This material is based upon work supported by the PNNL's Laboratory Directed Research and Development (LDRD) program, and U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Award Number 38637.

Model Benchmarking of a Droop-Controlled, Grid-Forming Inverter Model (REGFM_A1)

Wei Du

Staff Research Engineer

Pacific Northwest National Laboratory

WECC Model Validation Subcommittee Annual Meeting

May 25, 2023

OUTLINE

- **Timeline of REGFM_A1 Model**
- **Review the Basic Concept of Grid-Forming Droop Control**
- **Comparison with Field Test Results**
  - Comparison with CERTS Microgrid field test results
  - Comparison with OEM (SMA) field test results
- **REGFM_A1 Model Benchmarking Results**
  - Single-GFM Infinite-Bus system
  - Two-GFM islanded system

Timeline for the REGFM_A1 Model

Model spec approved (GFMDRP_A)
2021.12

2021.12
NREC sent the model spec to GFM OEMs

GFM vendor SMA provided detailed suggestions
2022.1

2022.5
Updated model spec to include Q_{max}/Q_{min} control block

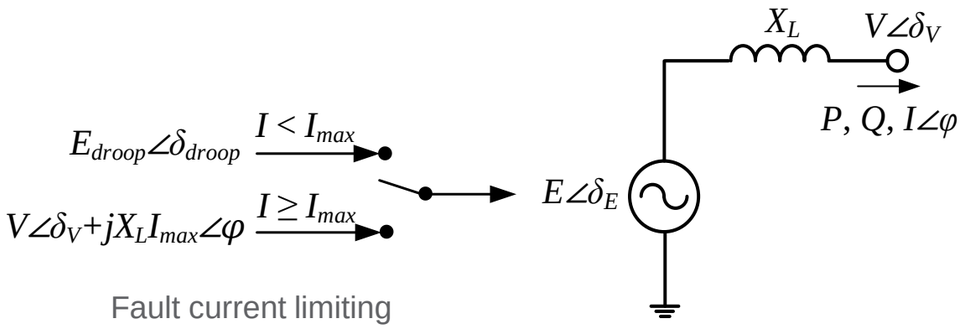
Updated model spec to include Vflag
2022.9

2023.2
Model renamed to **REGFM_A1**. Software vendors started to implement

Model benchmarking completed
2023.5

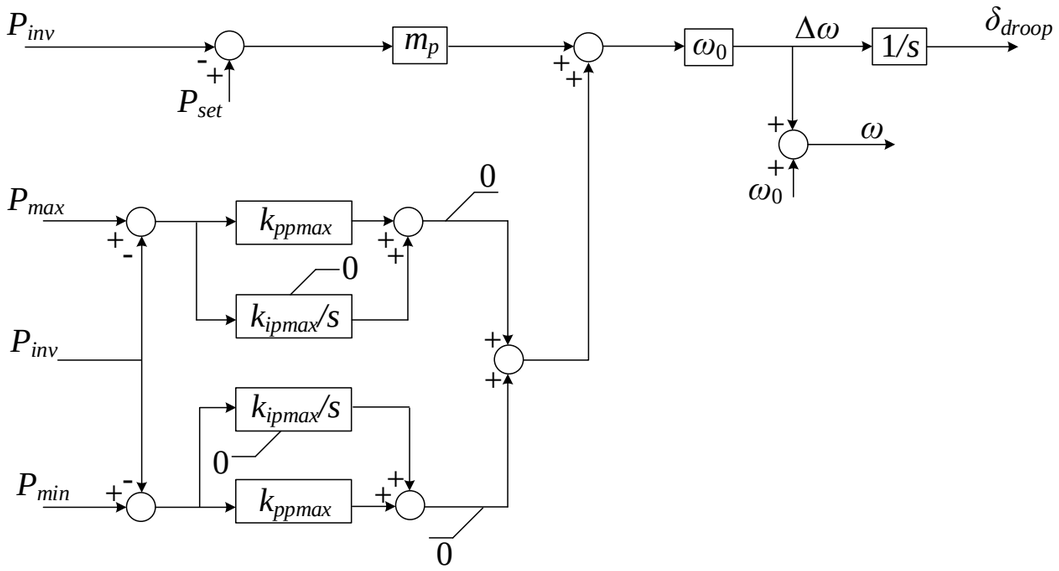
Model Specification of a Droop-Controlled, Grid-Forming Inverter (REGFM_A1)

- The model includes the voltage source representation, *P-f* and *Q-V* droop control, *P/Q* limiting, and fault current limiting
- Most of the control blocks came from the CERTS Microgrid Project[1,2]
- SMA suggested to add the Q_{max}/Q_{min} control block, and the Vflag=0 option

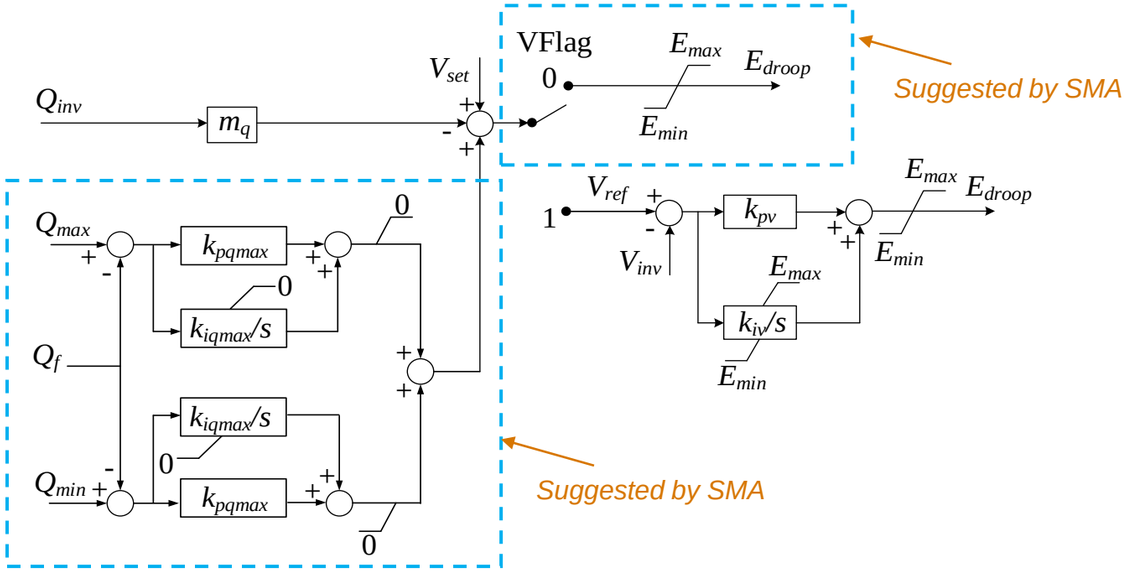


Fault current limiting

Voltage source behind impedance



P-f droop and P Limiting

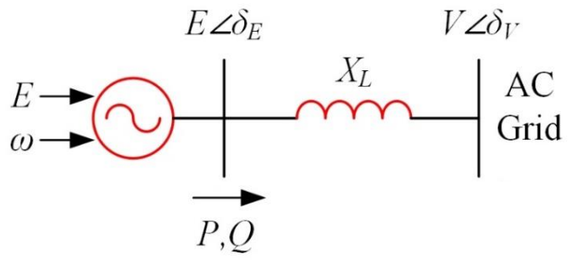


Q-V droop and Q Limiting

[1] Lasseter, Robert H., et al. "CERTS microgrid laboratory test bed." *IEEE Transactions on Power Delivery* 26.1 (2010): 325-332.
[2] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

Basic Concept of a Droop-Controlled, Grid-Forming Inverter

- A grid-forming inverter behaves as a controllable voltage source behind impedance
- Two ideal voltage sources cannot be paralleled. The coupling reactance X_L is very important for controller design
  - If X_L is well designed (e.g., 5%-20%): $P \propto \delta$, $Q \propto E$

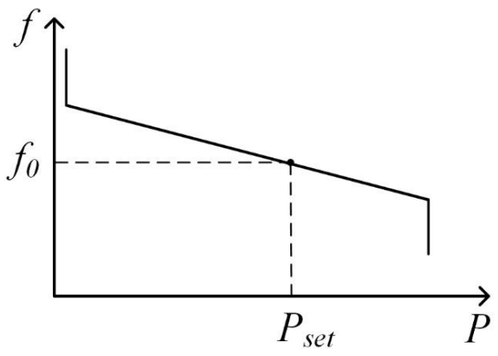


$$\delta_p = \delta_E - \delta_V$$

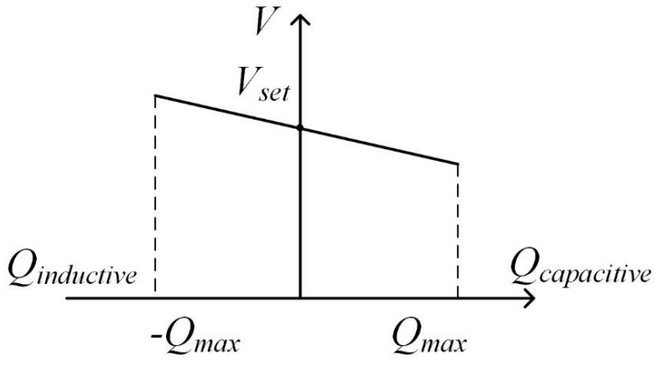
$$P = \frac{EV}{X_L}\sin\delta_p \approx \frac{EV}{X_L}\delta_p \qquad \delta_p = \int(\omega - \omega_0)dt$$

$$Q = \frac{E^2 - EV\cos\delta_p}{X_L} \approx \frac{E(E-V)}{X_L}$$

- Droop Control: Parallel multiple voltage sources in a system
  - *P* vs. *f* droop ensures the phase angles of multiple voltage sources are synchronized
  - *Q* vs. *V* droop avoids large circulating vars between voltage sources



P vs. f droop



Q vs. V droop

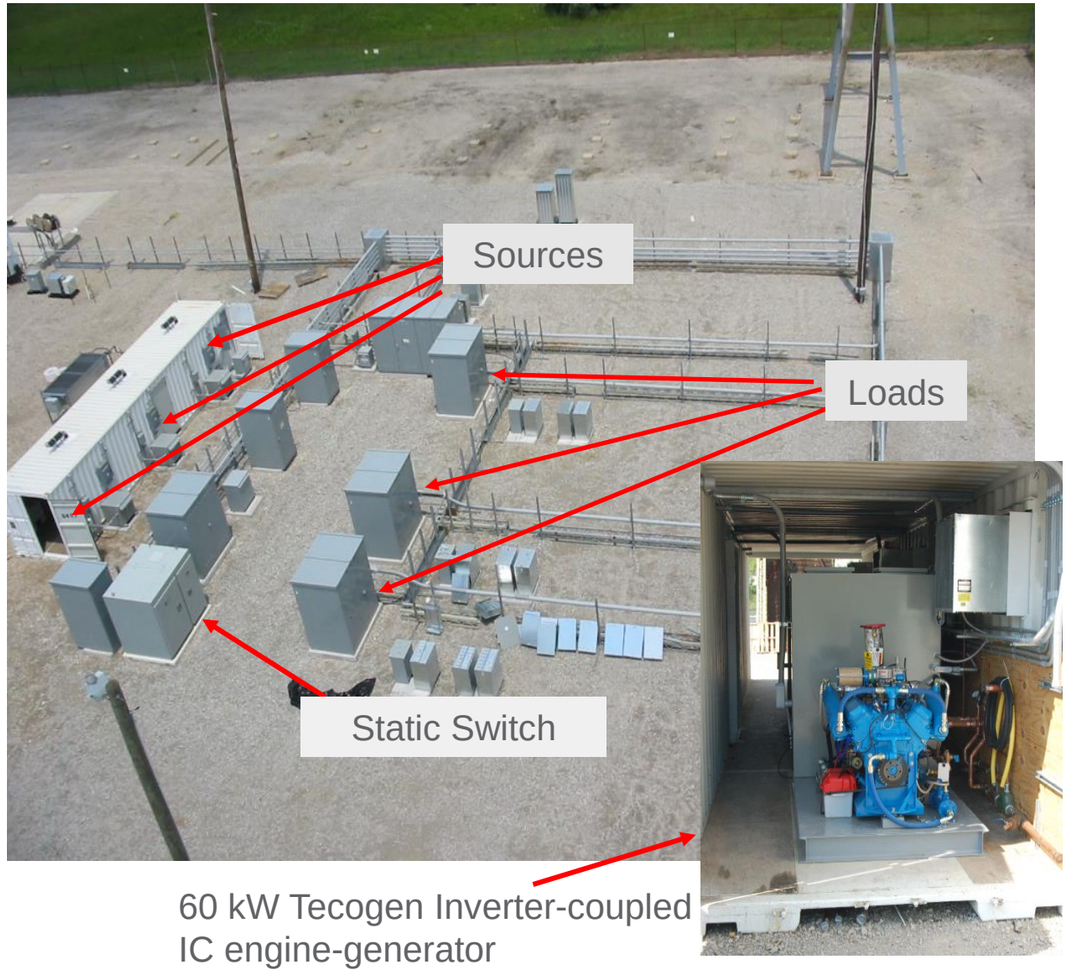
$\delta_P\uparrow \rightarrow P\uparrow \rightarrow \omega\downarrow \rightarrow \delta_P\downarrow$ (Negative feedback control)

Comparison with the CERTS Microgrid Field Test Results

CERTS/AEP Microgrid Testbed

- AEP/CERTS testbed: one of the earliest inverter-based microgrids in the world, funded by DOE
- *Principle Investigator: Prof. Bob Lasseter from University of Wisconsin-Madison*
- The CERTS Microgrid Program has been running for almost 20 years

