GFM IBR: Functional Specification, Simulation Strategies and Scenario Recommendations

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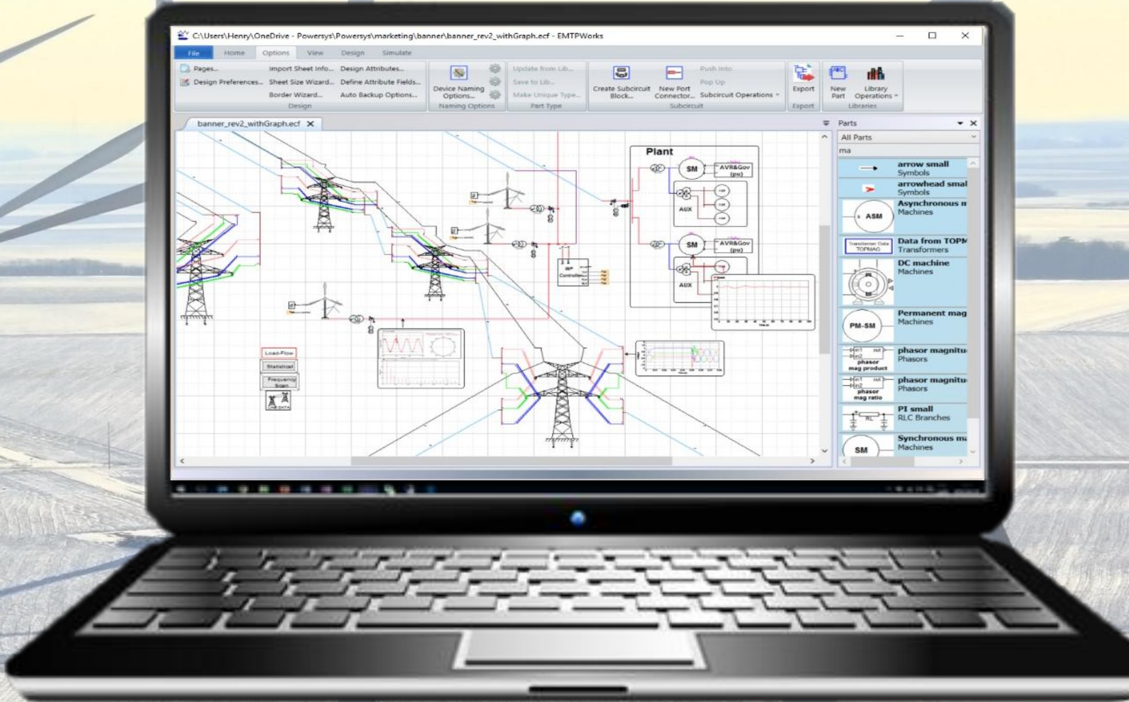

ESIG

2025 Spring Technical Workshop

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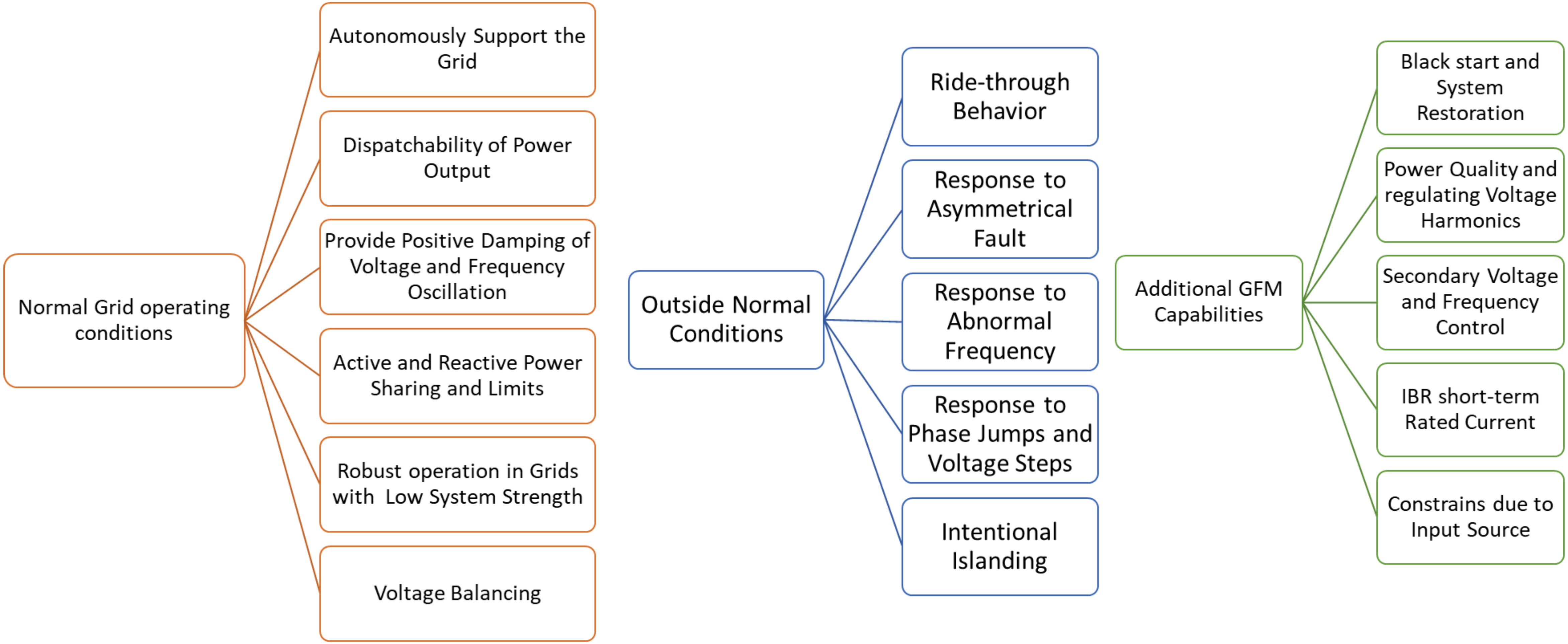
Why should we model IBRs in EMT mode?

- **Realistic representation of network components**
  - Detailed component models such as converters, transformers, controls, lines, harmonic filters
  - Nonlinearities and saturation such as transformer and machine saturation, etc.
- **High fidelity converter models: capture a wide range of response timeframes, from µs to ms and to seconds**
  - PWM switching and inner control (response time 100us-10ms)
  - Outer control such as active, reactive, PLL, FRT (response time 10ms-1s)
  - Upper-level control (plant level): frequency, voltage (response time 1-10s)
- **Grid stability under different scenarios**
  - Analysis of balanced or unbalanced conditions
  - EMT can capture phenomena like voltage instability, harmonics, or control interactions that traditional RMS simulations might miss.

Performance Requirements for GFM IBRs



- Normal Grid operating conditions
  - Autonomously Support the Grid
  - Dispatchability of Power Output
  - Provide Positive Damping of Voltage and Frequency Oscillation
  - Active and Reactive Power Sharing and Limits
  - Robust operation in Grids with Low System Strength
  - Voltage Balancing
- Outside Normal Conditions
  - Ride-through Behavior
  - Response to Asymmetrical Fault
  - Response to Abnormal Frequency
  - Response to Phase Jumps and Voltage Steps
  - Intentional Islanding
- Additional GFM Capabilities
  - Black start and System Restoration
  - Power Quality and regulating Voltage Harmonics
  - Secondary Voltage and Frequency Control
  - IBR short-term Rated Current
  - Constrains due to Input Source

- Performance Requirements for GFM IBRs – Chilean Grid Code (coordinador.cl)
- Specifications for Grid-forming IBRs-Unifi Consortium (unificonsortium.org)
- Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework (aemo.com.au)

Performance Requirements for GFM IBRs

Tests:

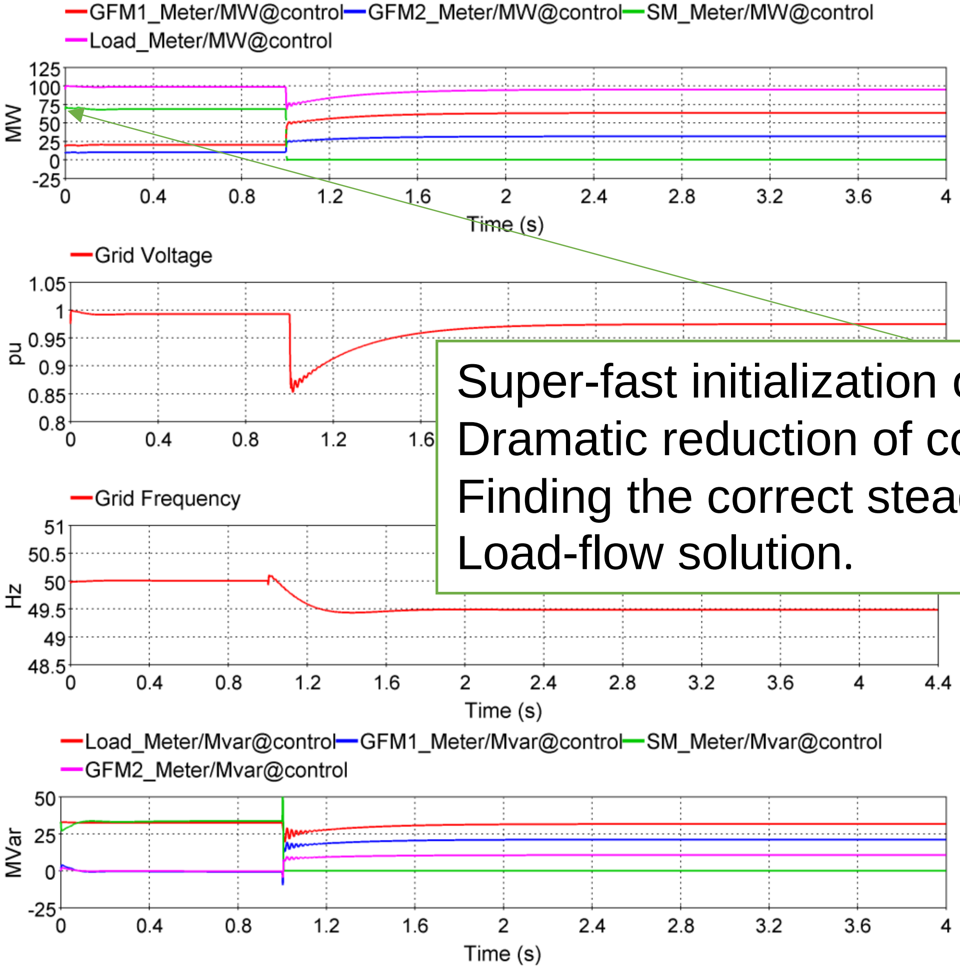
1. Loss of synchronous machine – discharging
2. Loss of synchronous machine – charging
3. Loss of synchronous machine – limits
4. Loss of synchronous machine – power balance
5. RoCoF up and down
6. SCR ramp down with fault
7. Angle step change
8. Isolated grids, unbalanced fault, IEEE 2800 requirements
9. GFM inverters with series-compensated transmission lines
10. BESS GFM, black-start
11. BESS GFM, secondary controller
12. GFM frequency scan
13. Protection, unit testing and system testing

- Performing tests for SMIB or wide-area EMT modeling?
- What are the benefits and challenges of wide-area modeling and study?
- Can GFM inverters provide all grid support functions at the same time?

