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.

Droop-based Grid-Forming Inverter Model (REGFM_A1)

Wei Du

Staff Research Engineer

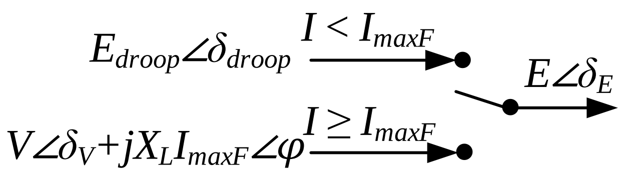
Pacific Northwest National Laboratory

WECC Model Validation Subcommittee Annual Meeting

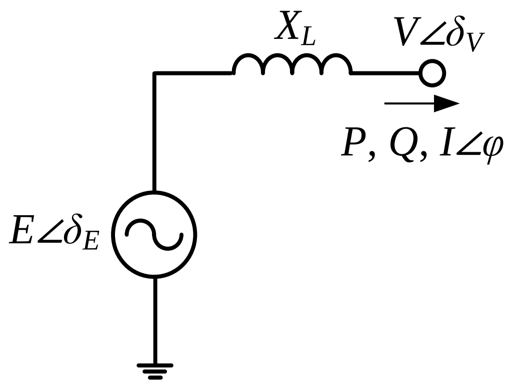
September 27th, 2023

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

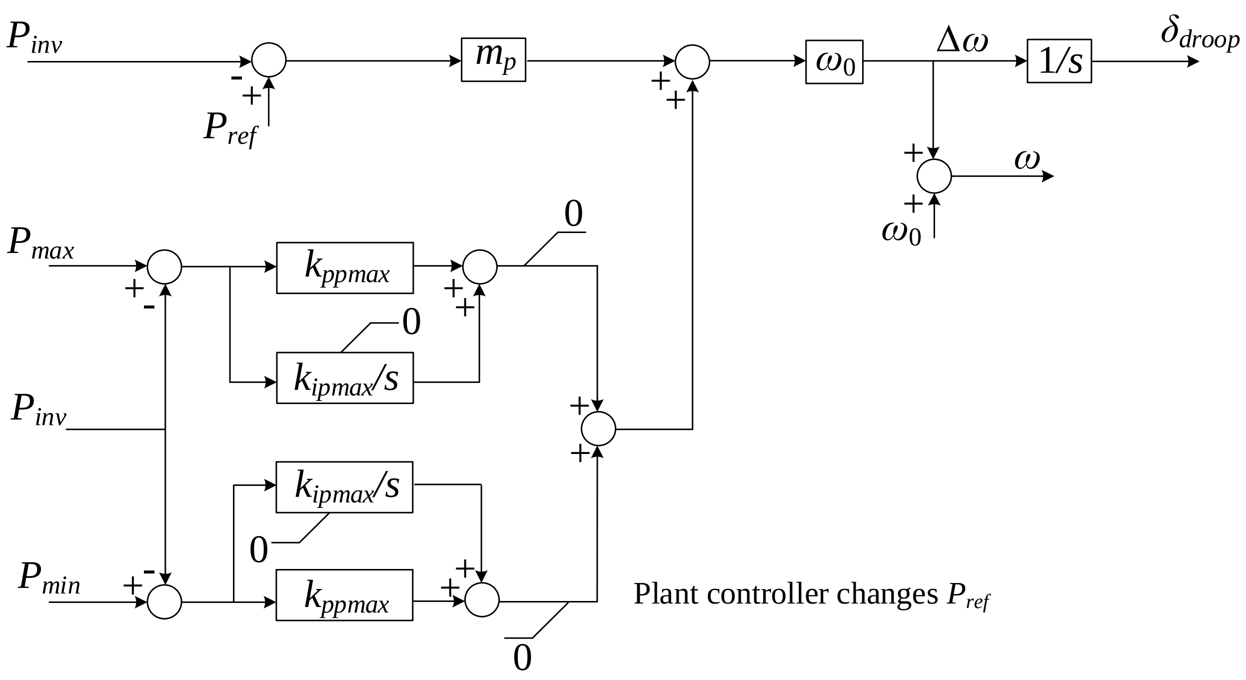
- The model includes a voltage source representation, *P-f* and *Q-V* droop controls, *P/Q* limiting controls, and a transient fault current limiting function
- Most of the control blocks came from the CERTS Microgrid Project funded by DOE
- SMA suggested to add the Q_{max}/Q_{min} control block, and the *Vflag*=0 option