A 100% Grid-Forming-Inverter-based testbed



60 kW Tecogen Inverter-coupled IC engine-generator

Wisconsin Energy Institute
UNIVERSITY OF WISCONSIN–MADISON

CERTS CONSORTIUM for ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

http://certs.lbl.gov/certs-der-pubs.html

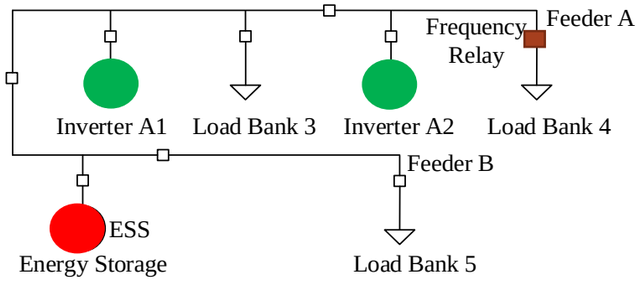
CERTS/AEP Testbed

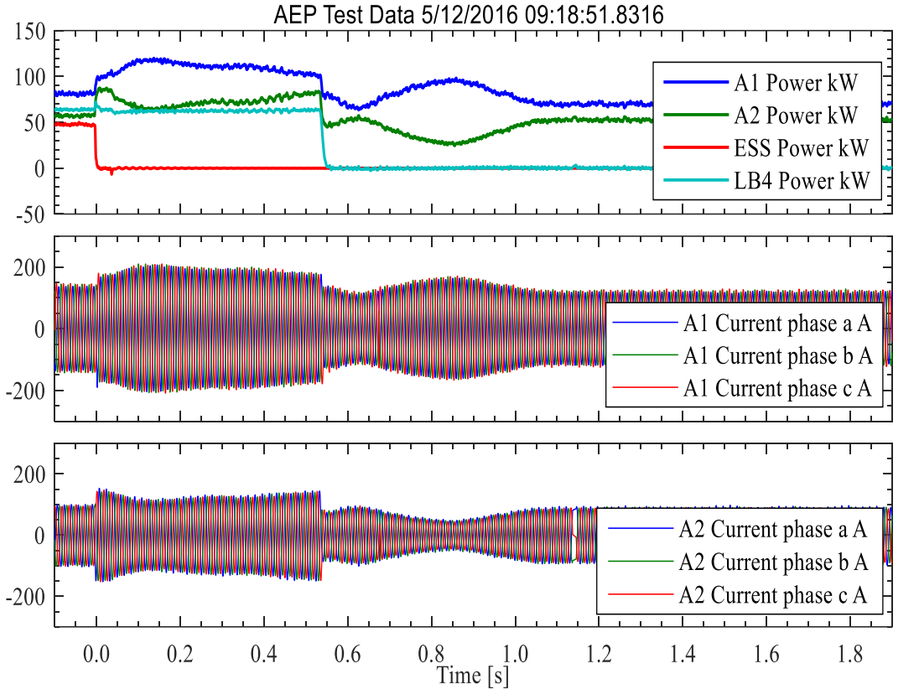
[1] Lasseter, R.H., Eto, J.H., Schenkman, B., Stevens, J., Vollkommer, H., Klapp, D., Linton, E., Hurtado, H. and Roy, J., 2010. CERTS microgrid laboratory test bed. IEEE Transactions on Power Delivery, 26(1)

Under-Frequency Load Shedding Testing (All-GFM-based System)

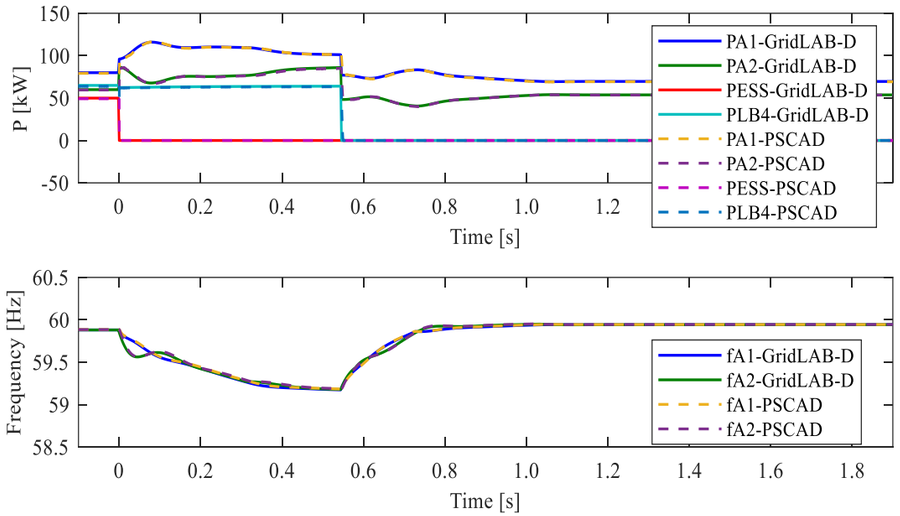
- After loss of the 58 kW ESS, the total 220 kW load exceeds the 193 kW maximum generation of A1 and B1
- Load Bank 4 is tripped in 0.5 s by the frequency relay
- The overload mitigation control helps to trigger under-frequency load shedding when the entire system is overloaded

CERTS/AEP Test Site

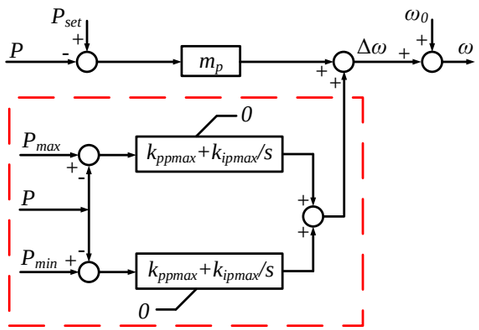




Field test results from CERTS/AEP testbed



EMT and phasor simulation results



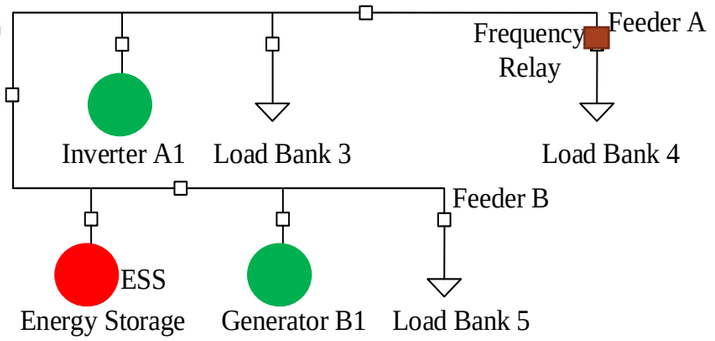
----EMT

——Phasor

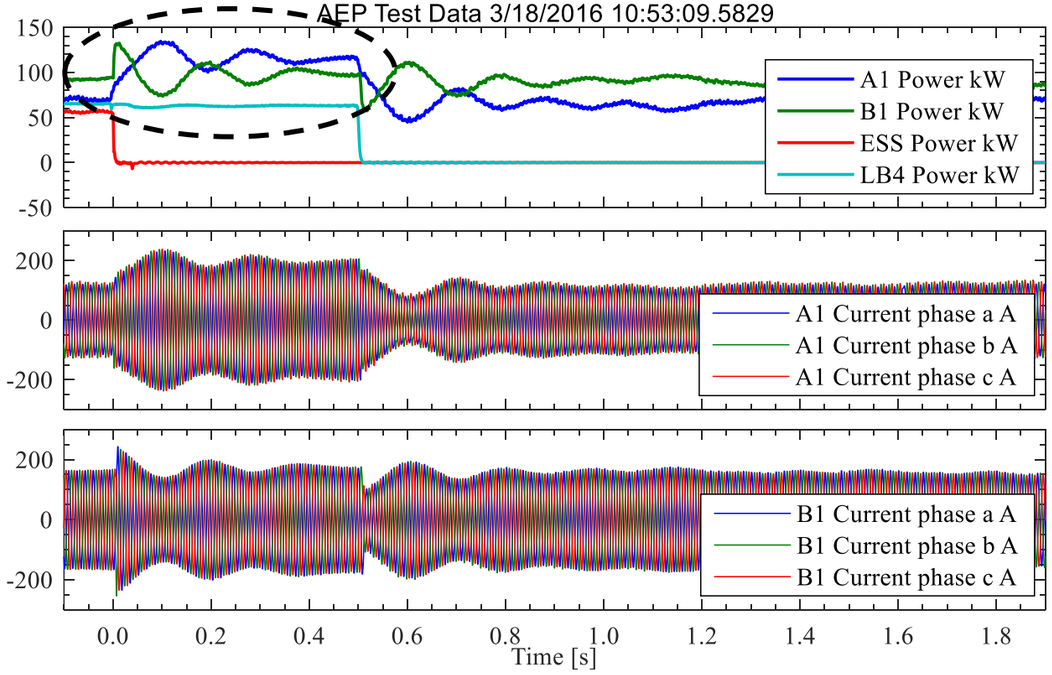
[1] Wei Du, Francis K. Tuffner, Kevin P. Schneider, Robert Lasseter, et al., “Modeling of Grid-Forming and Grid-Following Inverters for Dynamic Simulation of Large-Scale Distribution Systems”. IEEE Transactions on Power Delivery, 2020.

Under-Frequency Load Shedding (GFM & Machine Mixed System)

- The loss of ESS results in the overload of the entire microgrid
- Droop curve becomes vertical because of P_{max} control, triggering under-frequency load shedding
- GridLAB-D simulation, PSCAD simulation, and field test results match well with each other



CERTS/AEP Testbed



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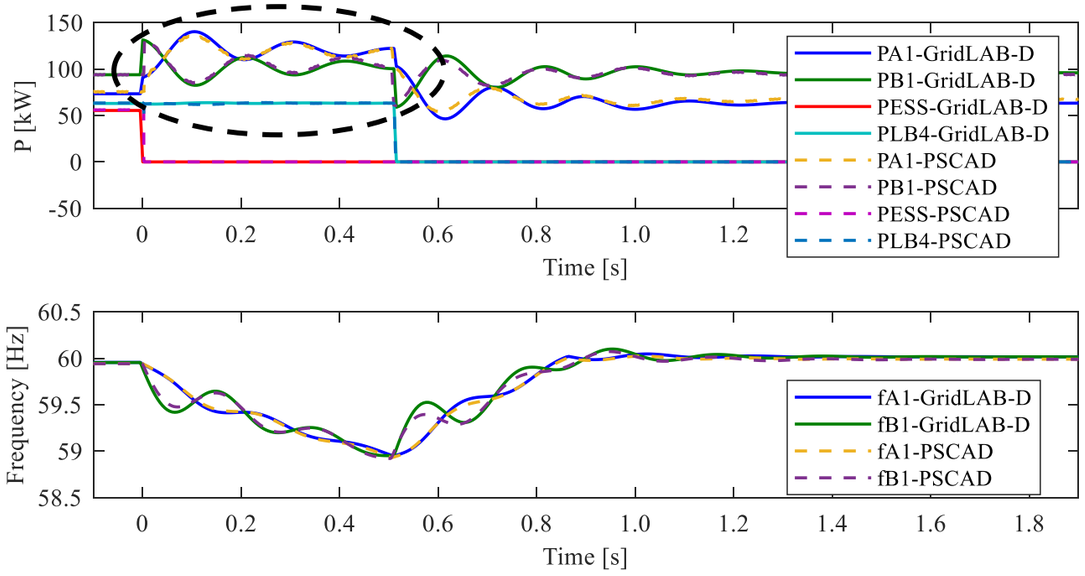
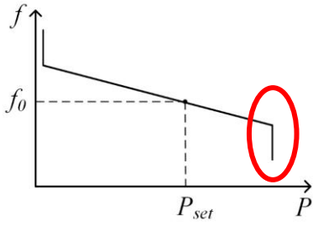


EMT and phasor simulation results

---- *EMT*

—— *Phasor*



[1] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

Comparison with the SMA GFM Field Test Results

Comparison between the SMA Field Test Results and the PSLF Simulation Results

- PSLF simulation results match the SMA hardware testing results
  - Case study was performed on the micro-WECC system for frequency regulation
  - IBR penetration level: 73%, 10% headroom
- Both the simulation and hardware testing show that droop-controlled GFM can significantly improve the system primary frequency response