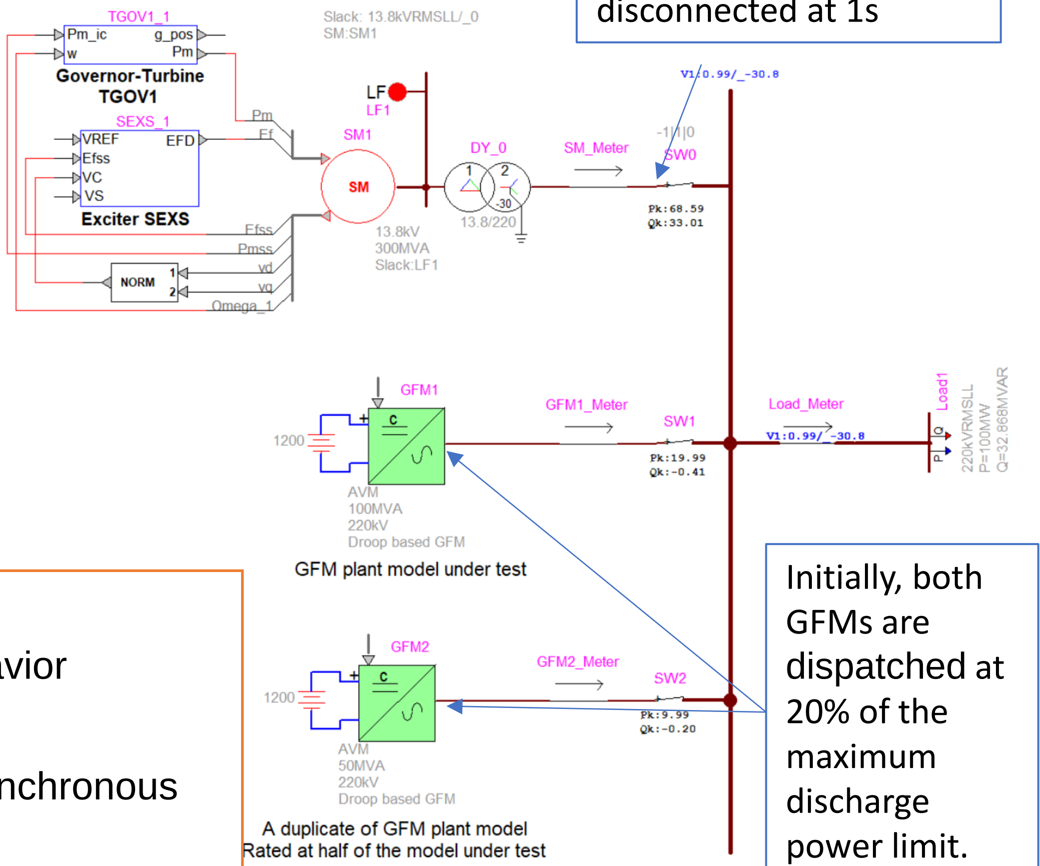
Performance Requirements for GFM IBRs

Test 1: Loss of synchronous machine – discharging

BESS GFM IBRs only, Testing for GFM Inverter basic functions



Super-fast initialization of EMTP. Dramatic reduction of computing times. Finding the correct steady-state from Load-flow solution.



Synchronous generator is disconnected at 1s

GFM plant model under test

A duplicate of GFM plant model
Rated at half of the model under test

Initially, both GFMs are dispatched at 20% of the maximum discharge power limit.

Challenges:

- Voltage source behavior
- Inertia response
- Surviving the last synchronous connection
- Oscillation damping

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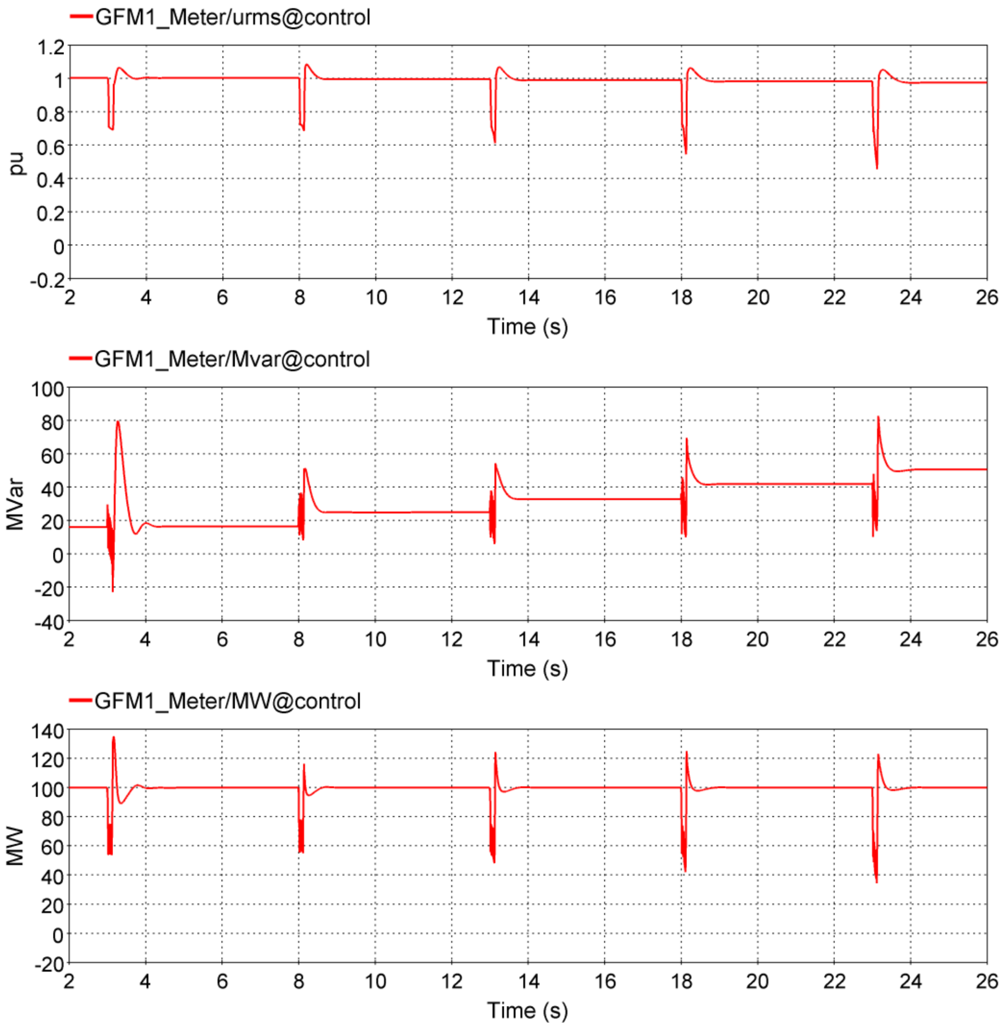
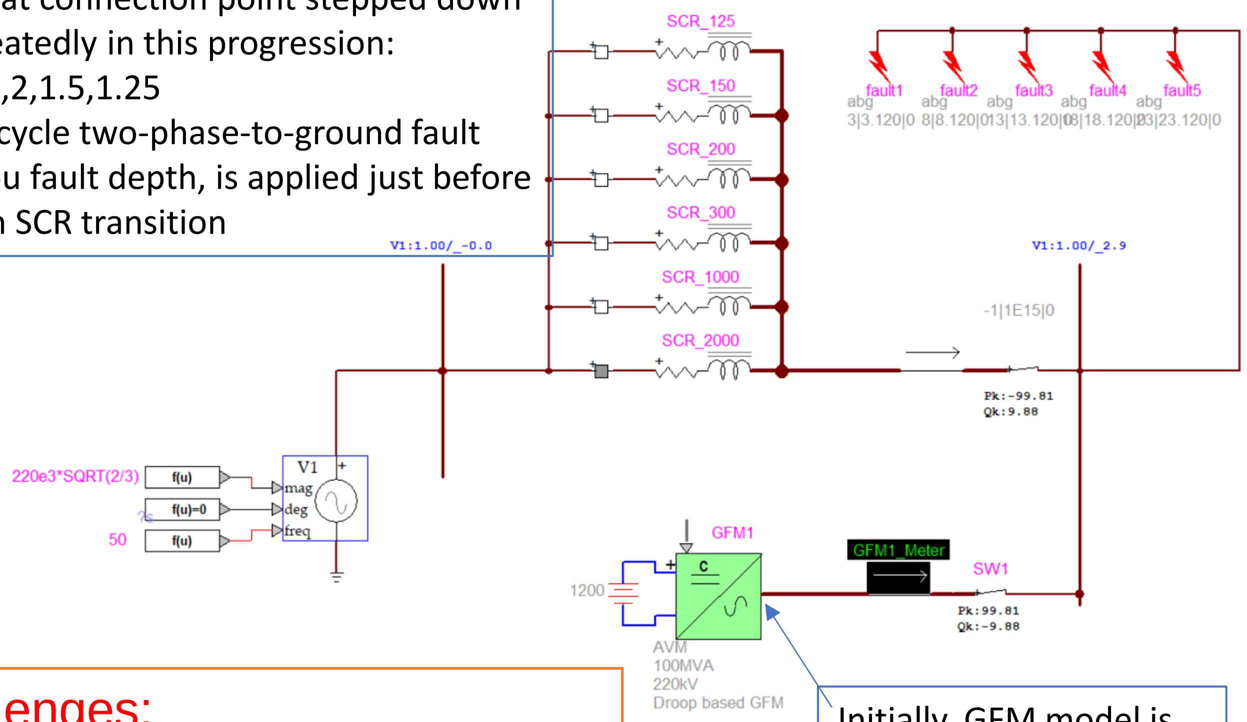
Performance Requirements for GFM IBRs

Test 6: SCR ramp down with fault



Testing for GFM Inverter control stability

- SCR at connection point stepped down repeatedly in this progression: 10,3,2,1.5,1.25
- A 6-cycle two-phase-to-ground fault 0.5pu fault depth, is applied just before each SCR transition



Initially, GFM model is dispatched at 100% of its maximum discharge power limit.