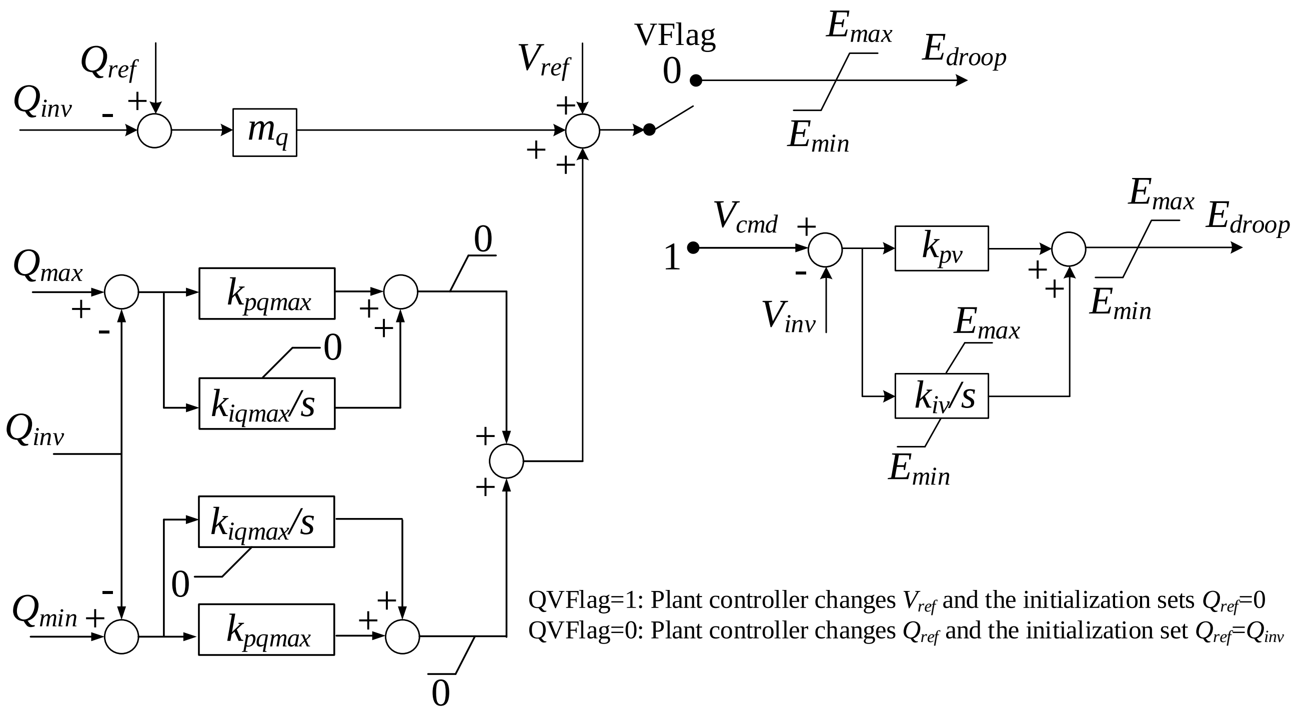
Fault current limiting



Voltage source behind impedance



P-f droop and P Limiting



Q-V droop and Q Limiting

Timeline for the REGFM_A1 Model

- 2021.12 — Model spec approved (GFMDRP_A)
- 2021.12 — NREC sent the model spec to GFM OEMs
- 2022.1 — SMA said the model “***looks quite good to represent the key elements***” and provided detailed suggestions
- 2022.5 — Updated model spec to include Q_{max}/Q_{min} control block
- 2022.9 — Updated model spec to include Vflag
- 2023.2 — Model renamed to ***REGFM_A1***. Software vendors started to implement
- 2023.5 — Model benchmarking completed. A few concerns were raised at MVS meeting
- 2023.9 — Present updates on REGFM_A1 and seek for approval for this version