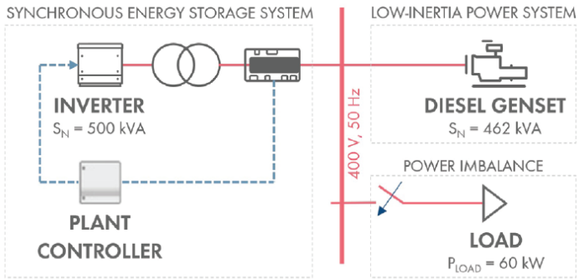
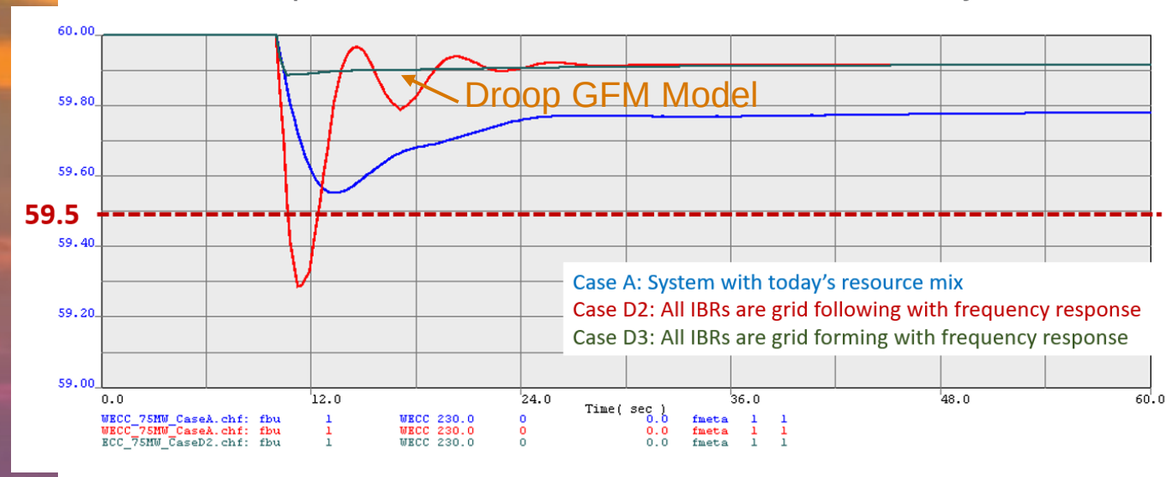
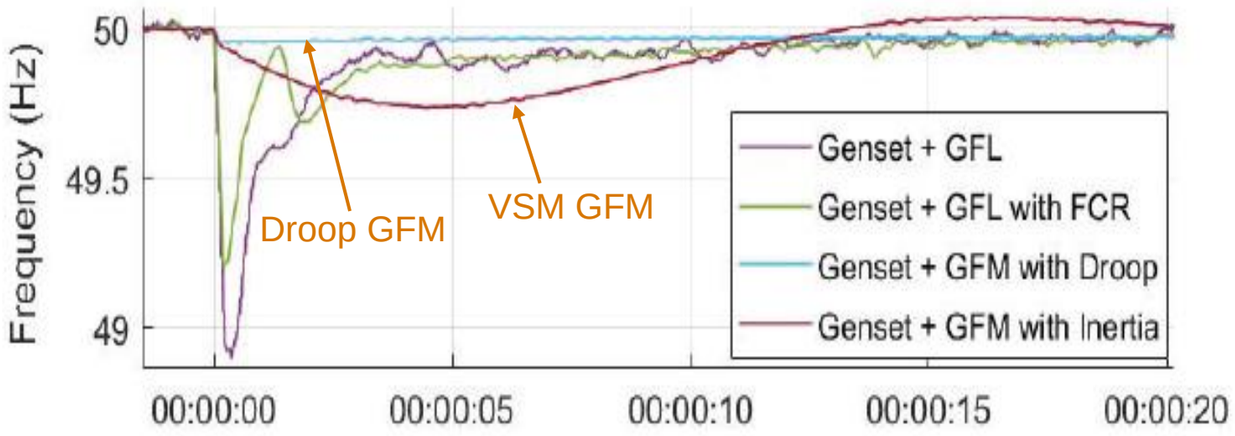


Fig. 7: Laboratory setup for demonstration of SESS control capabilities

73% penetration of GFMs in the micro-WECC system



SMA Hardware Test Results on a Small System[1]



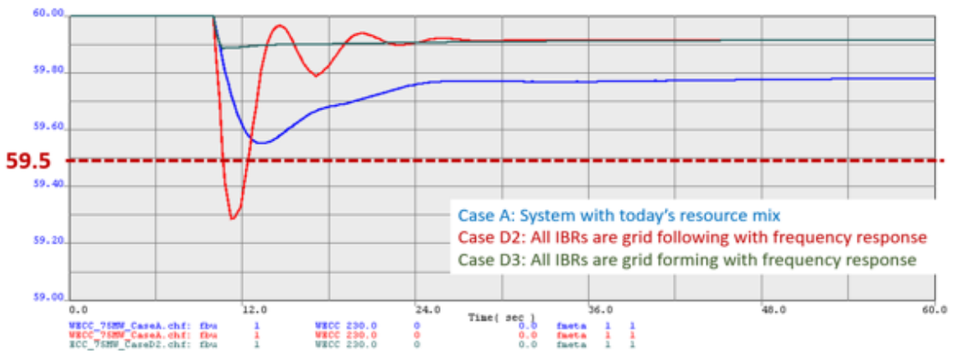
(Simulation credit: Dmitry, BPA)

[1] A. Knobloch *et al.*, "Synchronous energy storage system with inertia capabilities for angle, voltage and frequency stabilization in power grids," *11th Solar & Storage Power System Integration Workshop (SIW 2021)*, 2021, pp. 71-78

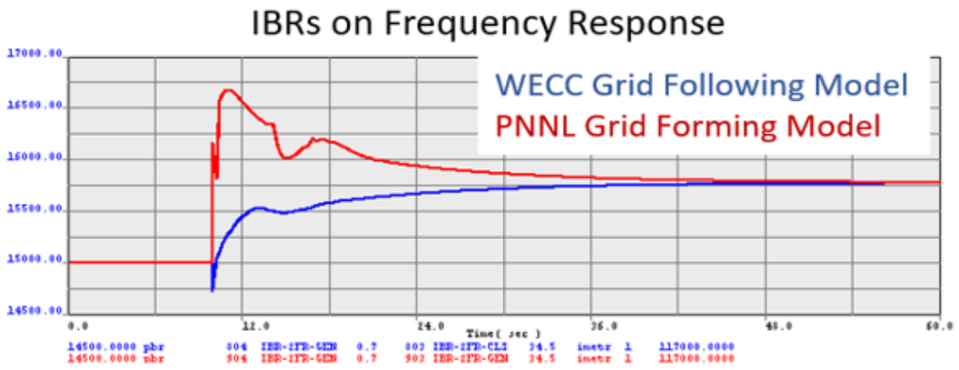
Comparison between the SMA Field Test Results and the PSLF Simulation Results

- The GFM unit behaves as a controllable voltage source behind impedance, so it increases the output power almost instantaneously after the disturbance
- The synchronous generator's output power is clamped so its speed does not change too much

PSLF Simulation Results of Micro-WECC System (Credit: Dmitry, BPA)



IBR Fast frequency response can be effective in maintaining system frequency (inverter-level, droop control, headroom)



SMA Hardware Test Results on a Microgrid[1]

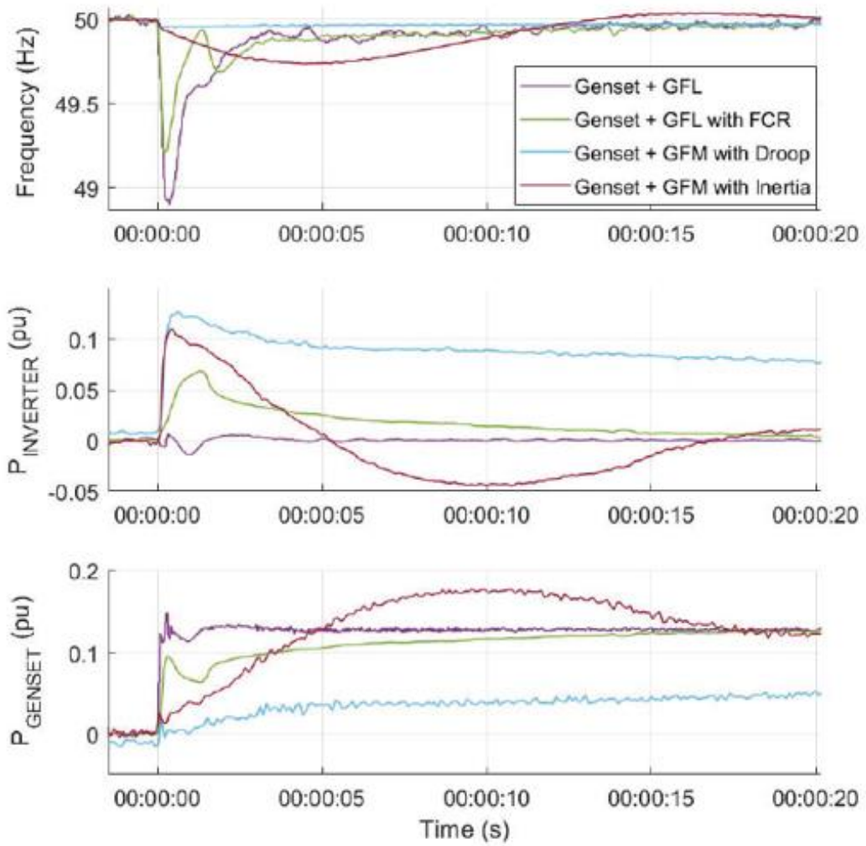


Fig. 8: Impact of different inverter system control modes on the frequency of a downscaled low-inertia power system at a power imbalance event

REGFM_A1 Model Benchmarking Results

Model Specification of a Droop-Controlled, Grid-Forming Inverter (REGFM_A1)

- The model includes the voltage source representation, *P-f* and *Q-V* droop control, *P/Q* limiting, and fault current limiting
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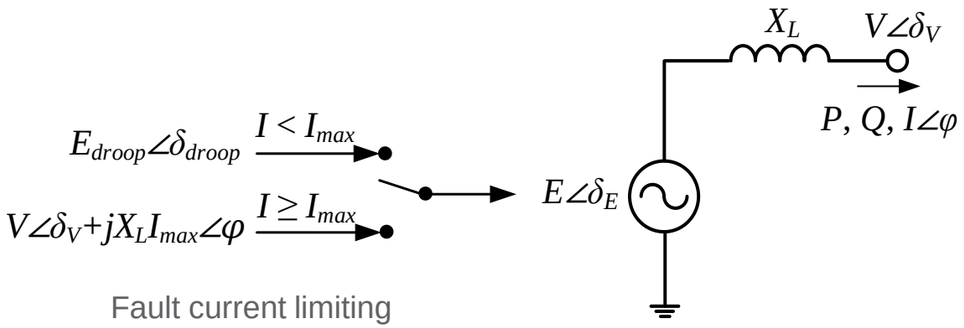
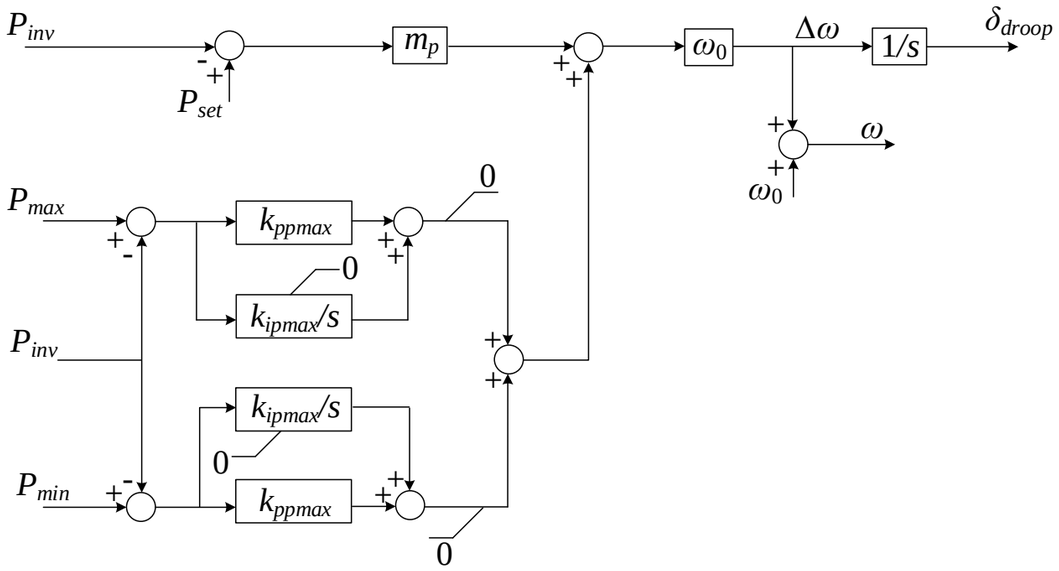
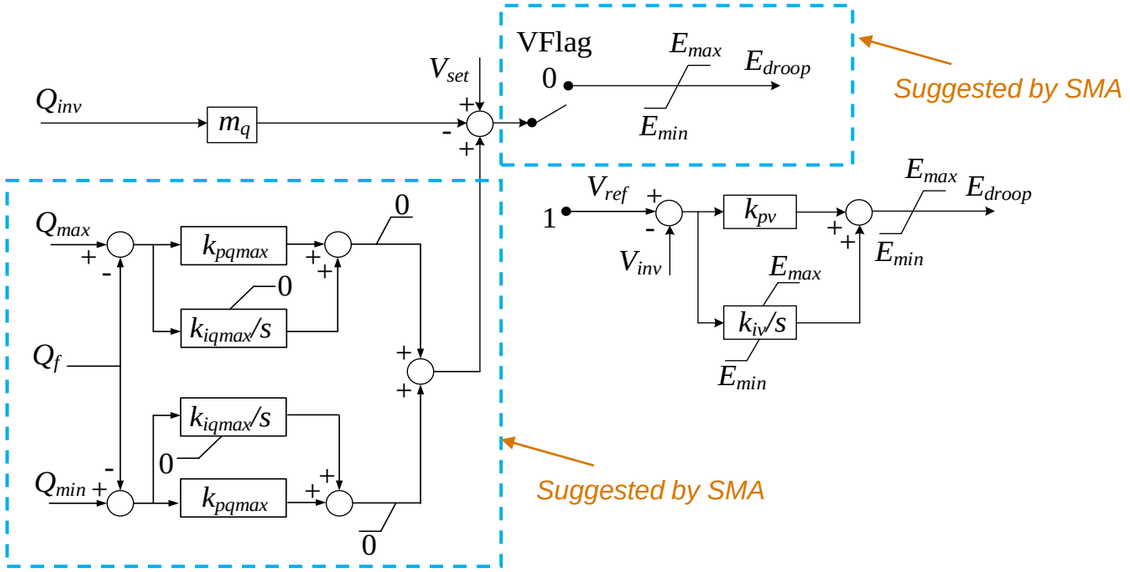