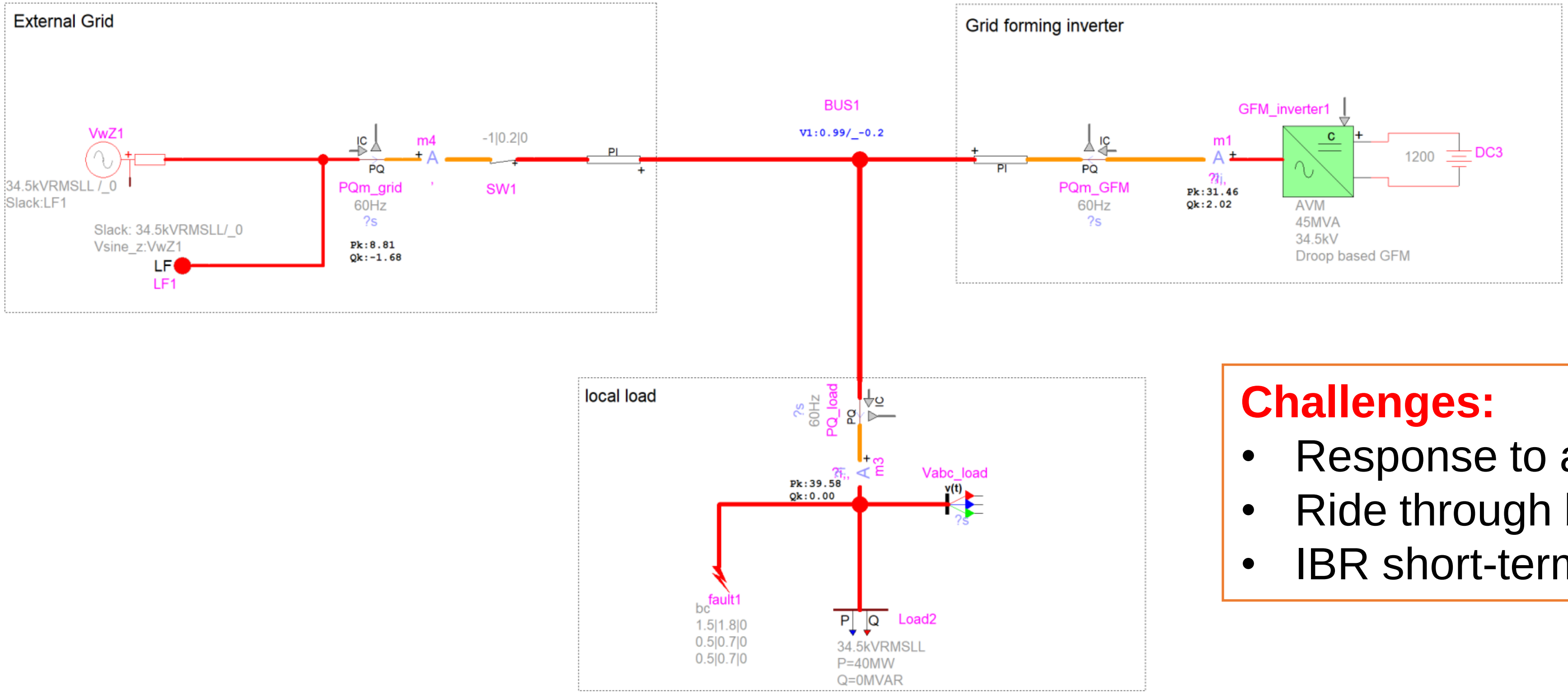
Challenges:

- Robust operation in grids with low system strength
- Oscillation damping

Performance Requirements for GFM IBRs

Test 8: Isolated grid, unbalanced fault, IEEE 2800 requirements

- At t=0.2s, the breaker connecting the external grid to the rest of the circuit is opened, and the GFM inverter supplies the load, thereby making a 100% inverter network.
- At t=0.5s, a two-phase fault (BC) occurs at Bus 1, and the fault clears at 0.7s

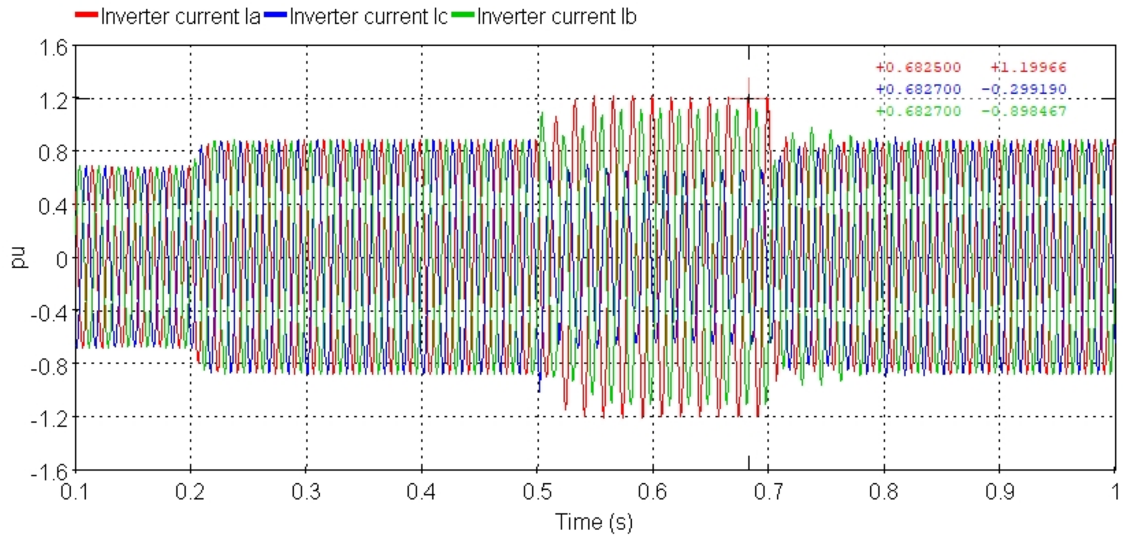


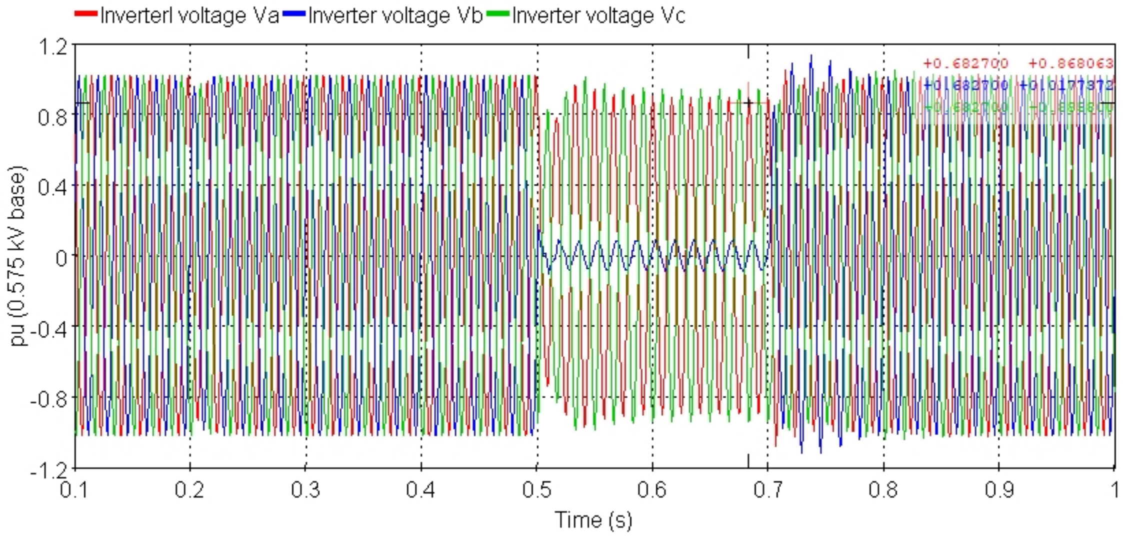
Challenges:

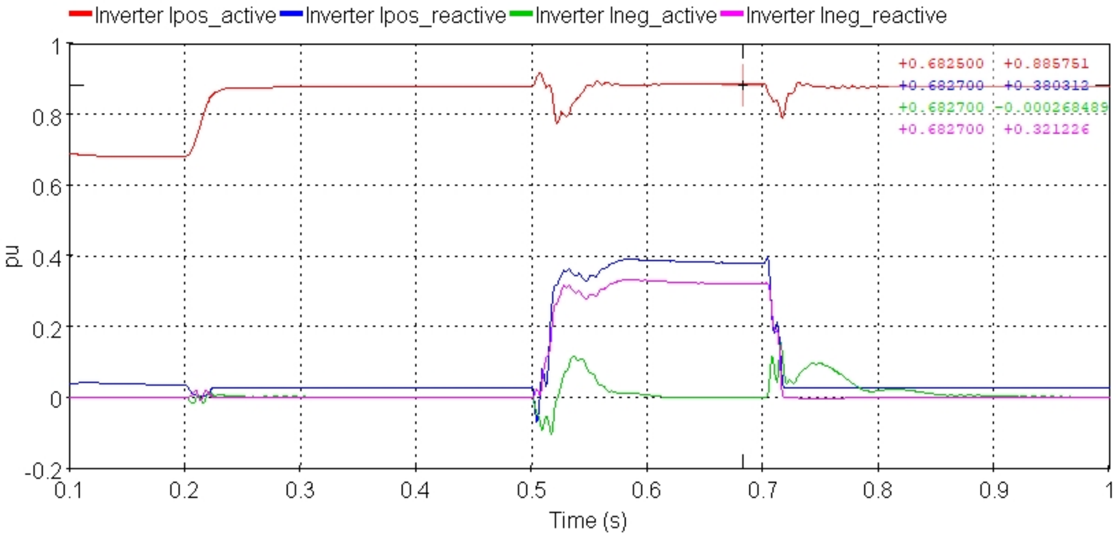
- Response to asymmetrical fault
- Ride through behavior
- IBR short-term rated current