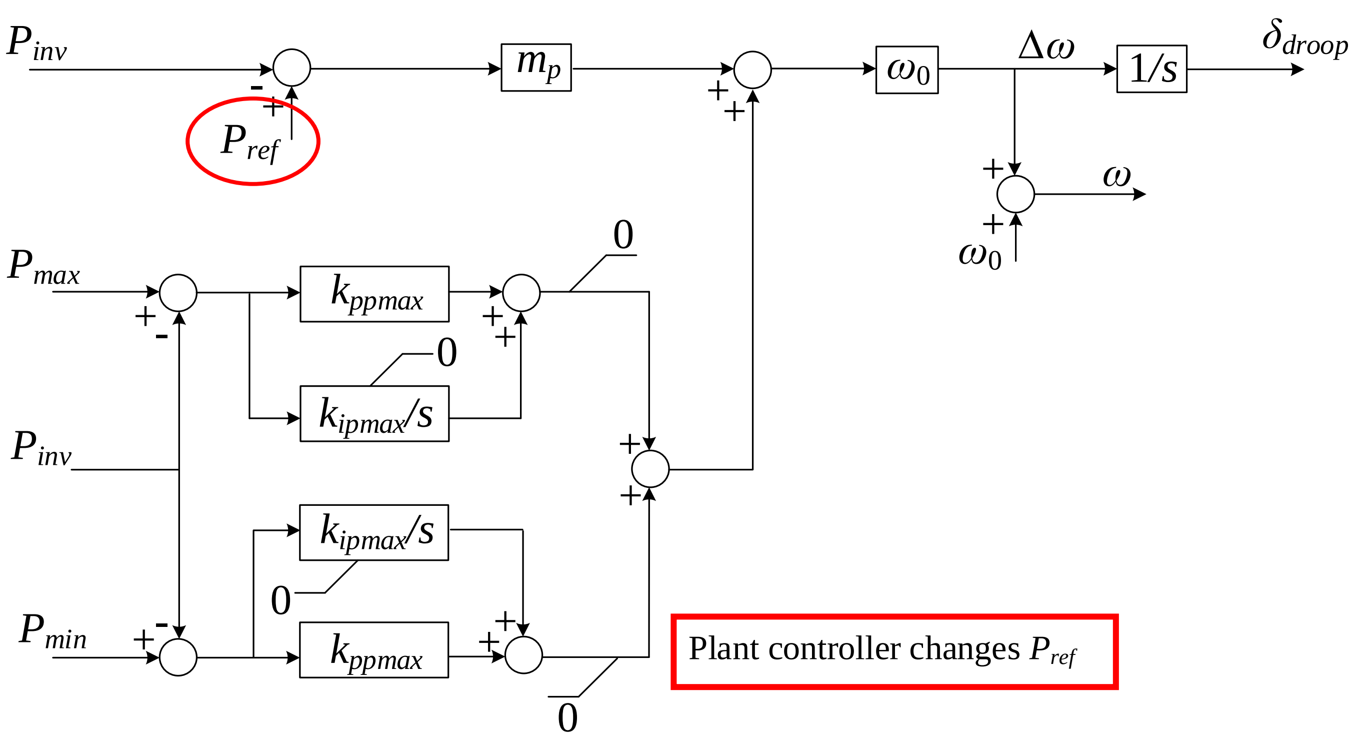
Multiple discussions including two small group meetings with several core MVS members were held to address the concerns