Fault current limiting

Voltage source behind impedance



P-f droop and P Limiting

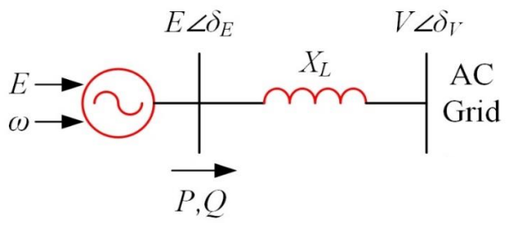


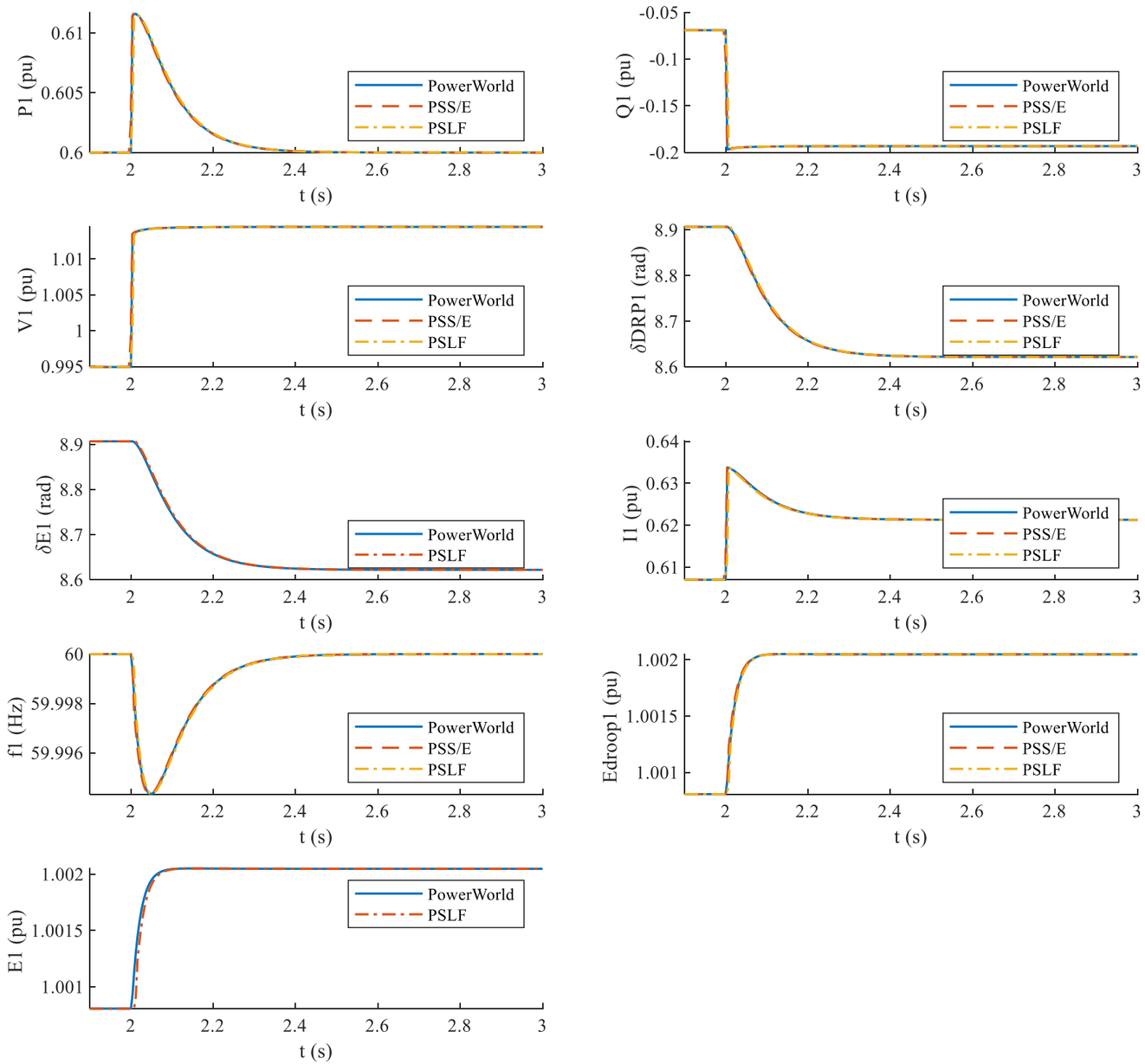
Q-V droop and Q Limiting

[1] Lasseter, Robert H., et al. "CERTS microgrid laboratory test bed." *IEEE Transactions on Power Delivery* 26.1 (2010): 325-332.
[2] Du, Wei, Robert H. Lasseter, and Amrit S. Khalsa. "Survivability of autonomous microgrid during overload events." *IEEE Transactions on Smart Grid* 10, no. 4 (2018): 3515-3524.

Single-GFM-Infinite-Bus System

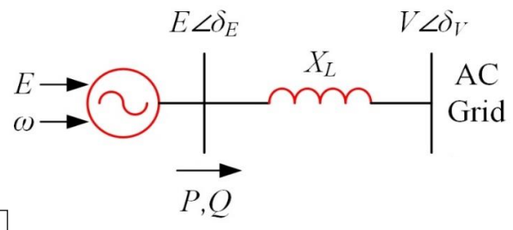
- 0.05 pu Step Increase in Voltage
  - VFlag=0

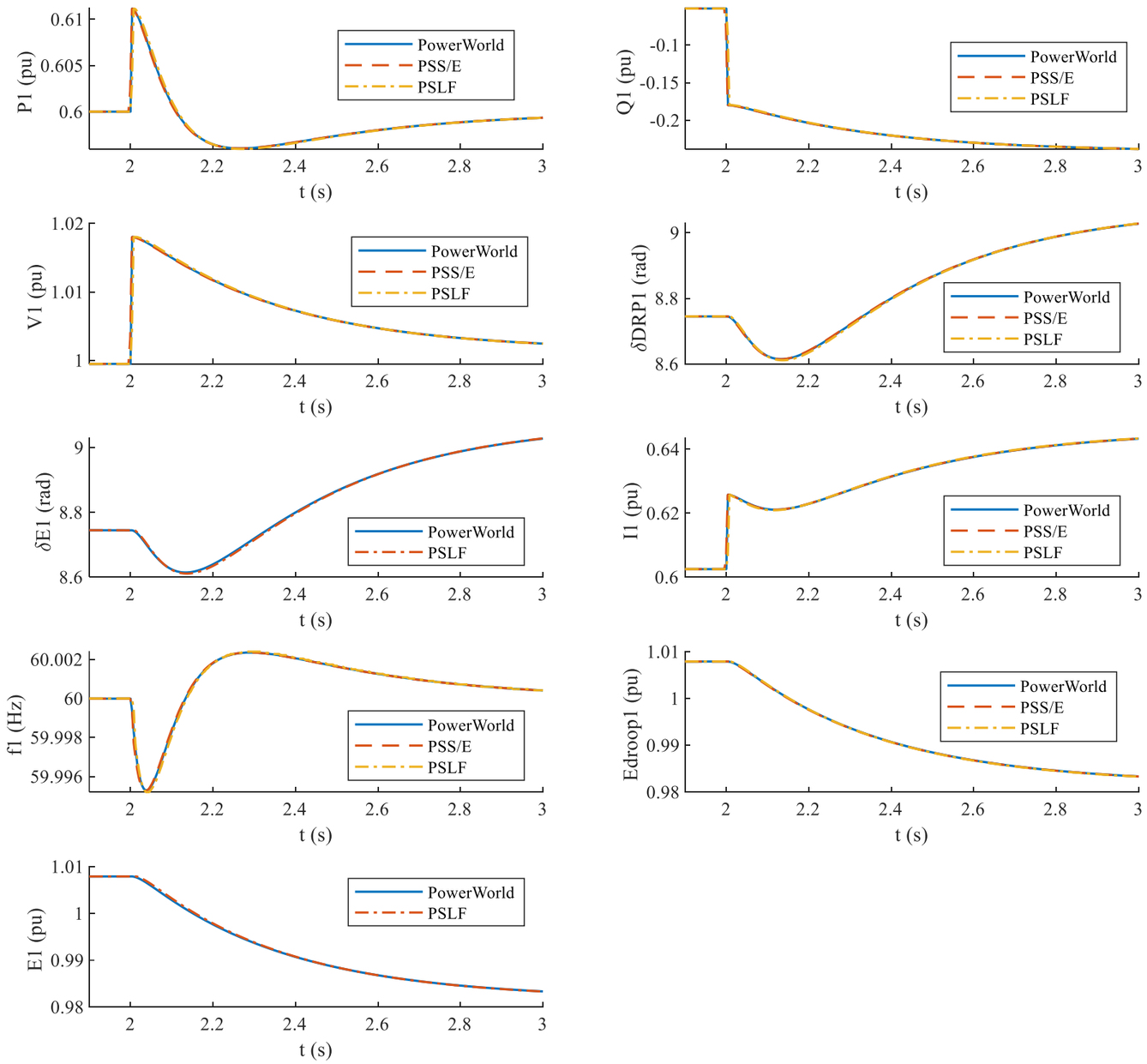




Single-GFM-Infinite-Bus System

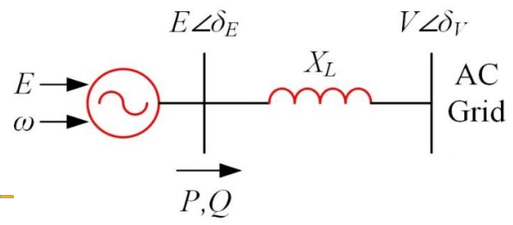
- 0.05 pu Step Increase in Voltage
  - VFlag=1

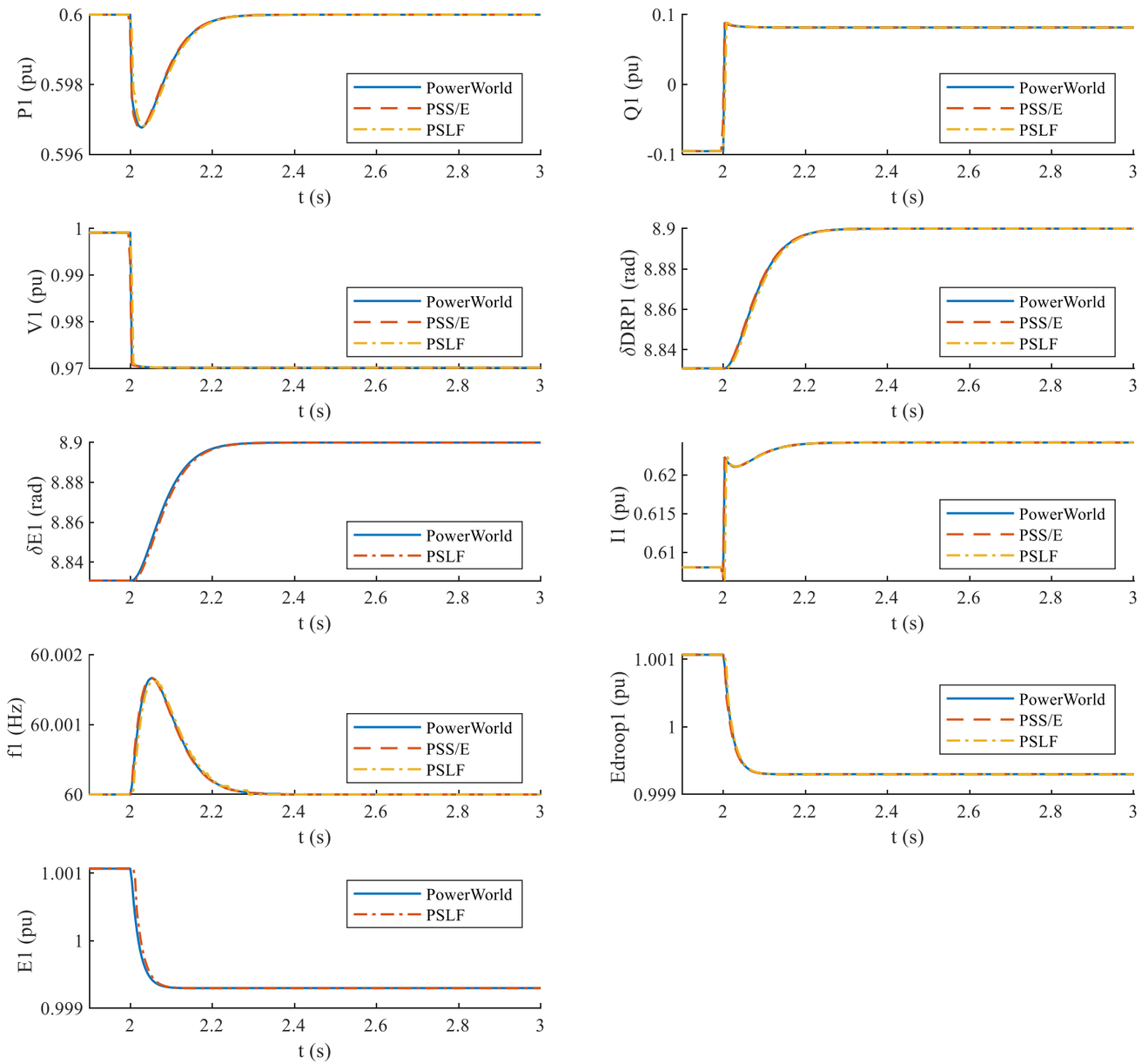




Single-GFM-Infinite-Bus System

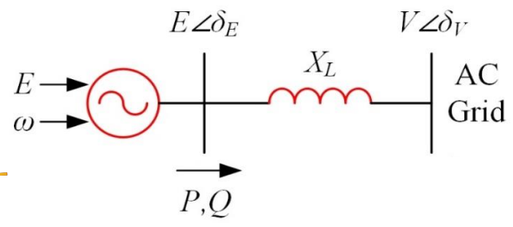
- 0.05 pu Step Decrease in Voltage
  - VFlag=0