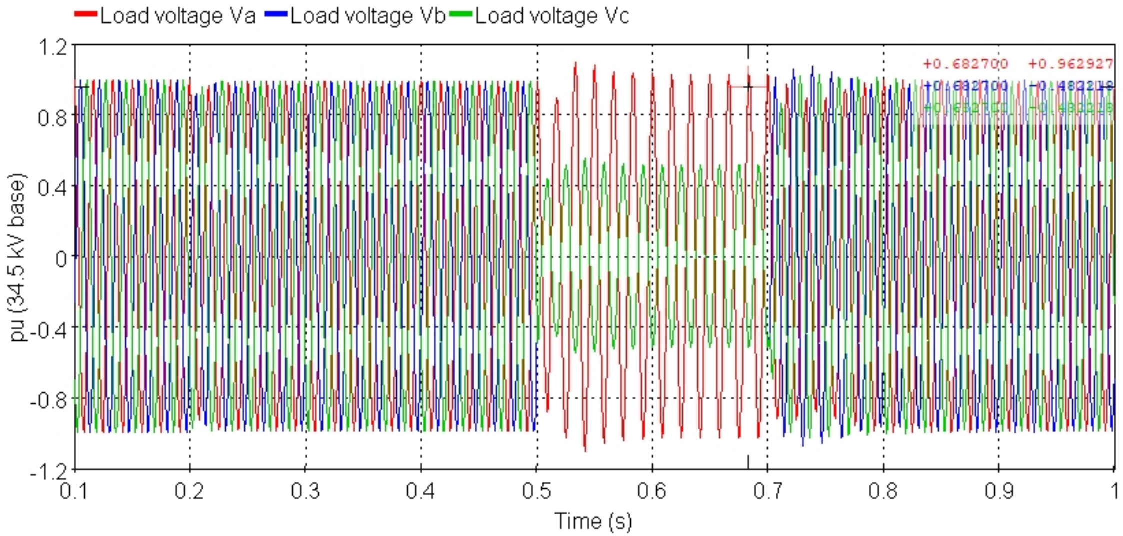
Performance Requirements for GFM IBRs

Test 8: Isolated grid, unbalanced fault, IEEE 2800 requirements







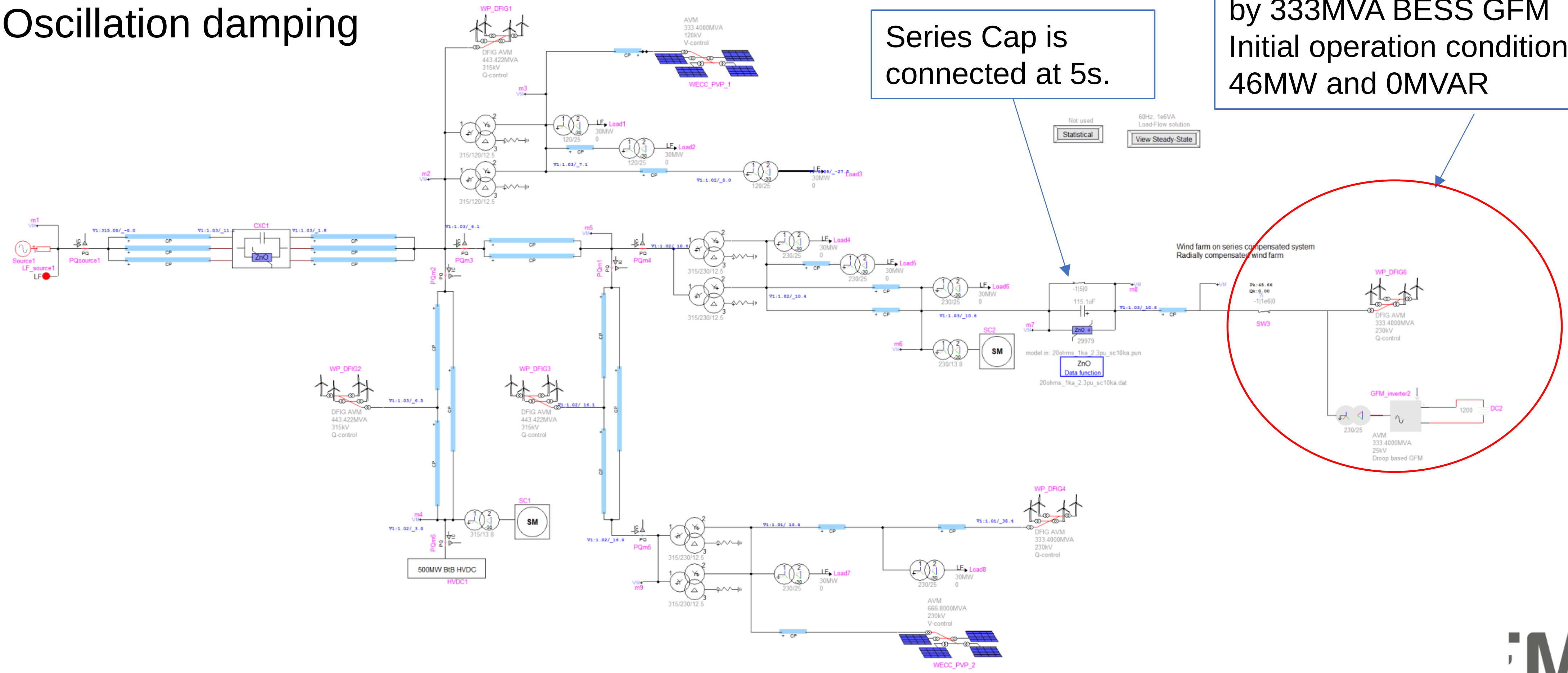


Performance Requirements for GFM IBRs

Test 9: GFM inverter with series-compensated transmission lines

Challenges:

- Sub-/Super-synchronous resonance mitigation
- Oscillation damping

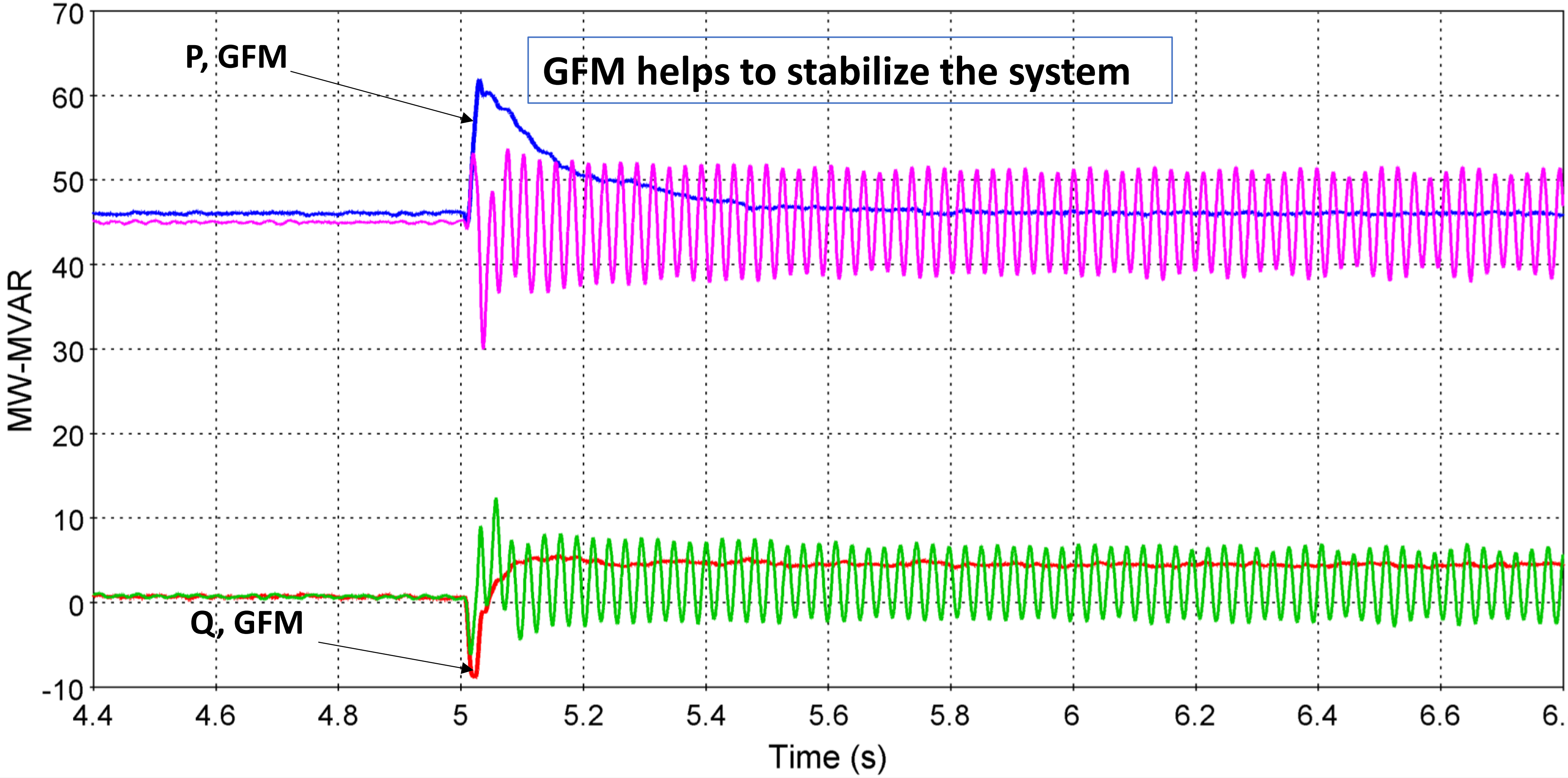


Series Cap is connected at 5s.

333 MVA DFIG WT is replaced by 333MVA BESS GFM
Initial operation conditions: 46MW and 0MVAR

Performance Requirements for GFM IBRs

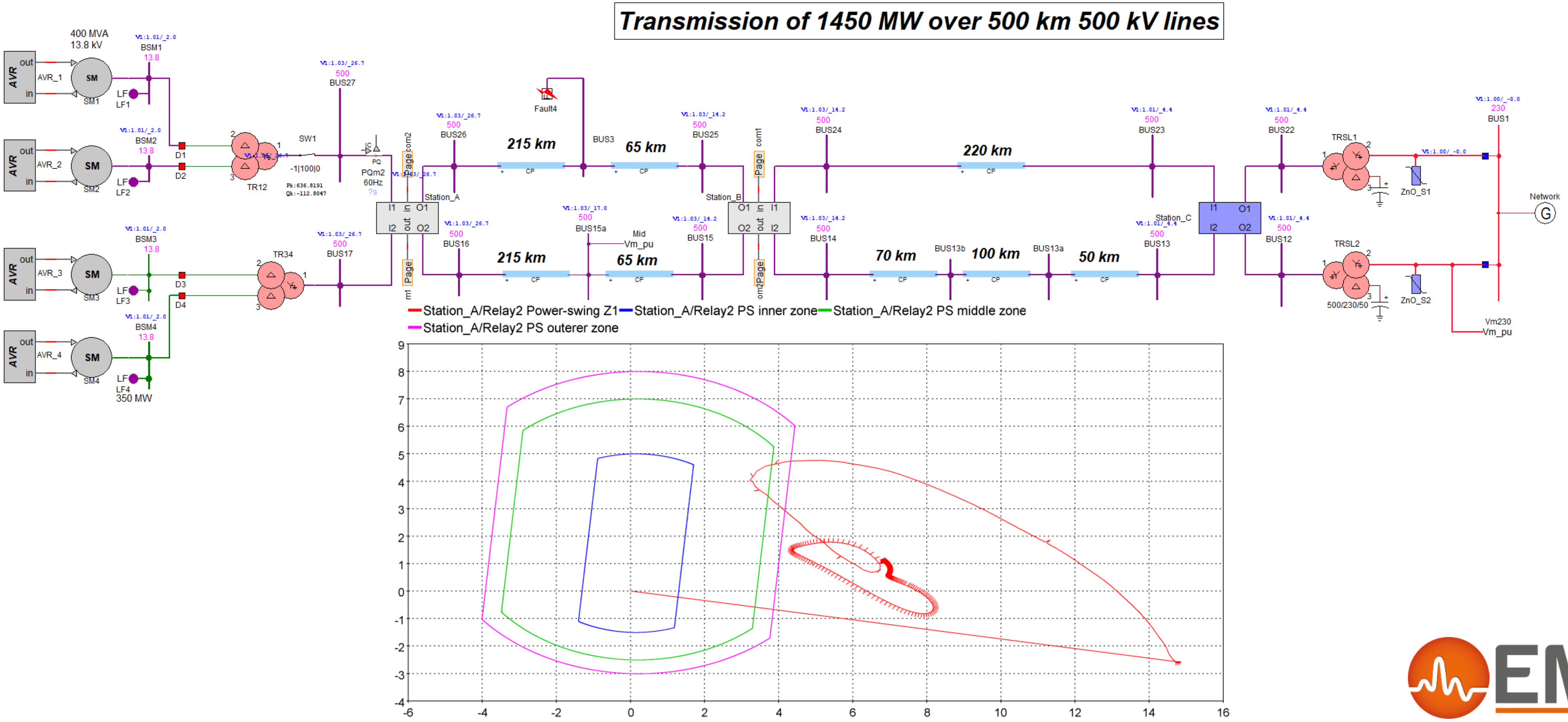
Test 9: GFM inverter with series-compensated transmission lines