Discussions of REGFM_A1 before the MVS Meeting

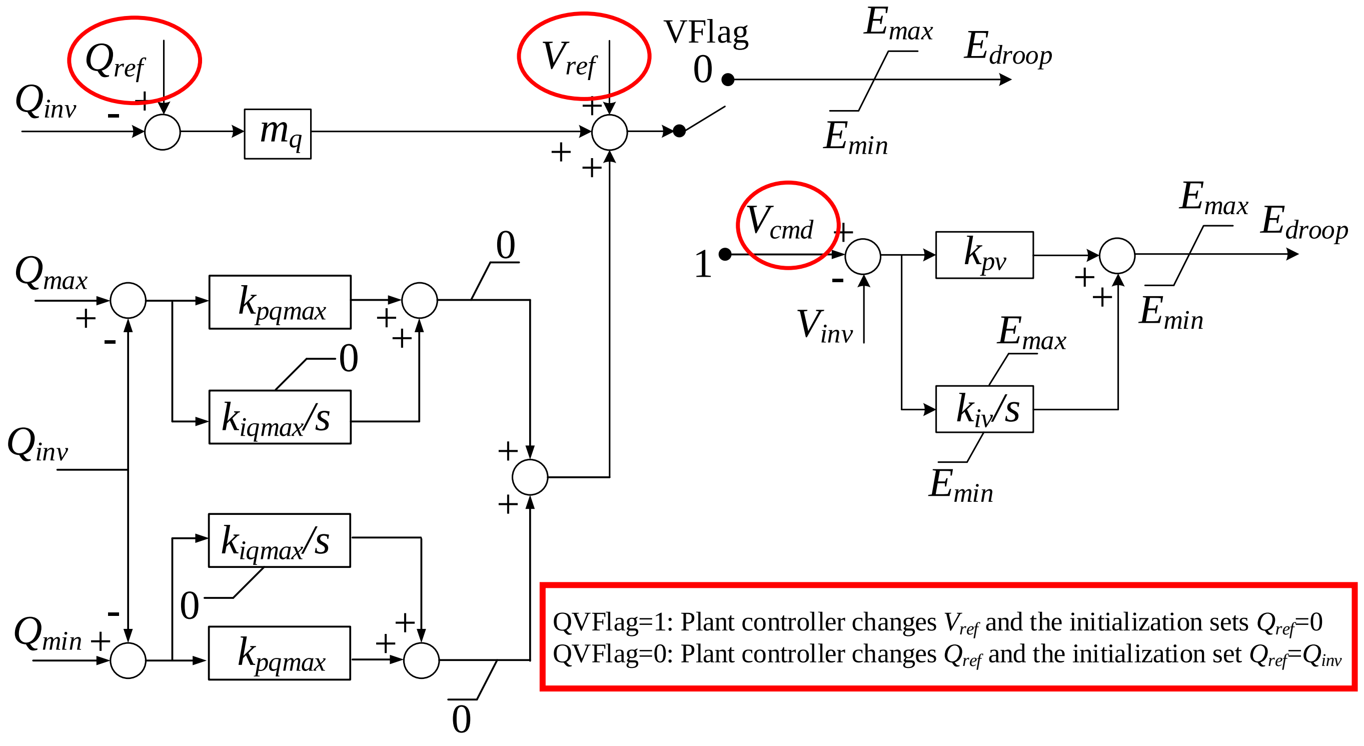
- A few core MVS members including ***Pouyan***, ***Song***, ***Juan***, ***Jay***, ***Jamie***, ***Jeff***, ***Doug***, ***Deepak***, and ***Wei*** held multiple discussions including two meetings to work together on addressing the concerns from last meeting, including
  - Rename a few variables of REGFM_A1 to align with existing generic renewable models
  - Clarify what variables should be used to interface with the plant controller model
  - The steady state current limiting and fault ride-through control of grid-forming inverters

Rename a Few Variables and Clarify the Variables to Interface with the Plant Controller

- Change the names P_{set}, Q_{set}, and V_{set} to be P_{ref}, Q_{ref}, and V_{ref}
- Change the name V_{ref} to be V_{cmd}
- Specify that the plant controller changes P_{ref} of the *P-f* path of REGFM_A1
- A QVFlag was added to determine which variable of the *Q-V* path the plant controller should change
    - When QVFlag=1, the plant controller changes V_{ref} and the initialization sets Q_{ref}=0
    - When QVFlag=0, the plant controller changes Q_{ref} and the initialization sets Q_{ref}= Q_{inv}