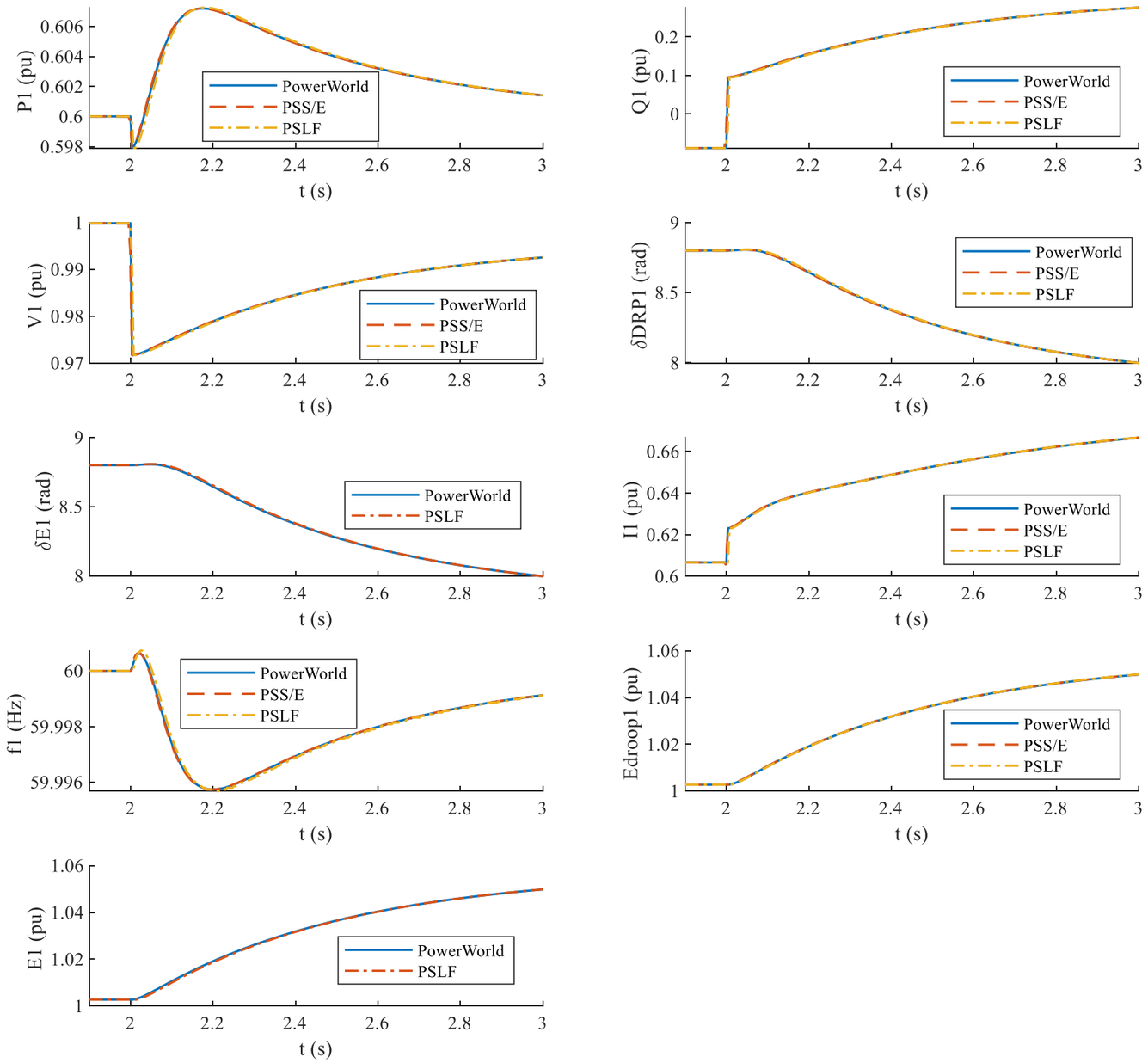




Single-GFM-Infinite-Bus System

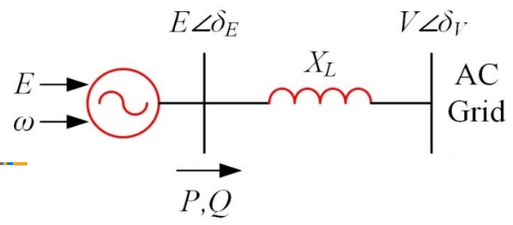
- 0.05 pu Step Decrease in Voltage
  - VFlag=1

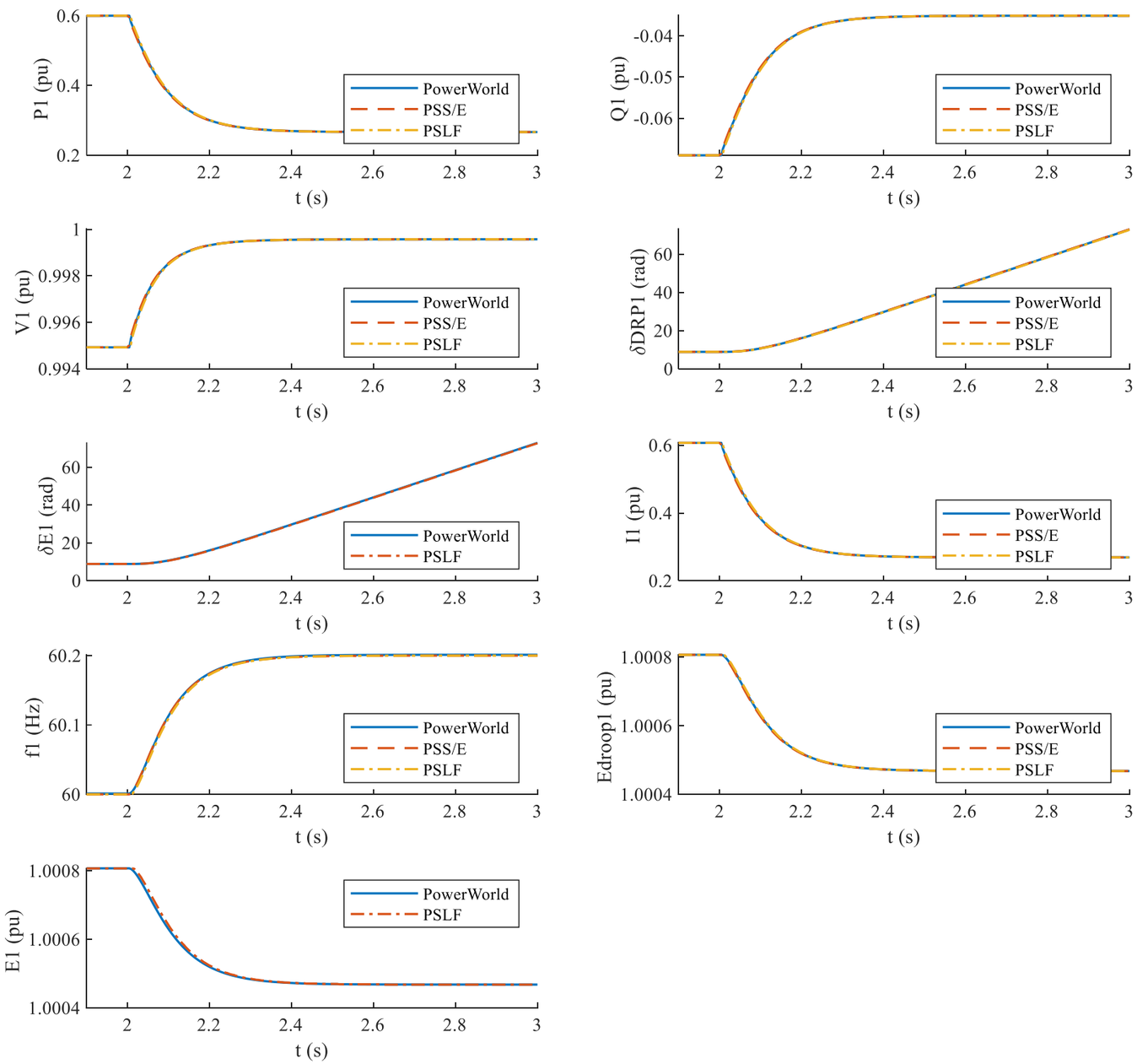




Single-GFM-Infinite-Bus System

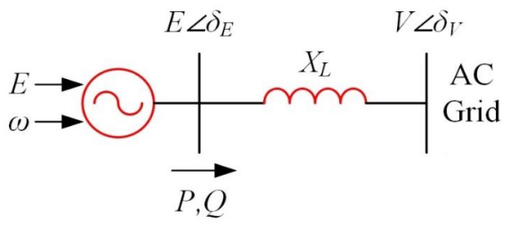
- Frequency step up from 60 Hz to 60.2 Hz
  - VFlag=0

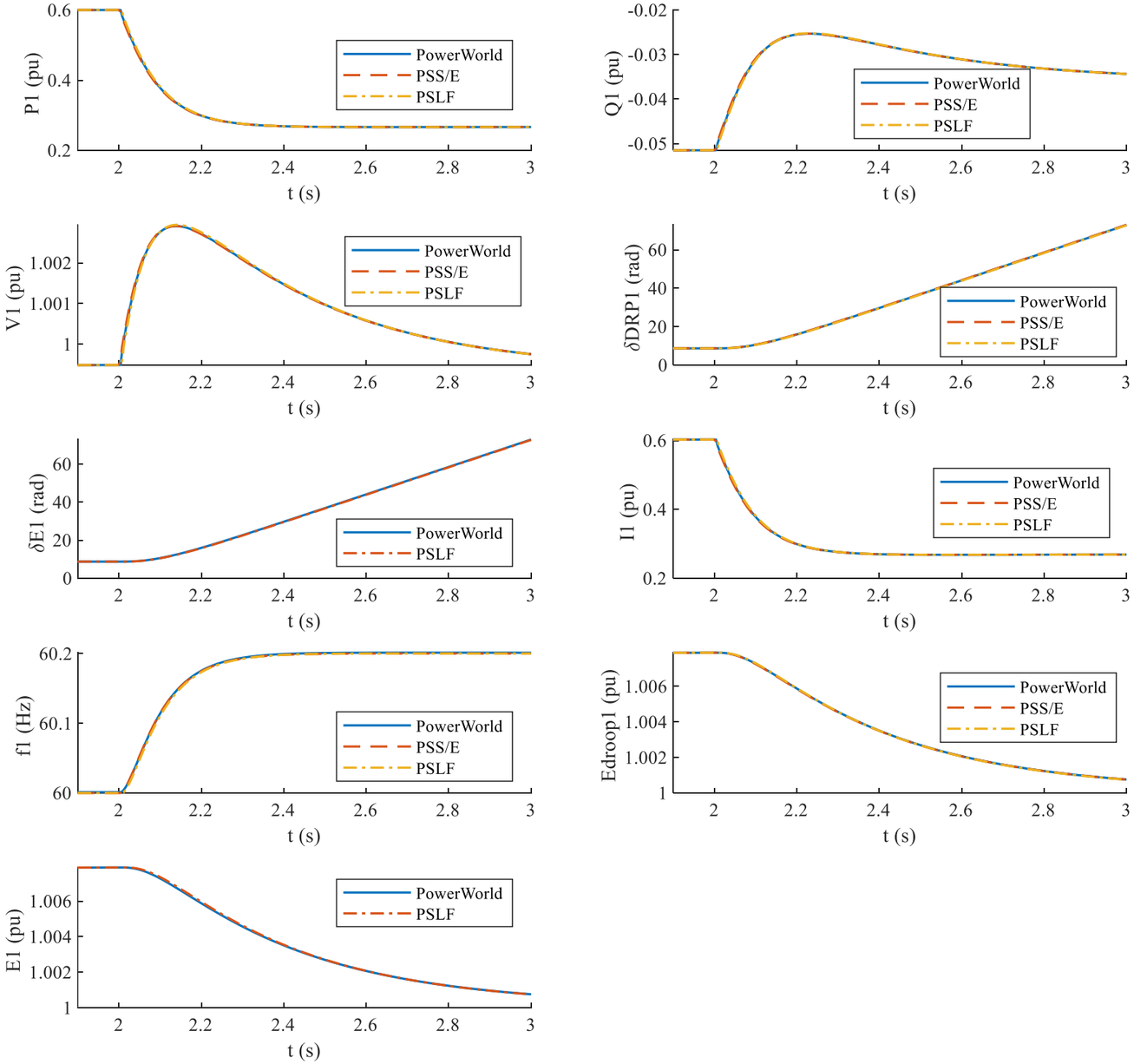




Single-GFM-Infinite-Bus System

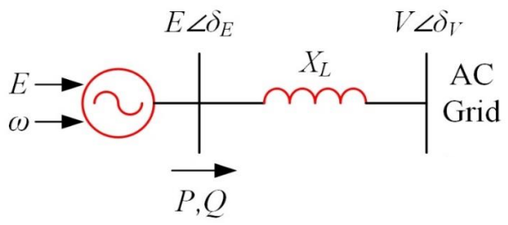
- Frequency step up from 60 Hz to 60.2 Hz
  - VFlag=1