Integration of GFM IBRs in Electric Grids

Test 13: Protection, power swing

A three-phase fault is applied at 0.2s, and then the line 26-25 is disconnected



Integration of GFM IBRs in Electric Grids

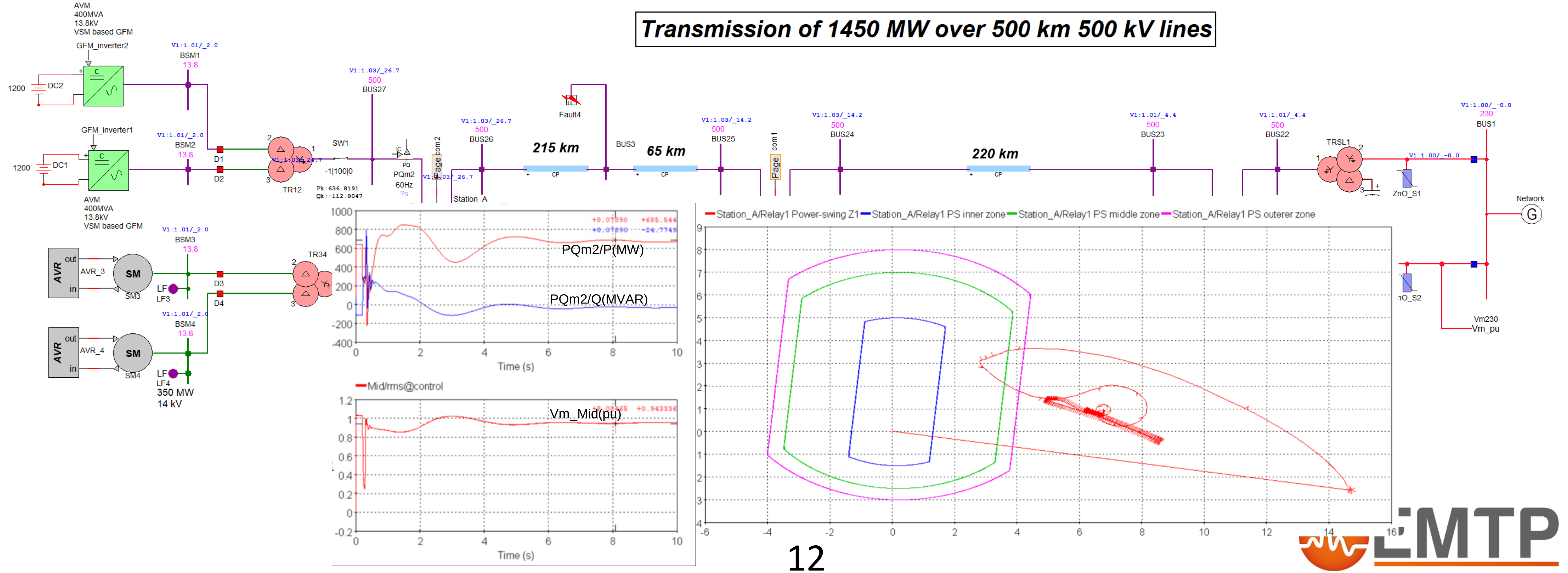
Test 13: Protection, power swing

- SG 1 and SG 2 are replaced by GFM inverters.
- A three-phase fault is applied at 0.2s, and then the line 26-25 is disconnected

Challenges:

- Ride through behavior
- Protection performance
- Protection coordination

Transmission of 1450 MW over 500 km 500 kV lines



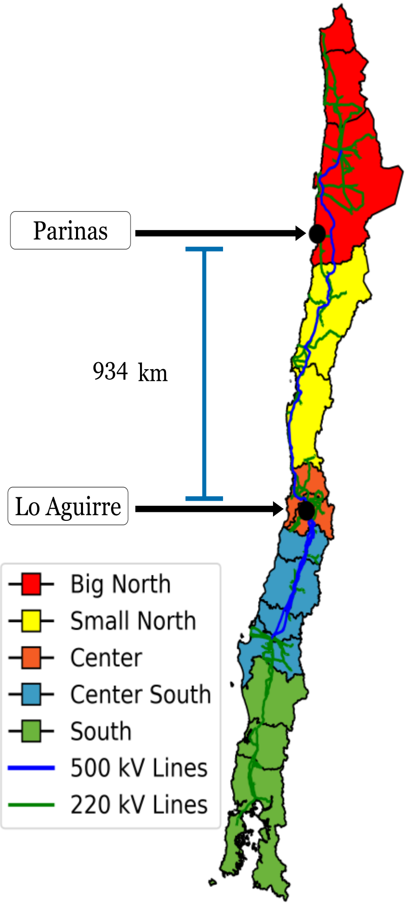
Integration of GFM IBRs in Large Grids

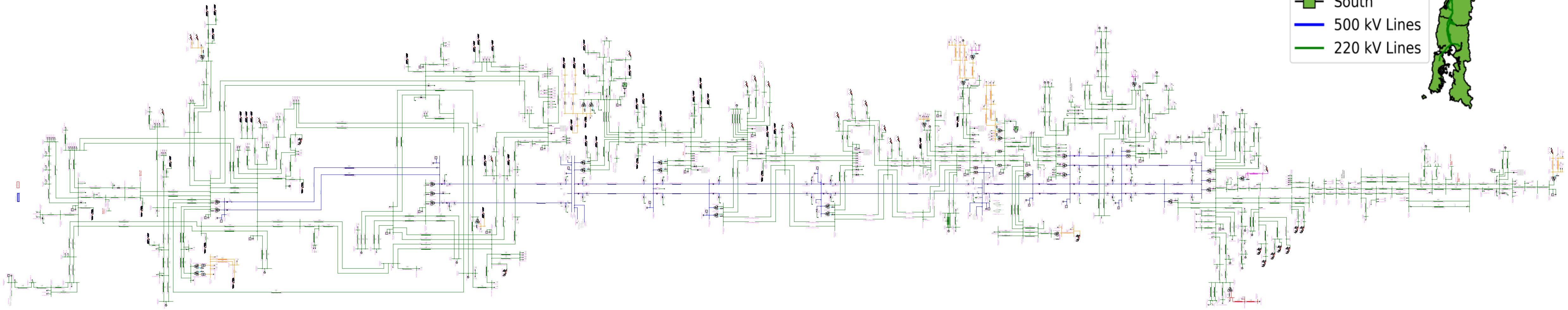
CEN grid (Coordinador Electrico Nacional)

- Four BESS GFM IBRs are installed
- 85% VRE
- A LLG fault applied to NPAzucar_Polpaico_500kV_C1 line

Challenges:

- Initialization
- Control interaction
- Voltage and frequency stability
- GFM inverter placement





Integration of GFM IBRs in Large Grids

CEN grid

- The model is composed of 32 wind parks, 59 solar plants, and 62 SG. The transmission system includes the complete bulk grid composed of 500kV, 220kV and 110kV transmission lines (678 in total)
- Components:
  - 8751 nodes (13196x13196 matrix)
  - 121 nonlinear functions
  - 507 loads
  - 306 transformers
  - 82577 control-diagram blocks
- Average number of iterations per time-point: 1.98

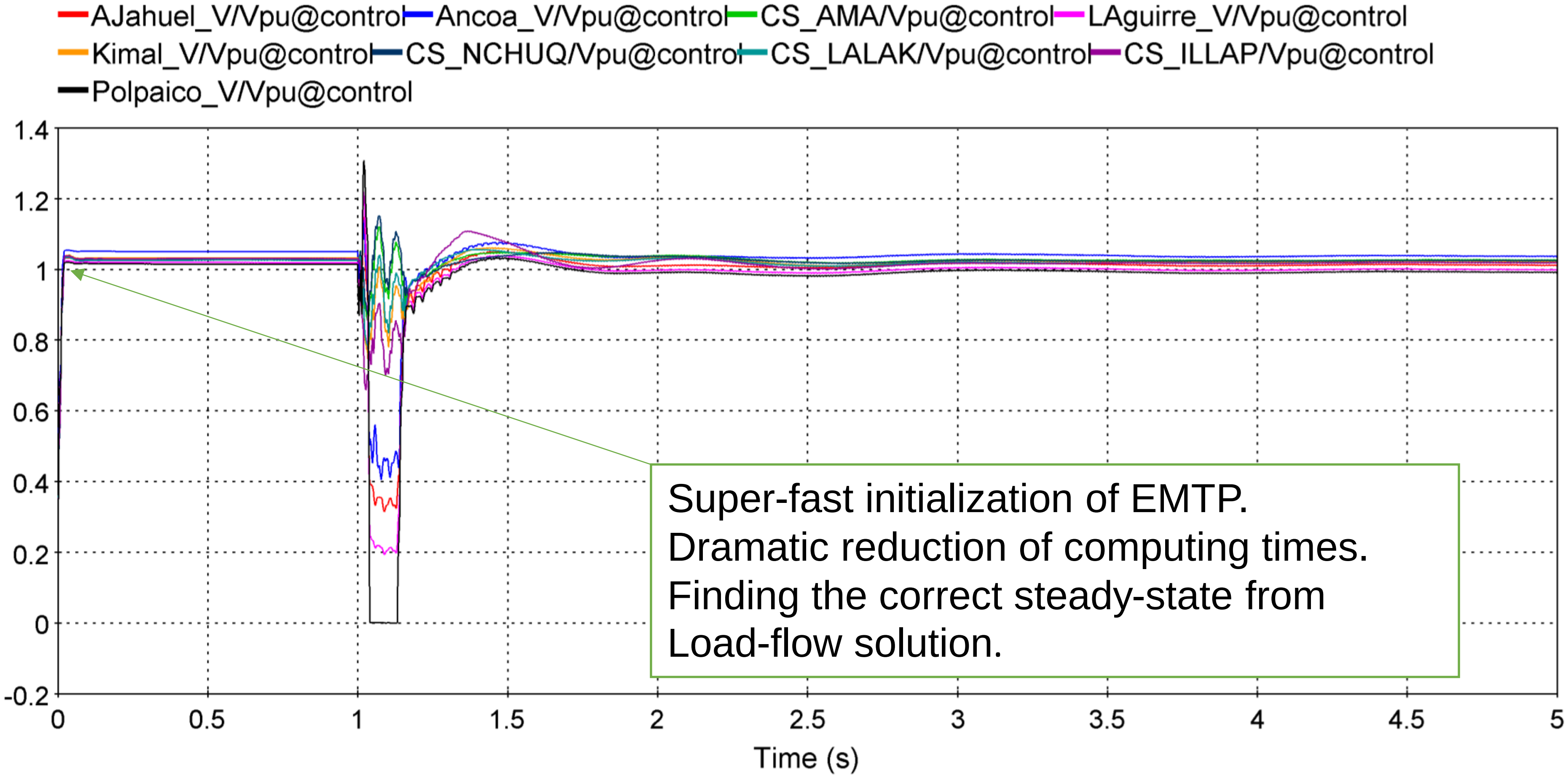
Computing times, Control solver 4
AMD Ryzen Threadripper PRO 5995WX
81 cores
1s → 10s
50µs time-step for all