P-f droop and P Limiting



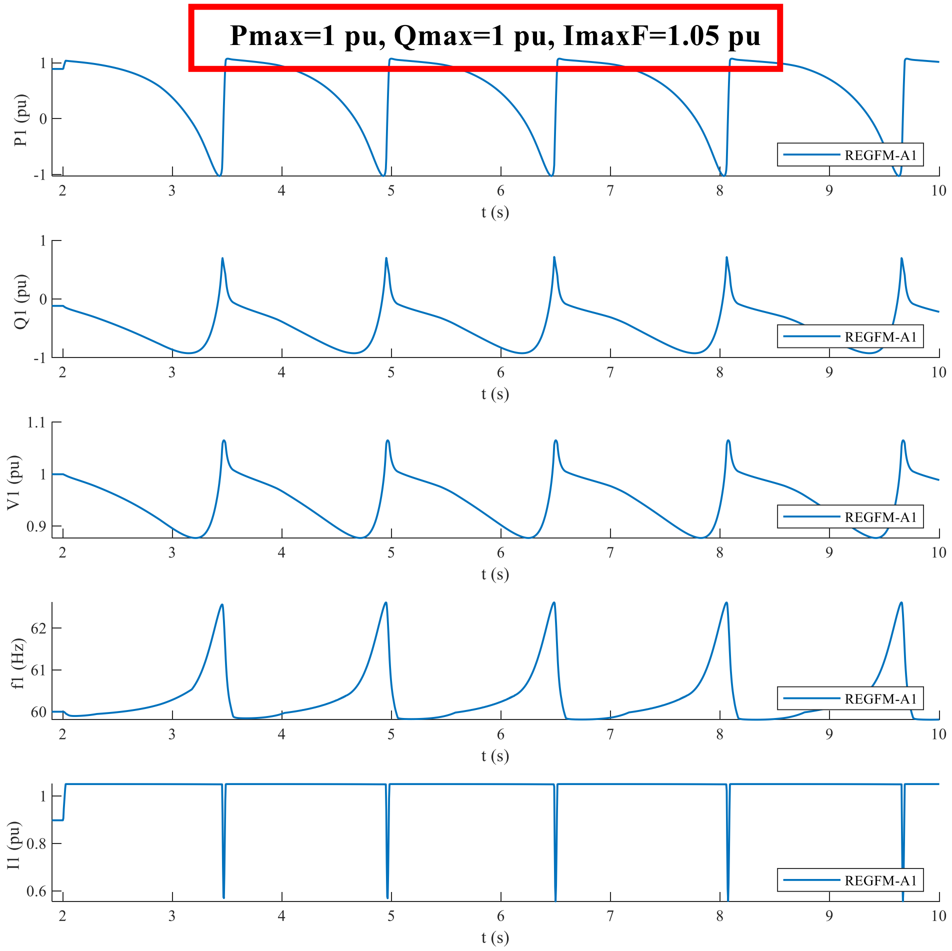
Q-V droop and Q Limiting

Steady State Current Limiting and Advanced Fault Ride-through Control of Grid-Forming Inverters

