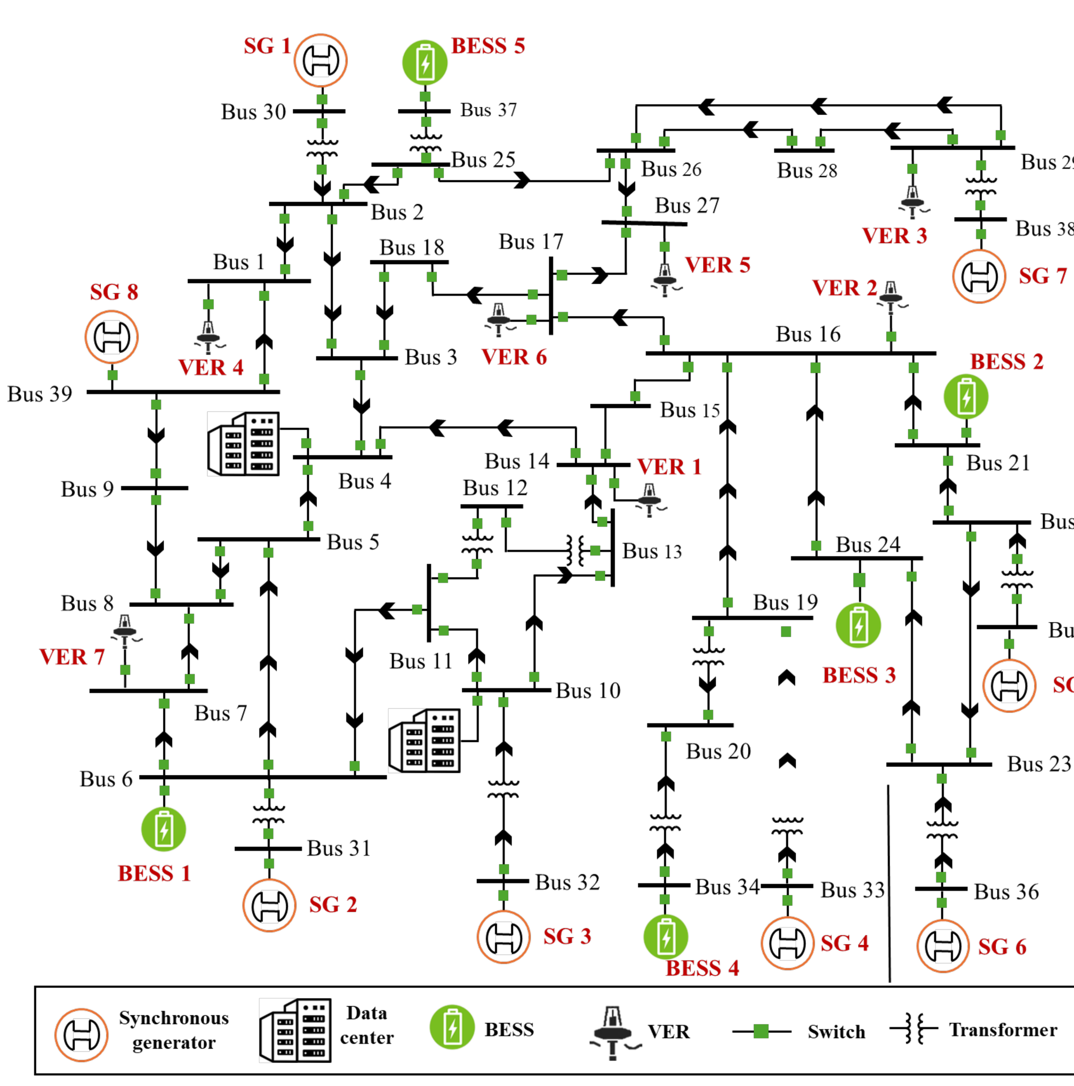
System is stable

Final Scheduling Results

RESULTS

Case Study on the Modified IEEE 39-bus System

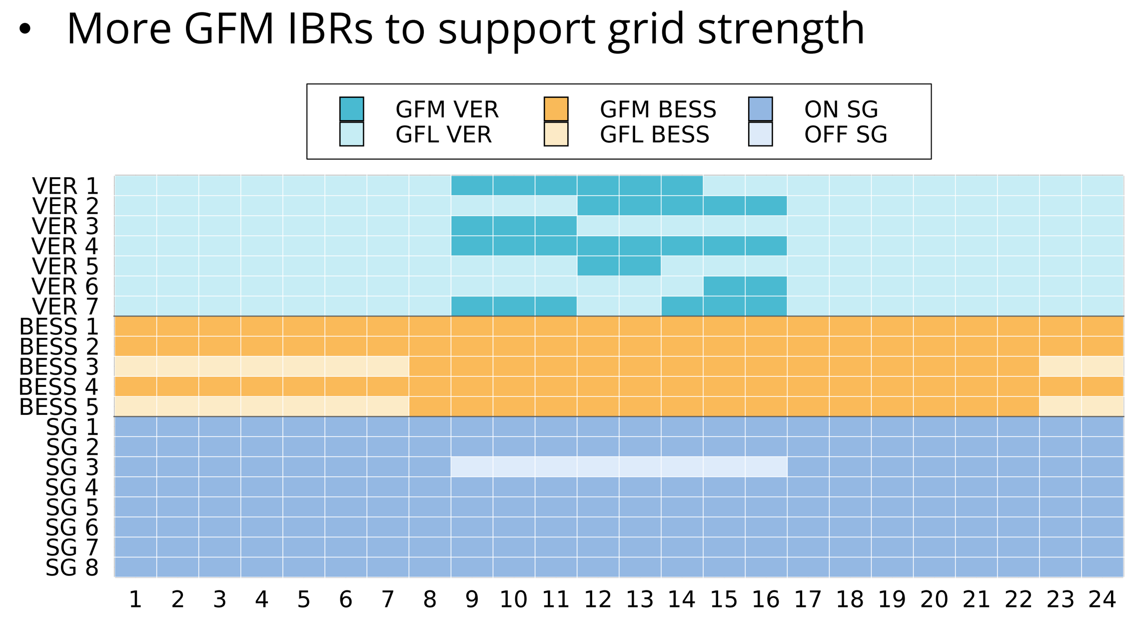
- Two SGs are replaced with BESS