Estimated time with
AMD Ryzen Threadripper PRO 7995WX: 6s

Integration of GFM IBRs in Large Grids

CEN grid

- Initialization

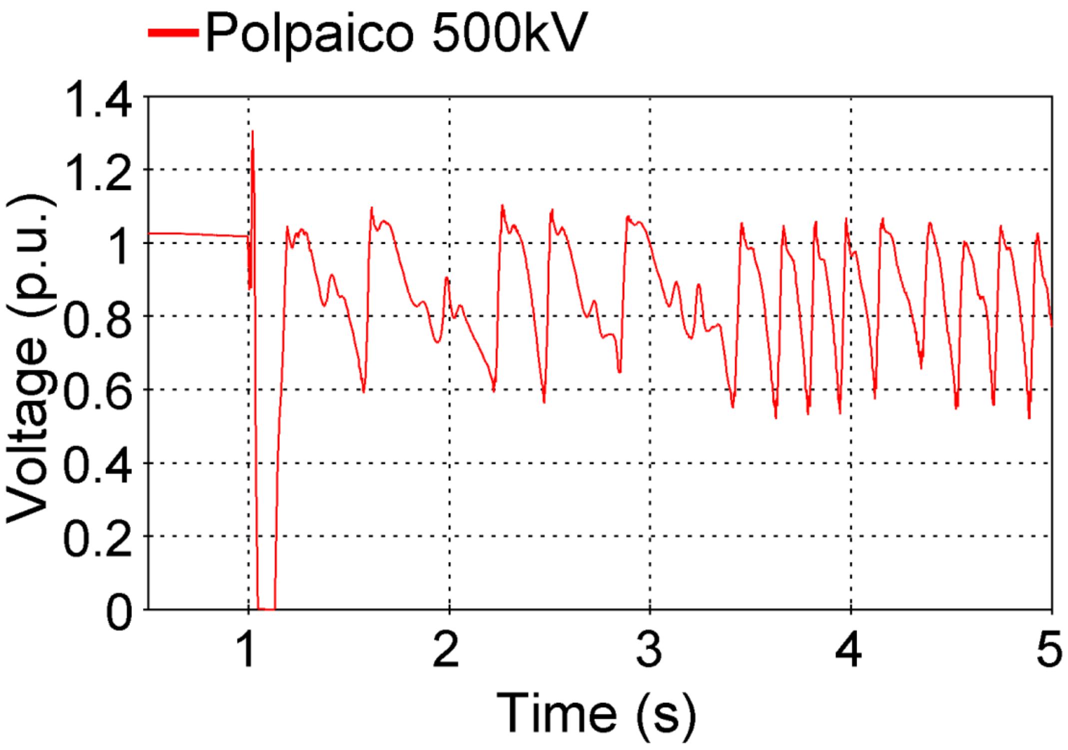


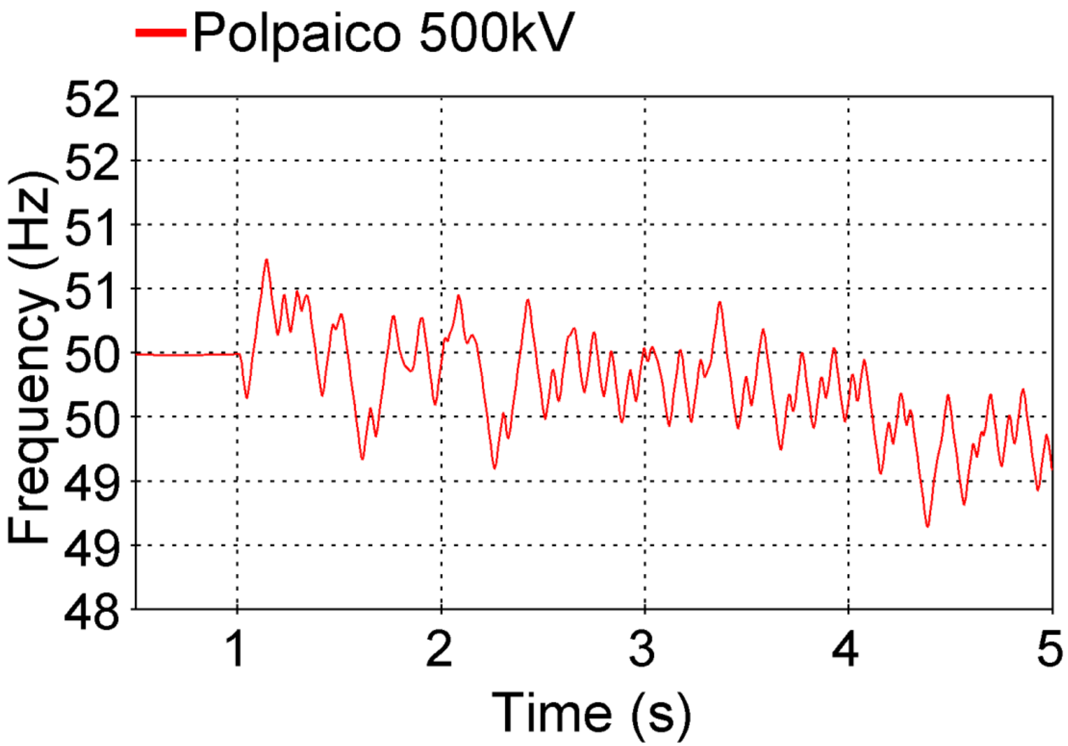
Super-fast initialization of EMTP.
Dramatic reduction of computing times.
Finding the correct steady-state from Load-flow solution.

Integration of GFM IBRs in Large Grids

CEN grid- Base case (without GFM IBRs)

- 70% of GFL VRE, only 50 MW of SG in the Northern region
- Fault: 2-phase-ground, 120 ms, Polpaico 500kV substation



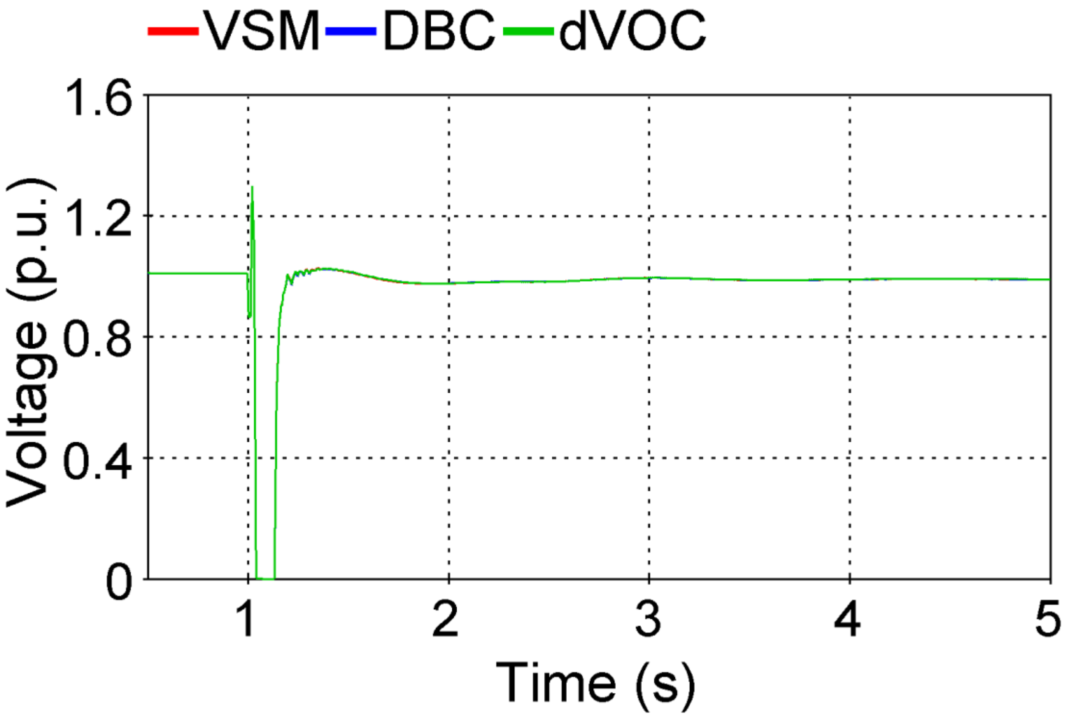


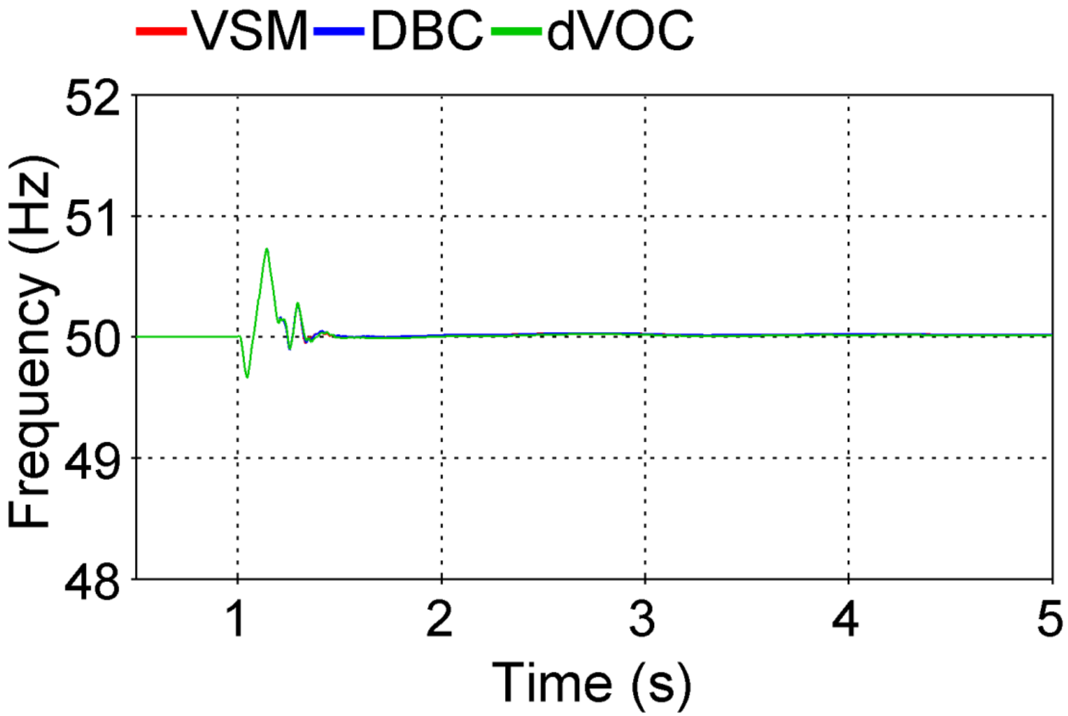
Integration of GFM IBRs in Large Grids

CEN grid

With GFM IBRs: Fault near Polpaico Substation

- Integration of 4×150MVA GFM BESS units in the NPG, in replacement of existing GFL VRE, Active power setpoint of 100MW
- Same fault as in Base case