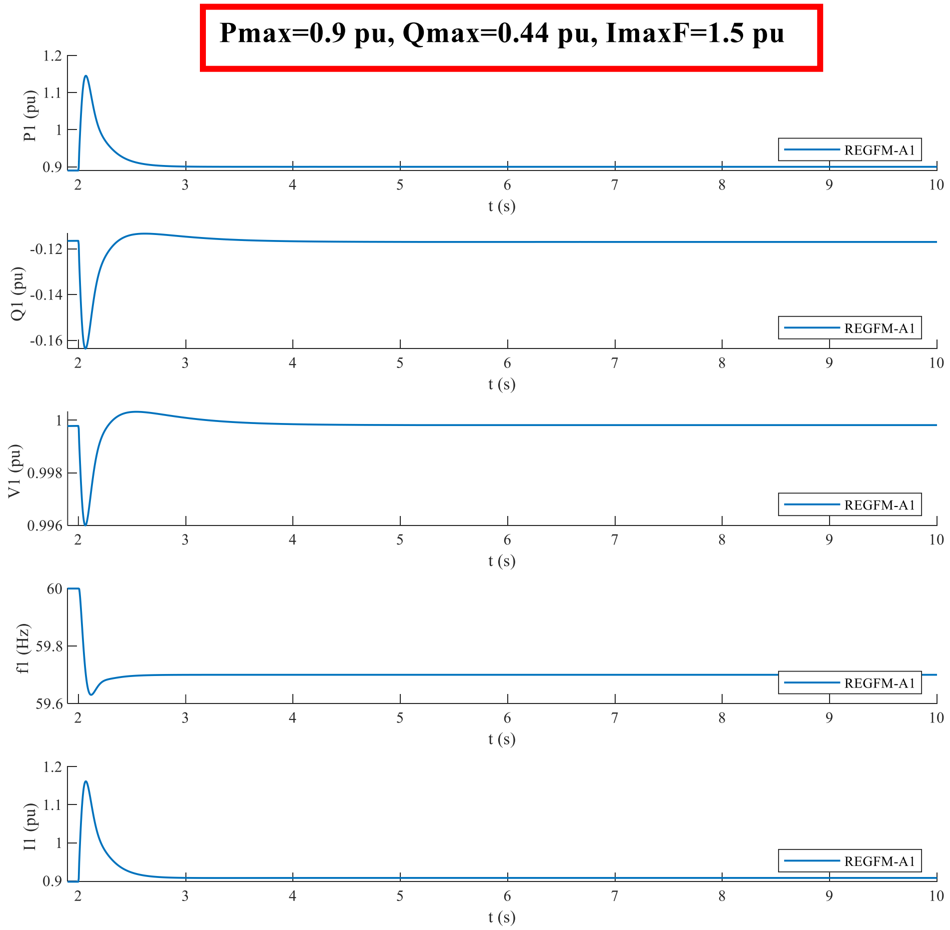
- One major concern raised in last MVS meeting was that the REGFM_A1 model might result in limit cycle issue without the steady state current limiting control during a frequency event
- A few additional steady state current limiting and advanced fault ride-through controls were proposed and discussed by the small group, and one OEM has been reached out for comments
- However, OEMs are currently sensitive about the current limiting and fault ride-through controls of GFMs because of IP concerns
- After further examine the limit cycle issue raised in last MVS meeting, it was found that it could be avoided by appropriately setting P_{max}, Q_{max}, and I_{maxF} of the existing REGFM_A1 model
  - **According to the discussion in the last small group meeting, if the limit cycle issue could be avoided by appropriately setting P_{max}, Q_{max}, and I_{maxF}, the small team agreed to list the REGFM_A1 model as an Approval Item,** and the steady state current limiting together with the advanced fault ride-through control will be further studied and included in the next version of generic model
  - Applicability and limitations of REGFM_A1 should be clarified in the model specification

Simulation Results of REGFM_A1 on the Frequency Event

- Simulation results show that the limit cycle issue can be avoided by appropriately setting P_{max}, Q_{max}, and I_{maxF}
- I_{maxF} is used for the transient current limiting during short-circuit faults, and its value should be set larger such as 1.5 pu or higher
- P_{max} and Q_{max} are used for limiting the steady state output P and Q, and their values should be set to ensure that MVAbase=1 pu (e.g., P_{max}=0.9 and Q_{max} =0.44 assuming a power factor of 0.9)



Inappropriate parameters can result in limit cycle issue



The limit cycle issue can be avoided by correcting the parameters

Conclusions

- **According to the discussion in the last small group meeting, if the limit cycle issue could be avoided by appropriately setting P_{max}, Q_{max}, and I_{maxF}, the small team agreed to list the REGFM_A1 model as an *Approval Item*,** and the steady state current limiting together with the advanced fault ride-through control will be further studied and included in the next version of droop-based generic model
- Applicability and limitations of REGFM_A1 have been clarified in the updated model specification
    - The REGFM_A1 model includes a voltage source behind impedance representation, *P-f* and *Q-V* droop controls, active and reactive power limiting controls, and a transient fault current limiting function. Therefore, this model can be used to study most events such as the frequency response, islanding and islanded operation, and typical faults with a normal clearing time (e.g., a 6-cycle fault), etc.
    - The REGFM_A1 model does not include the steady state current limiting control and advanced voltage ride-through control for long duration faults. The steady state current limiting control and advanced voltage ride-through control will be included in the future version of generic GFM IBR model

Acknowledgement

- I'd like to thank all the contributors listed in the REGFM_A1 model specification for their contributions to this model

PNNL-32278

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

September 2023

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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James Weber	PowerWorld
Jeff Bloemink	PowerTech Labs
Doug Tucker	Western Electricity Coordinating Council (WECC)
Zhenyu Huang	Pacific Northwest National Laboratory
Francis K. Tuffner	Pacific Northwest National Laboratory
Renke Huang	Pacific Northwest National Laboratory