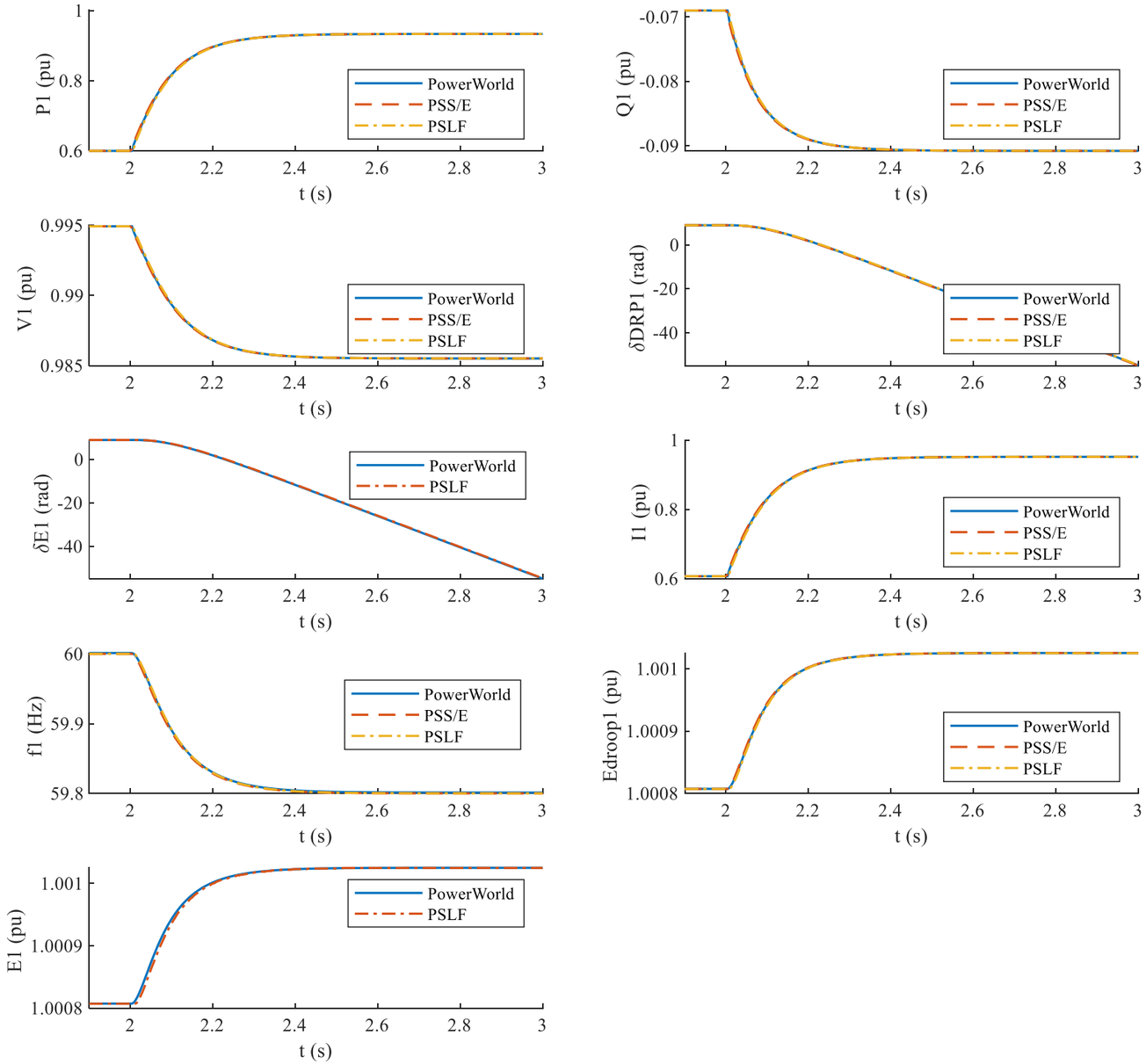




Single-GFM-Infinite-Bus System

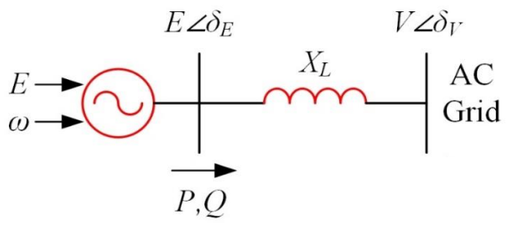
- Frequency step down from 60 Hz to 59.8 Hz
  - VFlag=0

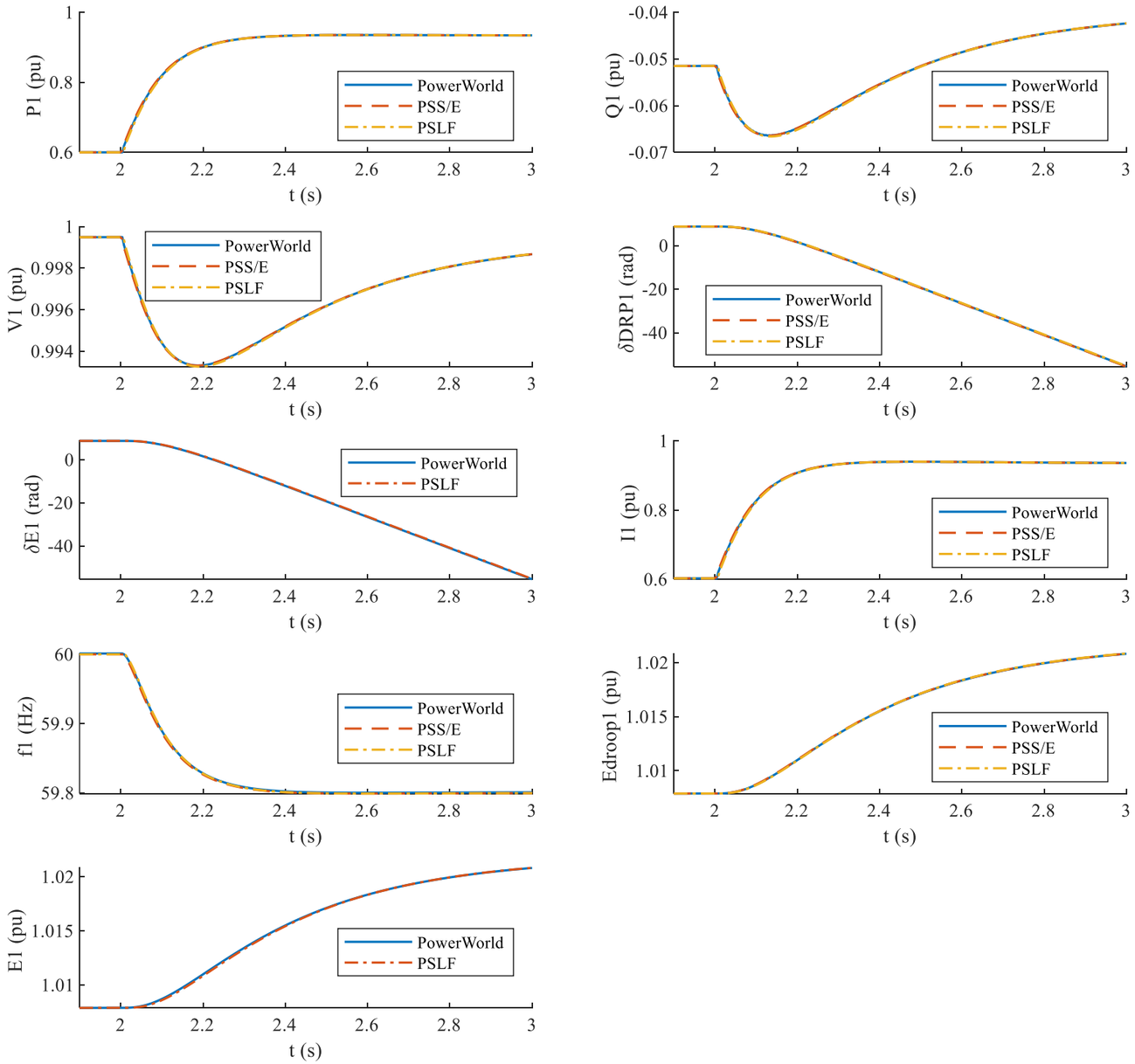




Single-GFM-Infinite-Bus System

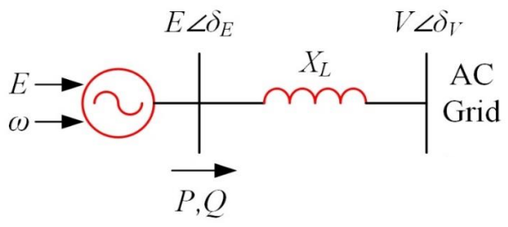
- Frequency step down from 60 Hz to 59.8 Hz
  - VFlag=1