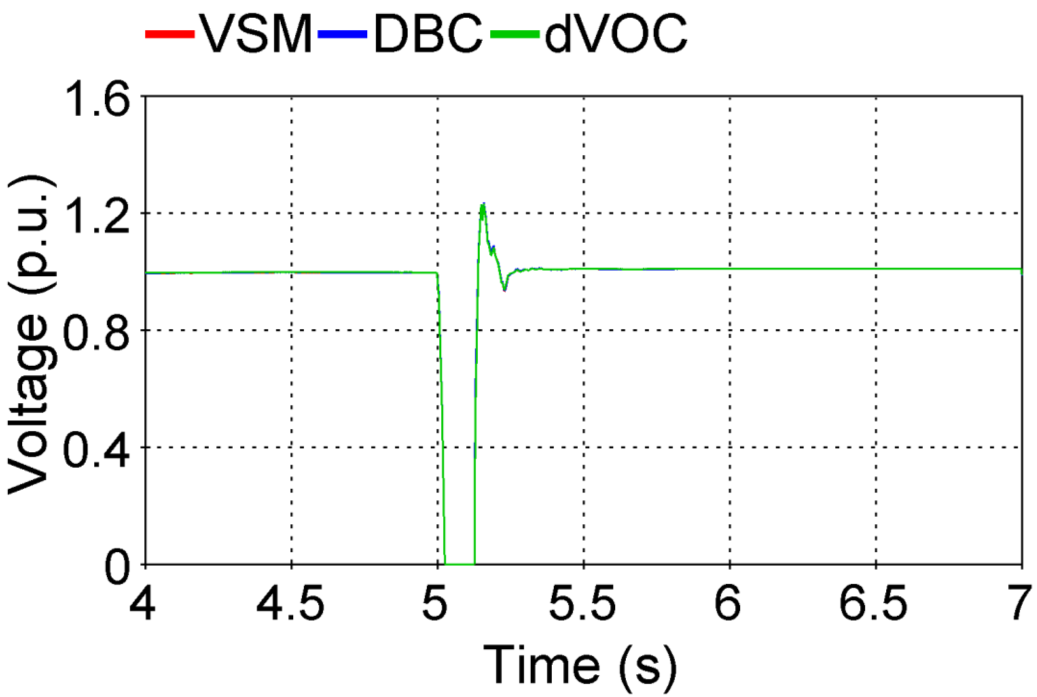


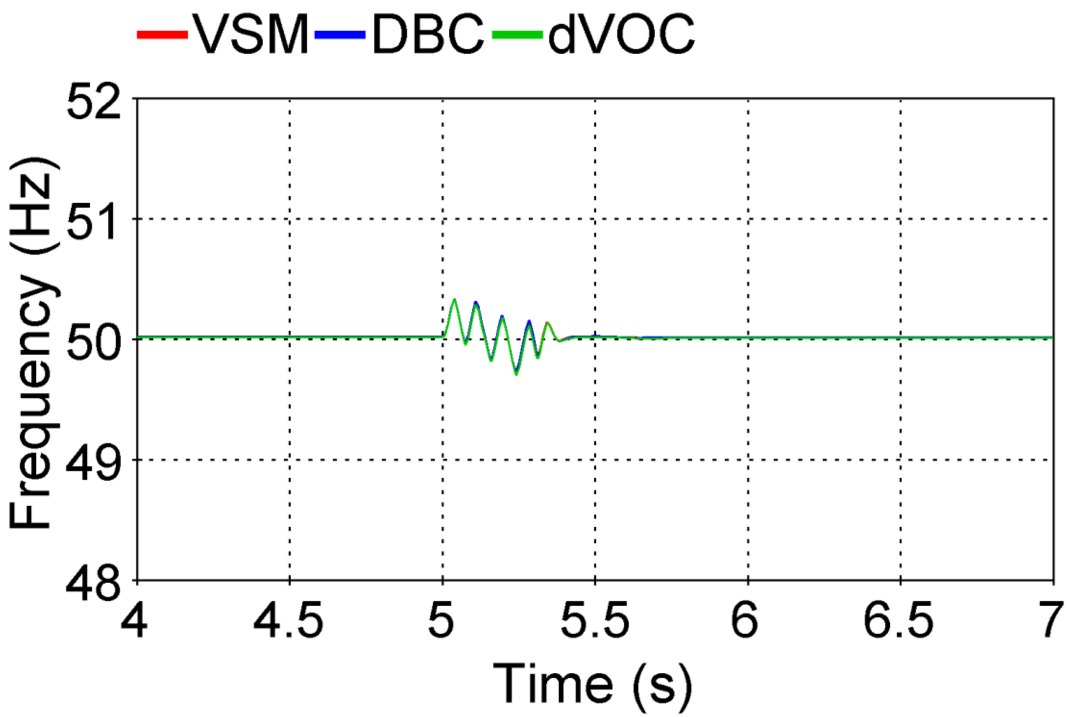
Integration of GFM IBRs in Large Grids

CEN grid

With GFM IBRs: Islanding event

- 2-phase-ground fault of 120ms duration at Parinas 500kV substation at t=5s, followed by the trip of both the faulted and the parallel healthy circuits of the 500kV line Parinas-Cumbres.
- Separation into two islands, leaving the northern and most critical island with 2,782MW (88.8%) of GFL VRE generation and 300MW (9.6%) of GFM BESS. Only a 50MW SG (last and only SG unit) remains in this island.

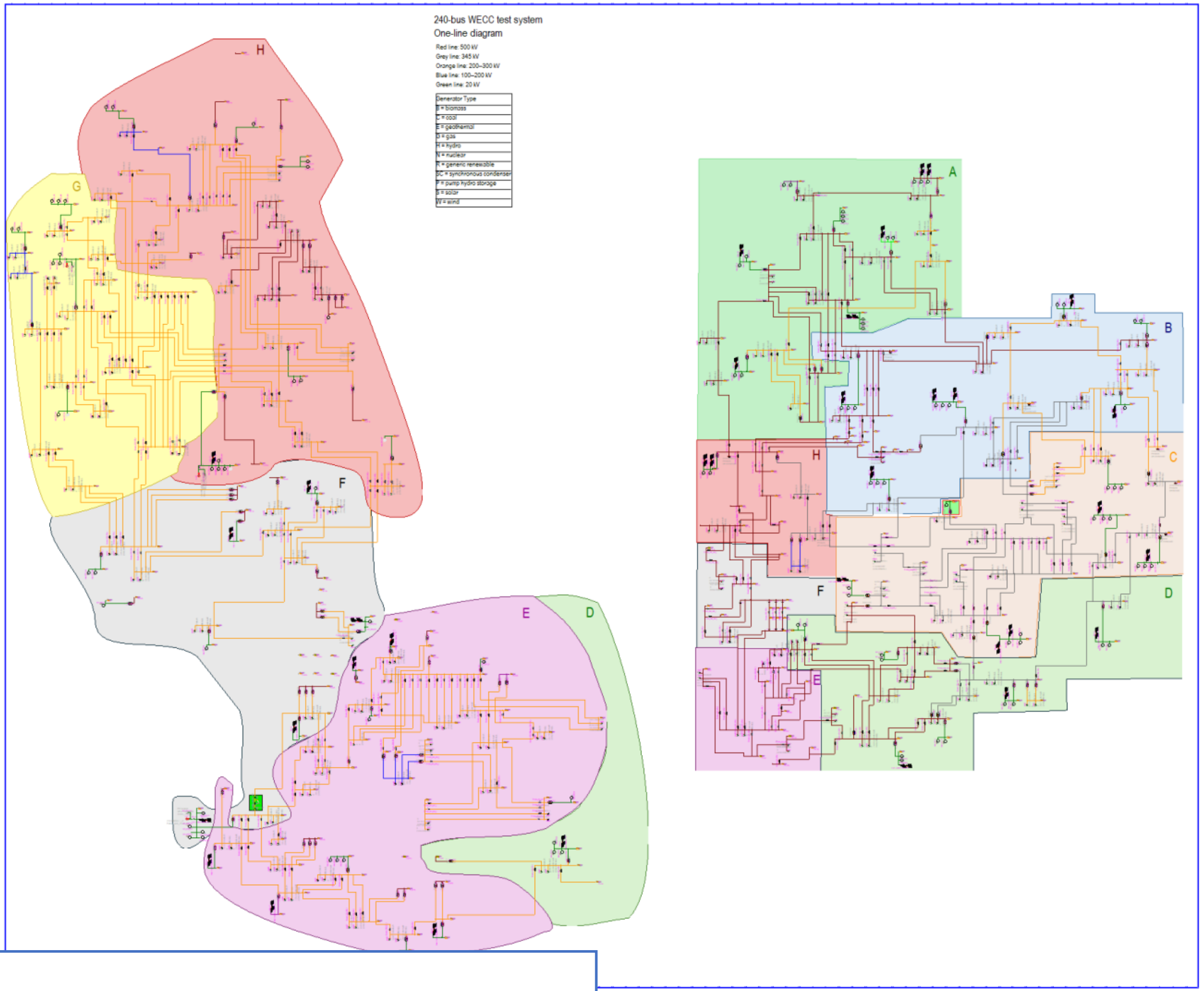




Integration of GFM IBRs in Large Grids

WECC 240 bus system in EMTP®

- Synchronous machines, with controls and magnetization data: 103
- PVs: 68 with detailed controls (WECC models)
- PPCs: 34 (WECC models)
- Nonlinear models: 34
- Transformer units: 570
- RLC branches: 3279
- PI-lines: 320, 960 phases
- Ideal switches: 519
- Loads: 819
- Control diagram blocks: 15470
- Nodes: 3977
- Matrix A size: 5914x5914
- Number of iterations per time-point: 1.04