Summary

- 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 approve this REGFM_A1 model

Thank you

Wei Du

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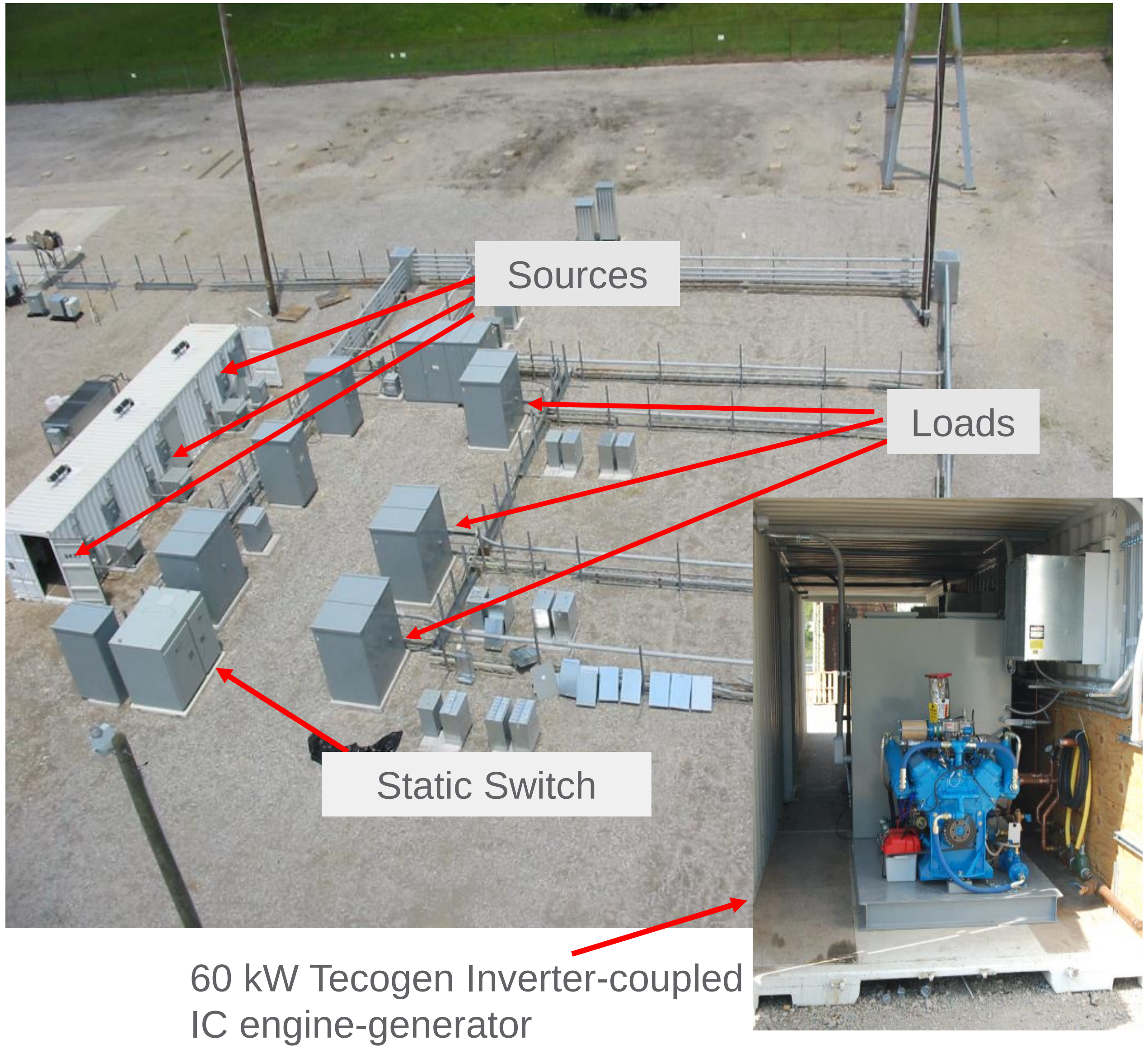
Backup Slides
(Already presented in May)