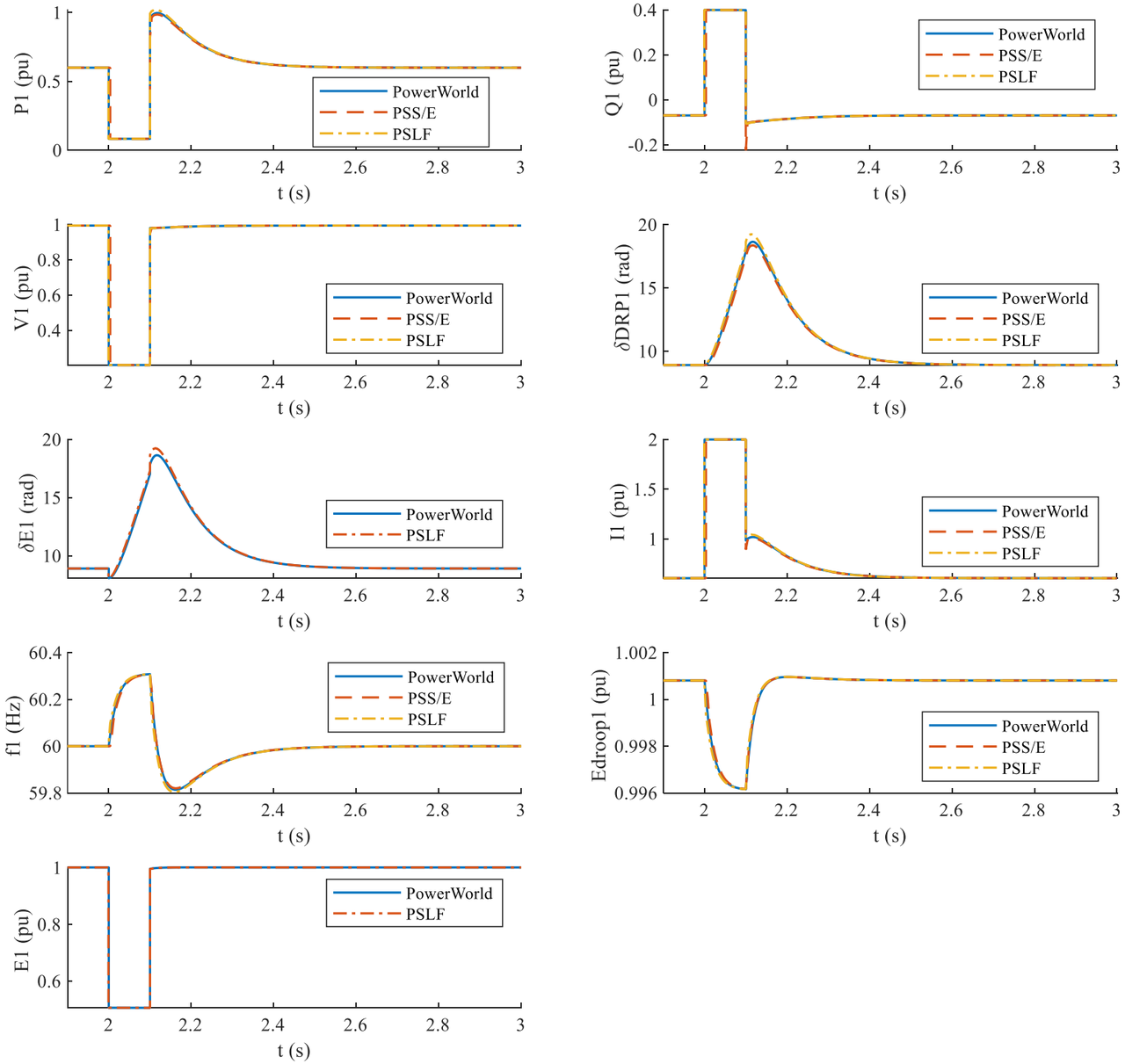




Single-GFM-Infinite-Bus System

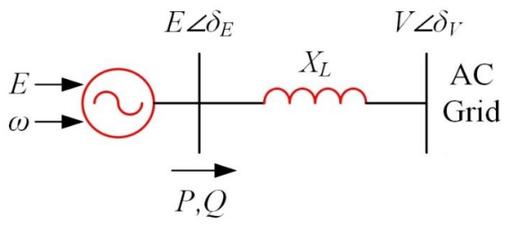
- 0.1 s Short-Circuit Fault
  - VFlag=0

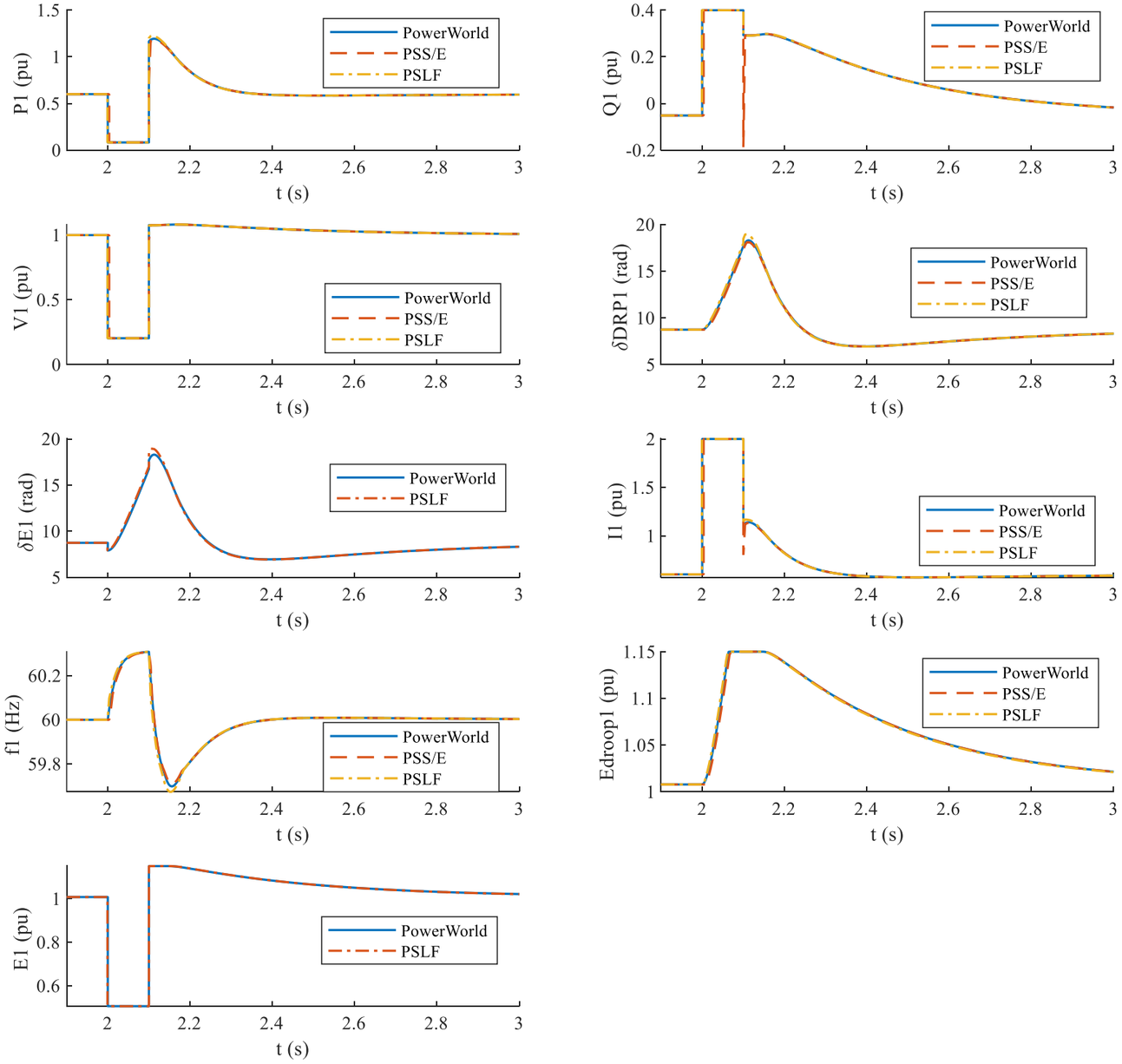




Single-GFM-Infinite-Bus System

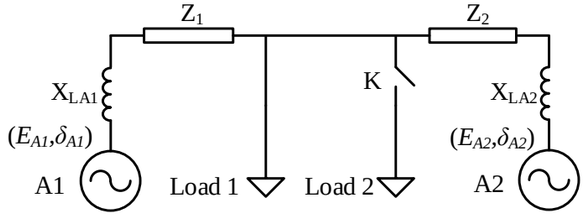
- 0.1 s Short-Circuit Fault
  - VFlag=1



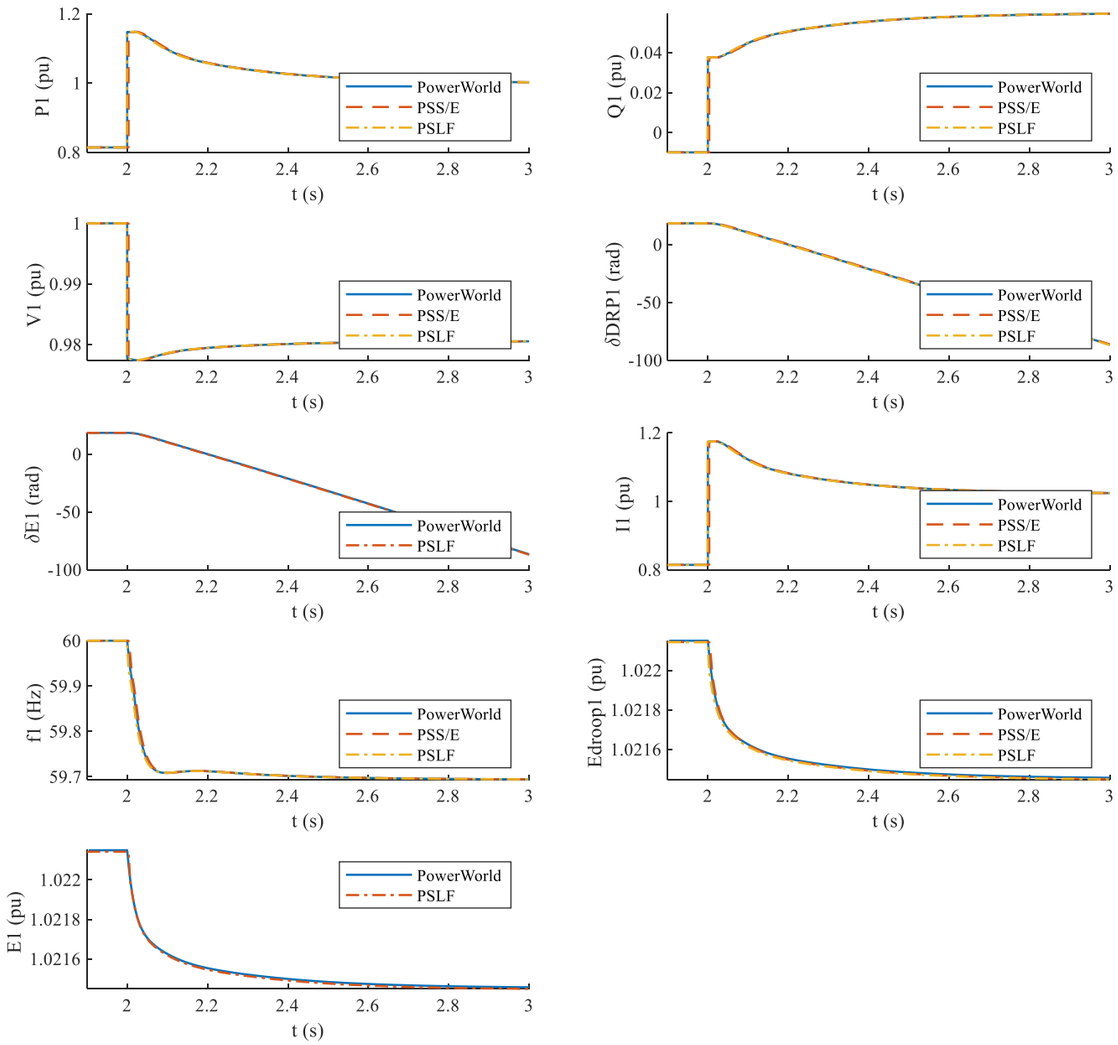


Two-GFM Islanded System

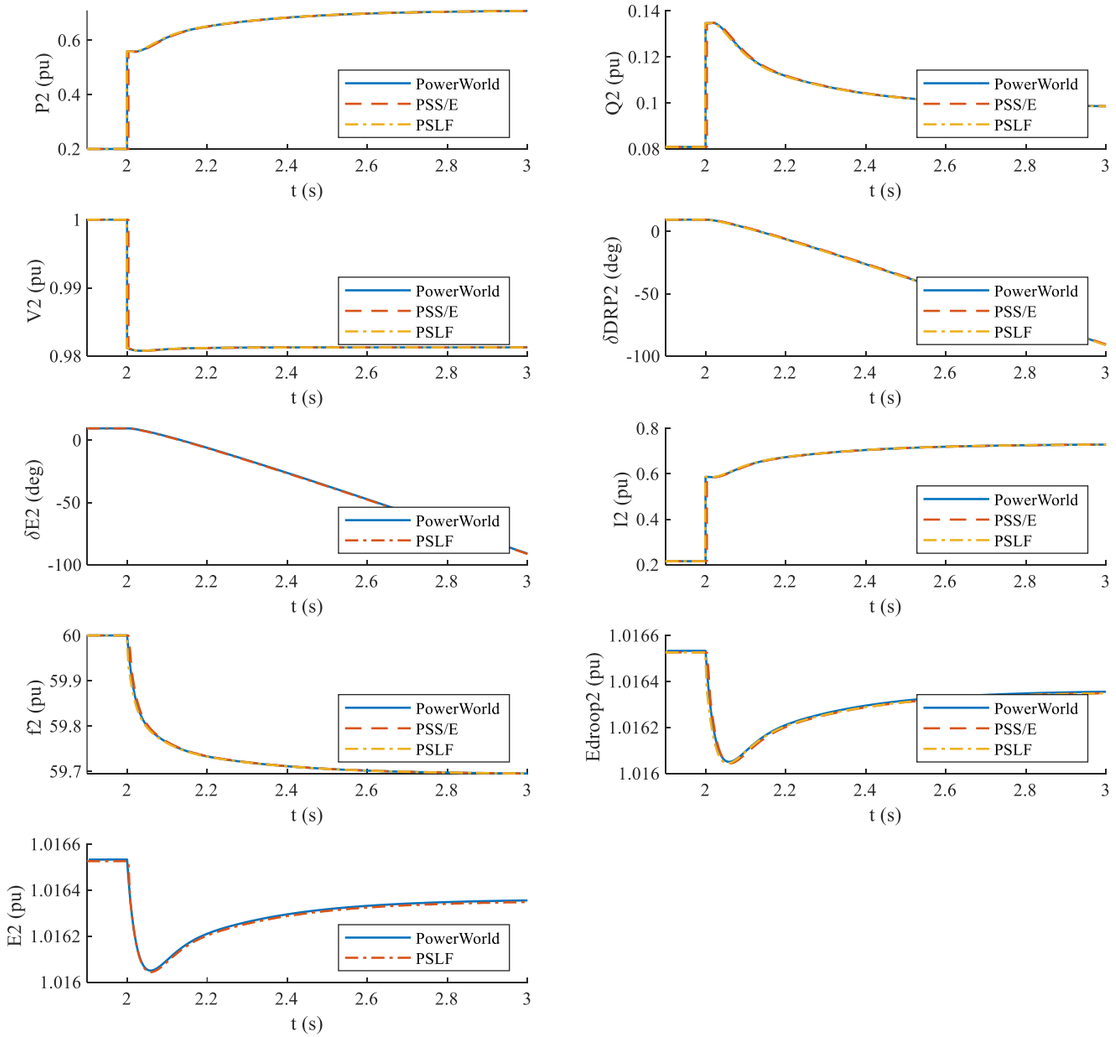
- Step Increase in Load
  - VFlag=0



A Two-GFM Islanded System



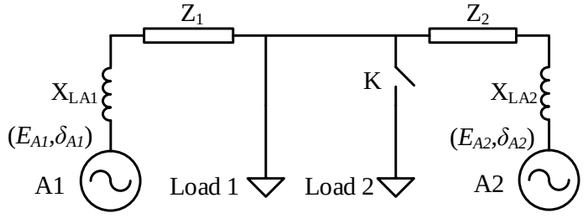
Response of GFM1



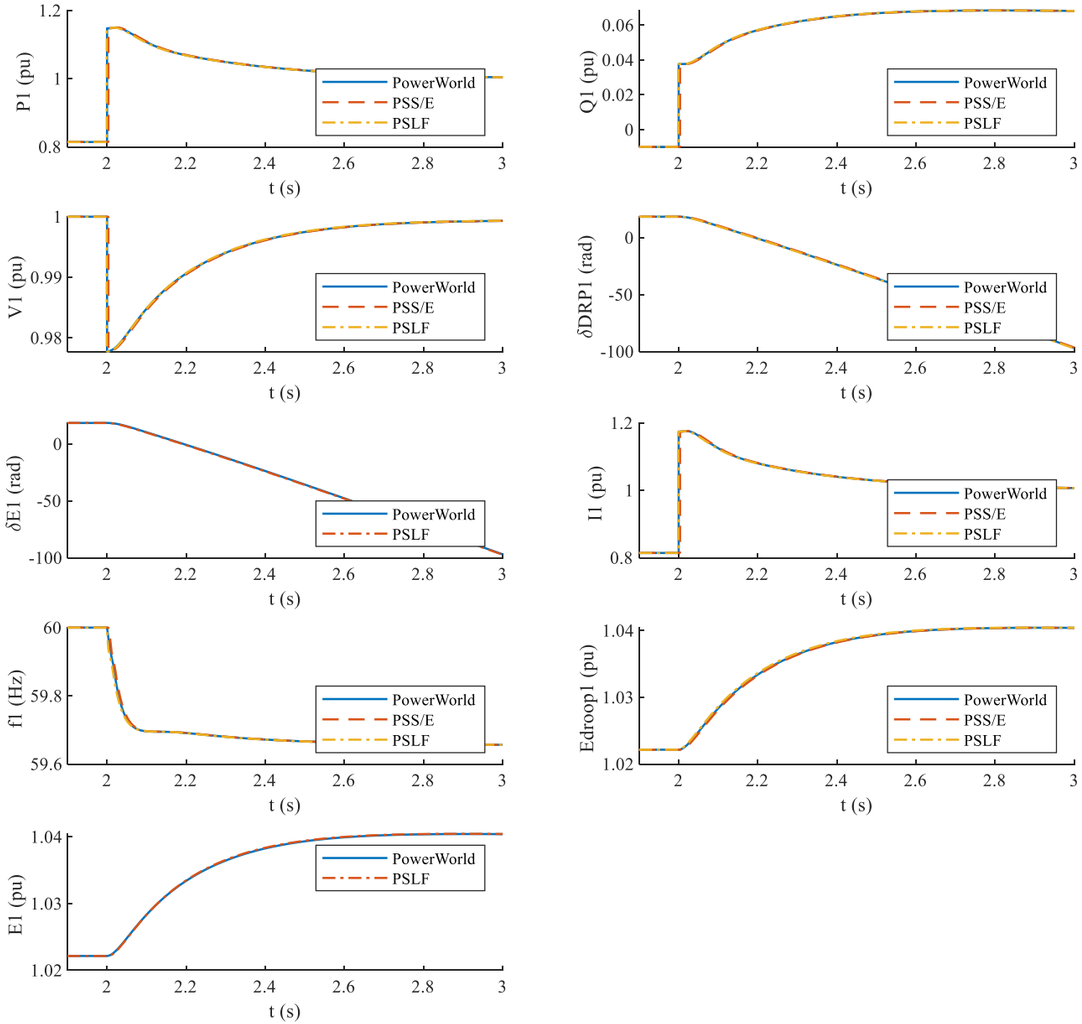
Response of GFM2

Two-GFM Islanded System

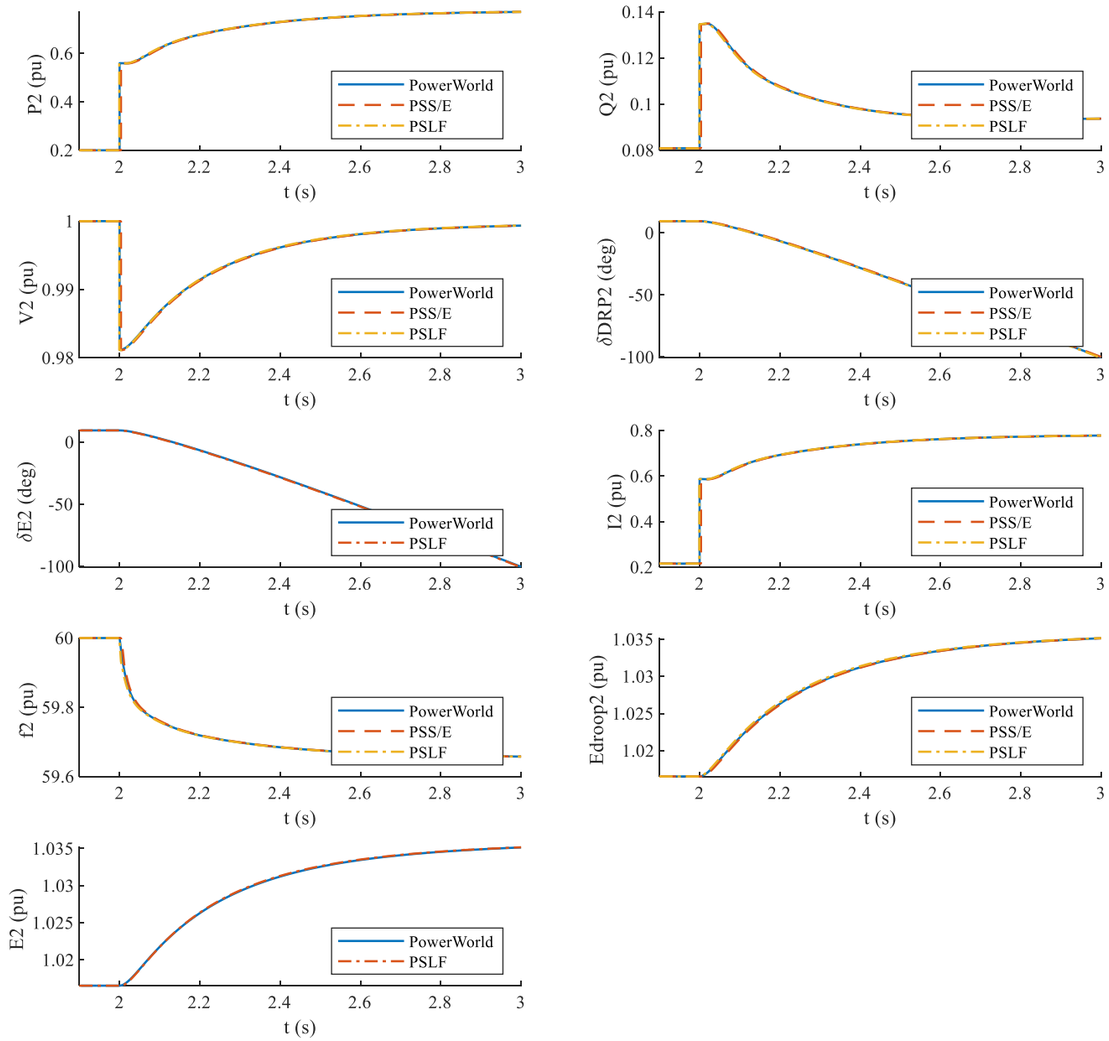