- Include three additional BESS and seven VERs



Modified IEEE 39-Bus system

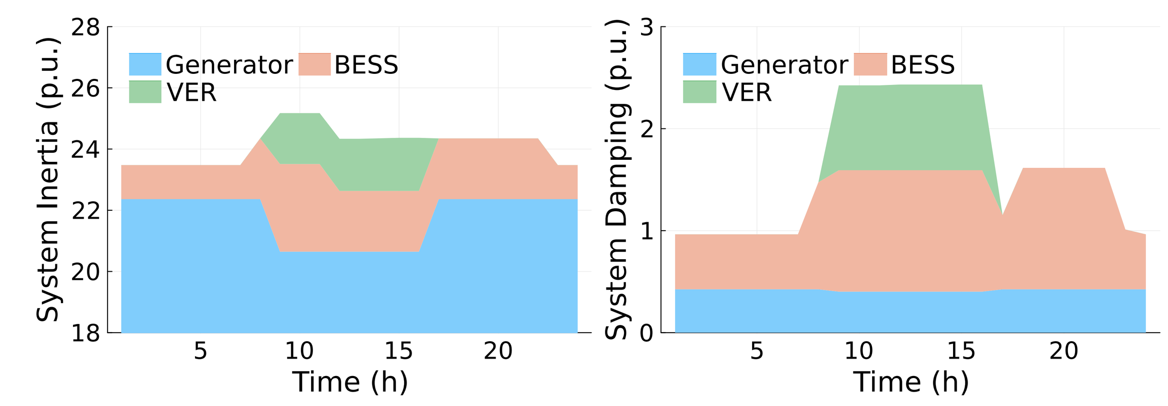
SG on/off Status and IBR GFL/GFM Mode

- One SG is off due to high VER output in daytime
- More GFM IBRs to support grid strength