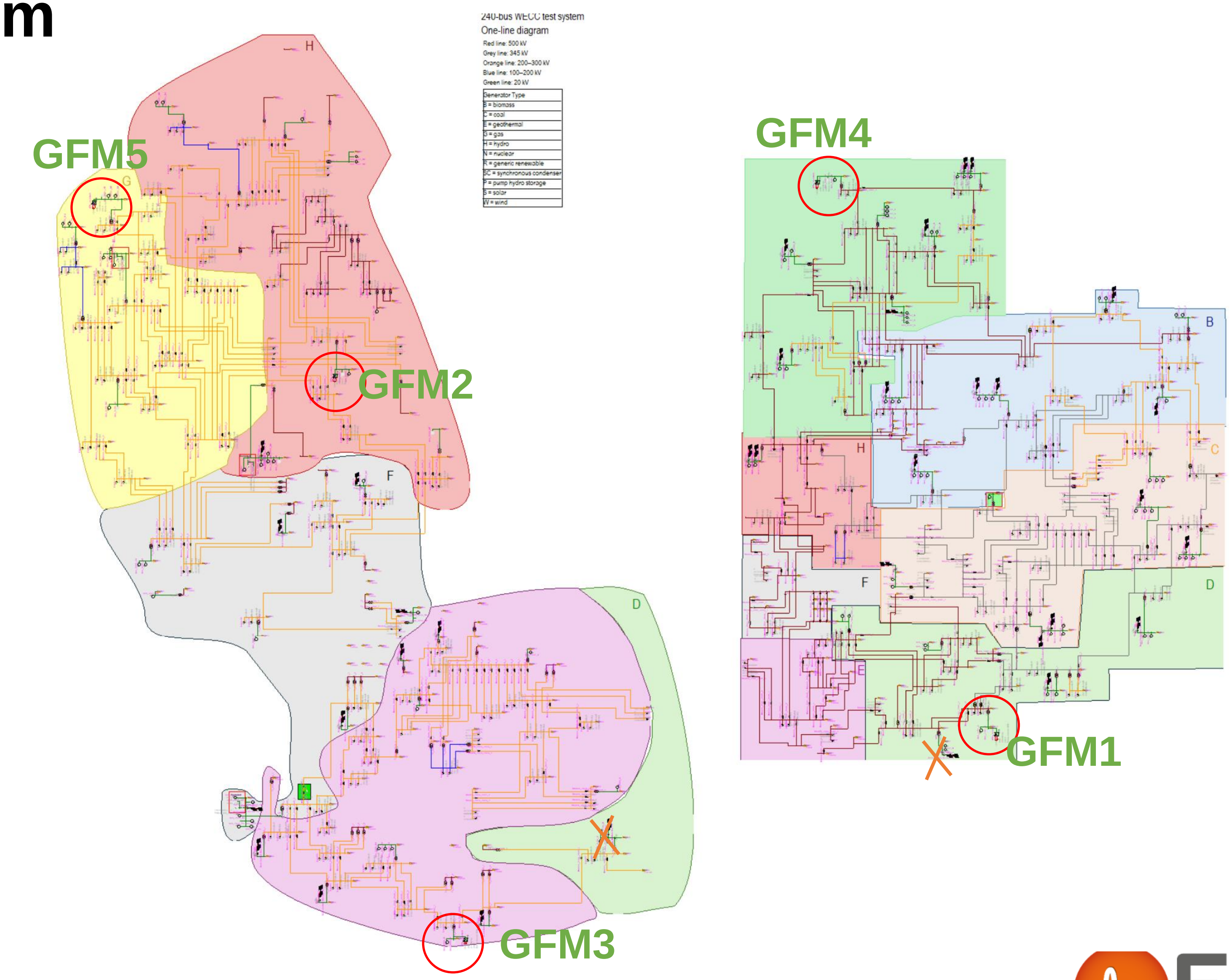


Computing time
12th Gen Intel(R) Core(TM) i7-12800H   2.40 GHz
1s → 25s, 50μs time-step, 1-CPU!

Integration of GFM IBRs in Large Grids

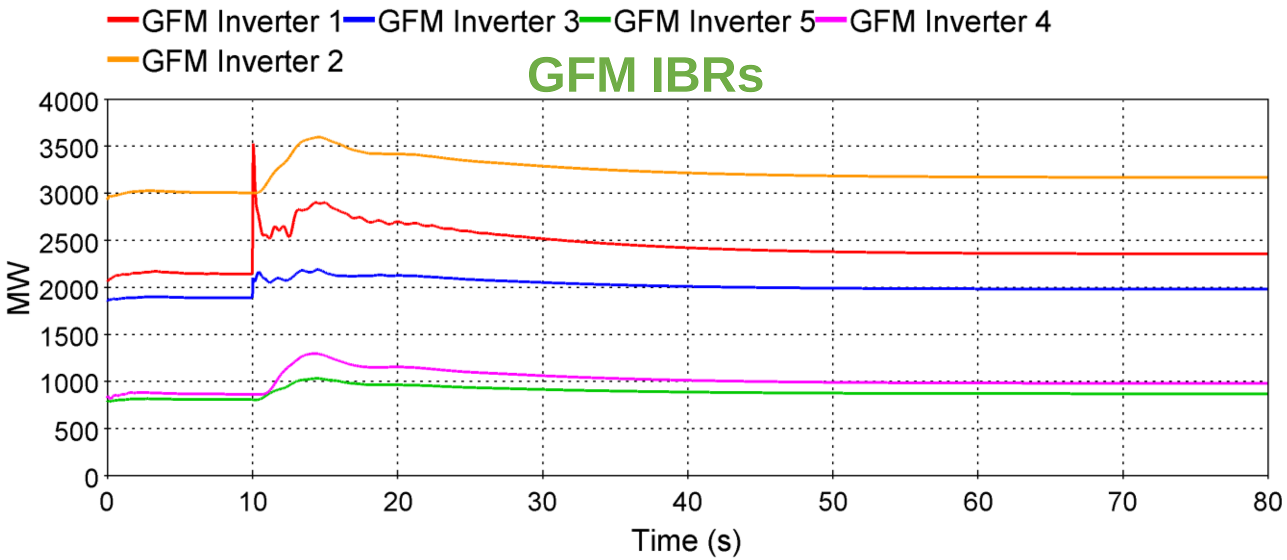
WECC 240 bus system

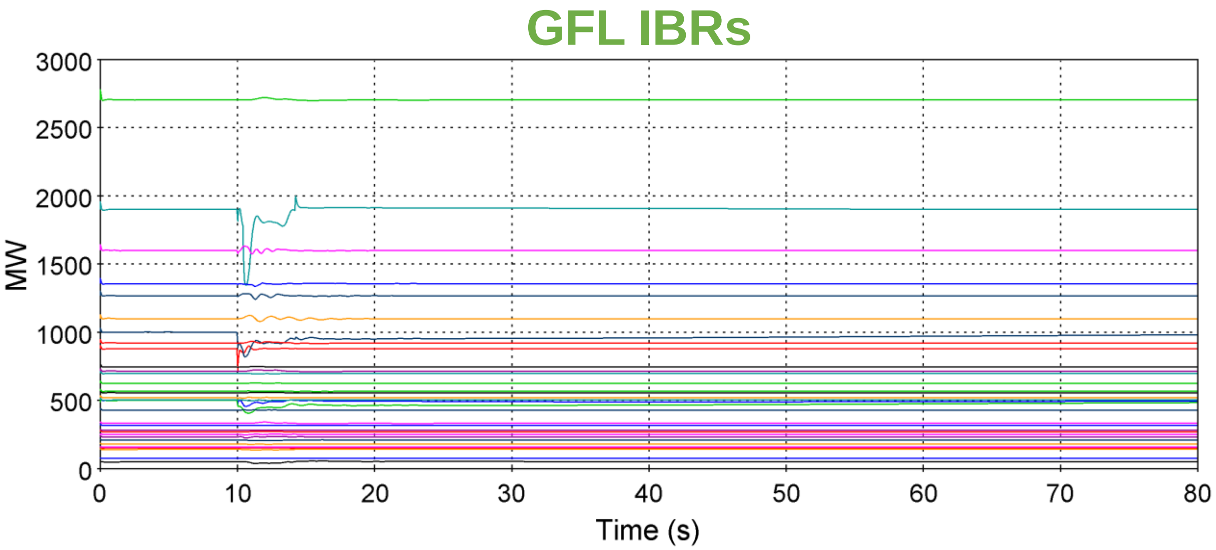
- ○ 5 SGs (14.9 GVA) are replaced with 5 BESS GFM inverters
- ✗ 7 power plants (17.7 GVA) are disconnected at 10s



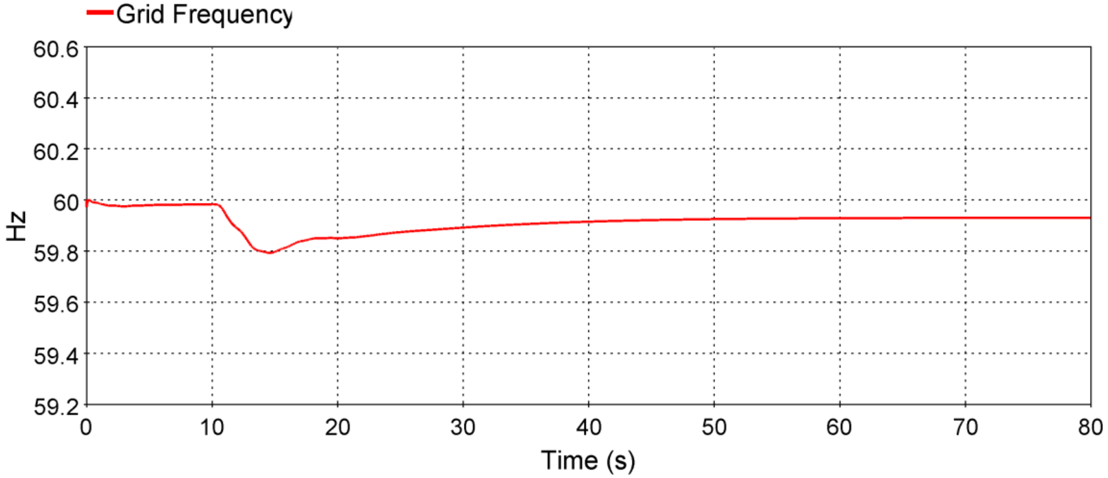
Integration of GFM IBRs in Large Grids

WECC 240 bus system





Initialization and stability
From load-flow to time-domain



Conclusion

- Efficient and accurate models can be developed in EMT-type simulation tool.
- The test systems demonstrated the performance of models.
- The results for the Chilian grid and WECC grid proved GFM IBRs can positively impact the dynamic behavior and stability of grids composed mostly of VRE resources.
  - System parameters and conditions, such as the penetration of GFL IBRs and their associated control strategies, the presence of SC, as well as the availability of dynamic compensation devices, play a pivotal role in the minimum amount of GFM required in large grids.
- While the performance of GFM IBRs shows promissory, extensive research remains to be conducted to test additional capabilities and attributes for this technology in large grids, such as short-term current contribution, protection coordination, and black start capabilities
- Benchmark needs: proposed in this presentation

Thank you!