- Step Increase in Load
  - VFlag=1



A Two-GFM Islanded System



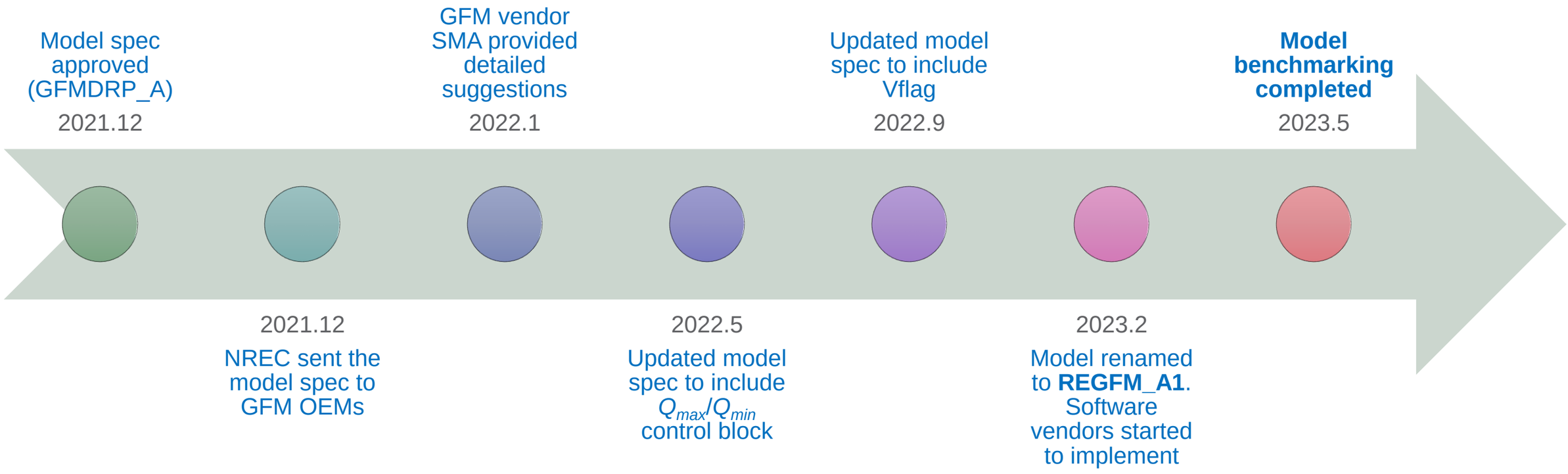
Response of GFM1



Response of GFM2

Conclusions

- *Model spec approved in December 2021*
- *Model spec received detailed suggestions from a GFM OEM*
- *Simulations results compare well with the field test results*
- *Model benchmarking completed and all models match very well*



I’d like to make a motion to finally approve this REGFM_A1 model

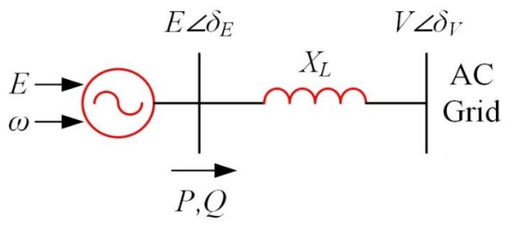
Thank you

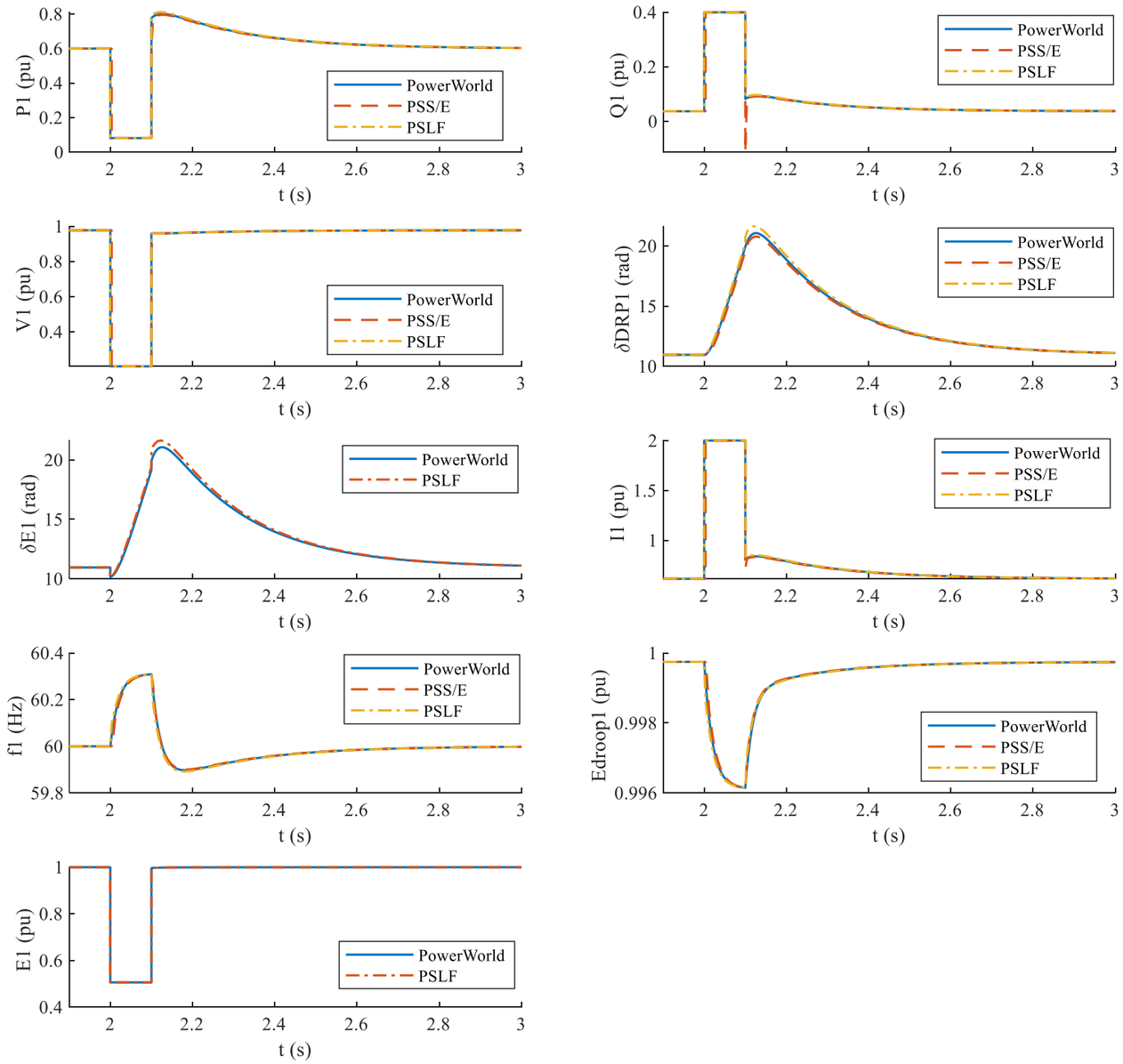
Wei Du
Wei.du@pnnl.gov

Backup Slides

Single-GFM-Infinite-Bus System

- SCR=2
  - VFlag=0





Single-GFM-Infinite-Bus System

- SCR=1
  - VFlag=0