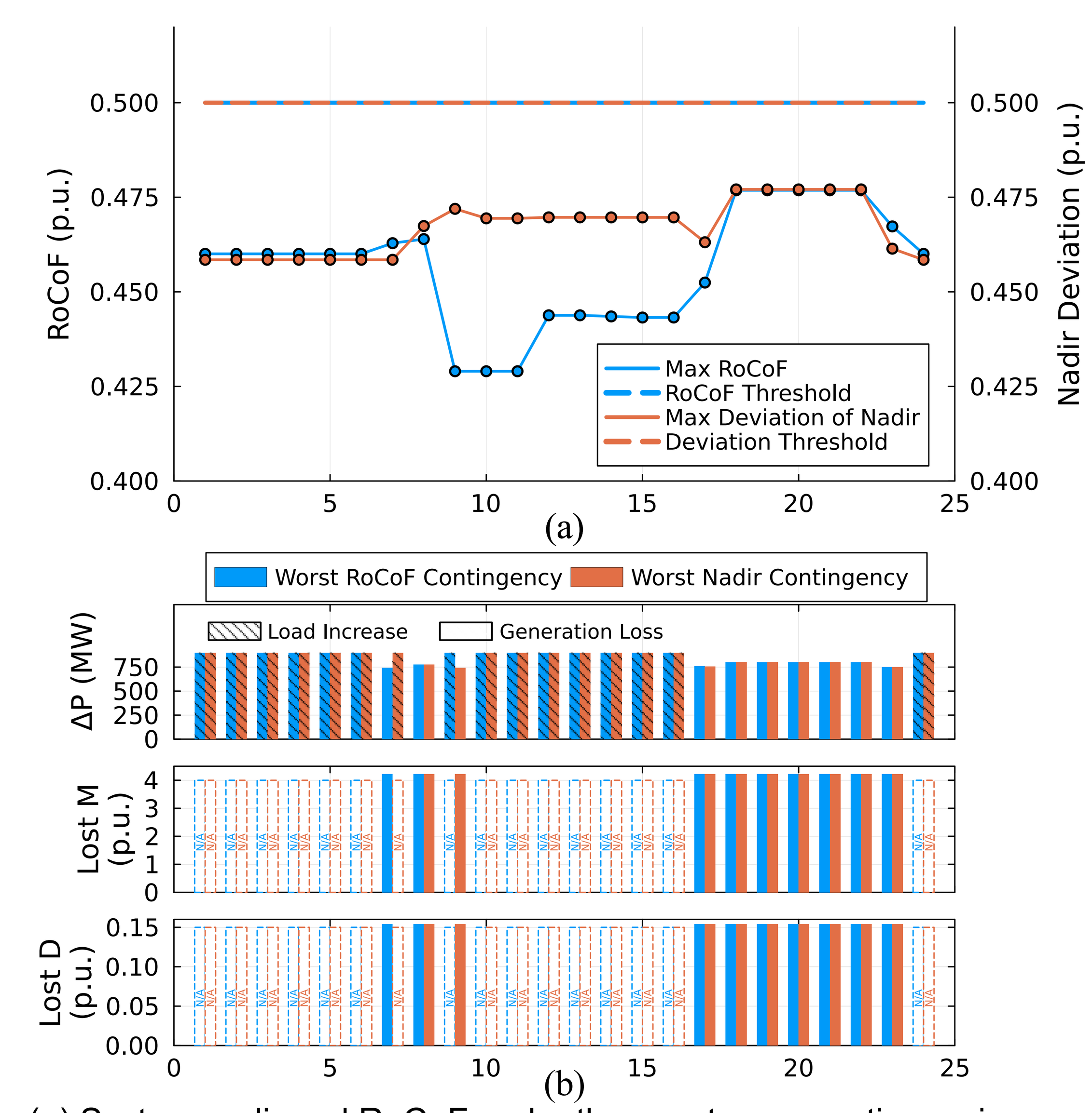
System Inertia and Damping

- Physical inertia is low in daytime because one SG is turned off to reduce costs
- GFM IBRs provide virtual inertia and damping to enhance grid strength



Grid Strength and Stability

- All scheduling intervals are verified to be stable through eigenvalue analysis and time-domain simulations in ANDES
- Both frequency nadir and RoCoF remain within security limits under the worst-case contingencies



(a) System nadir and RoCoF under the worst-case contingencies;
(b) Identified worst-case contingencies

CONCLUSIONS & IMPACT

- Co-optimizing unit commitment with IBR control modes and virtual inertia/damping scheduling can maintain **frequency and voltage stability** in weak, high IBR penetrated grids
- The proposed framework enables **BESS** to operate as an **actively dispatchable stability resource** for evolving modern grid with predictable and measurable performance
- This project provides a promising pathway to preserve **contingency resilience** through the adoption of BESS in low-inertia systems

FUTURE DIRECTIONS

- Incorporate more detailed device models to improve model fidelity
- Extend the formulation with optimization-under-uncertainty techniques to account for uncertainties and validate the framework on larger, real-world systems

For additional information, contact:

Wei Wang
509-375-2237
w.wang@pnnl.gov