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

CERTS/AEP Testbed

Wisconsin Energy Institute
UNIVERSITY OF WISCONSIN–MADISON

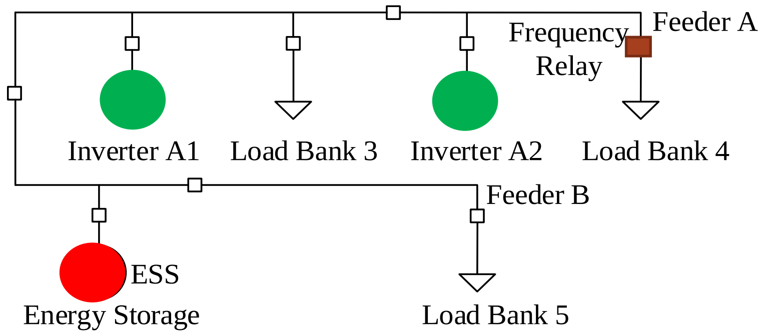
CERTS CONSORTIUM for ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

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

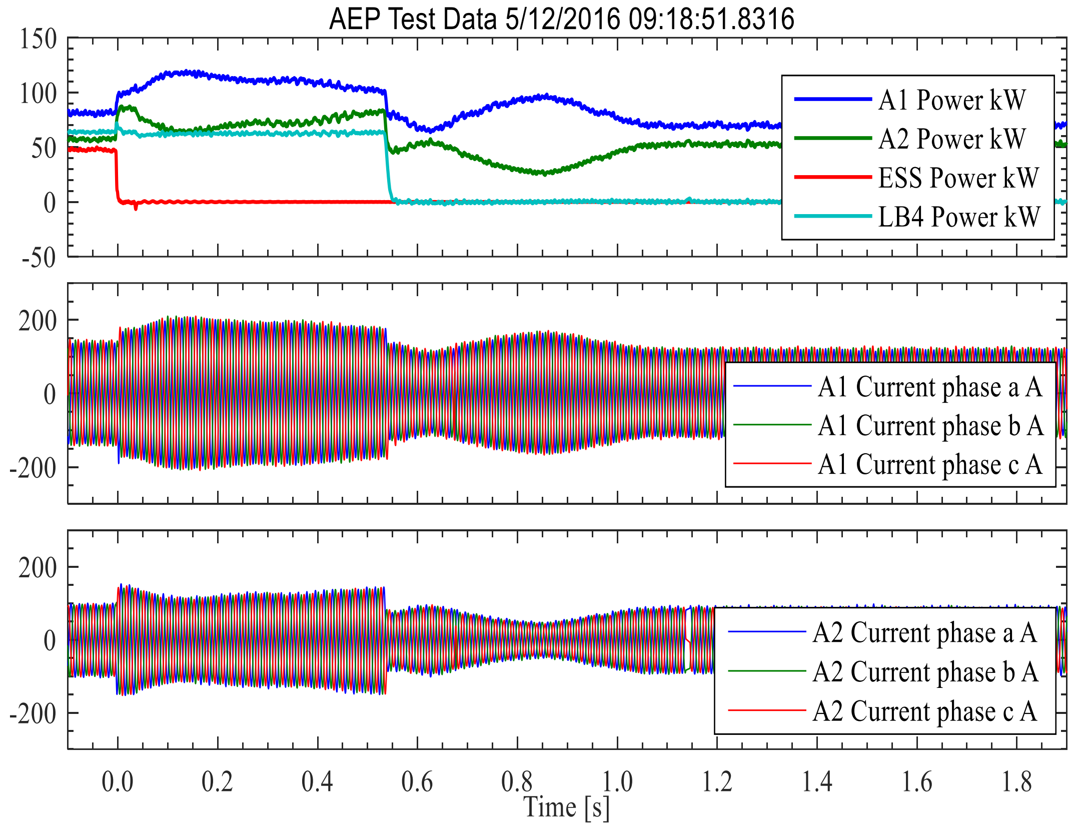
[1] Lasseter, R.H., Eto, J.H., Schenkman, B., Stevens, J., Vollkommer, H., Klapp, D., Linton, E., Hurtado, H. and Roy, J., 2010. CERTS microgrid laboratory test bed. IEEE Transactions on Power Delivery, 26(1)

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

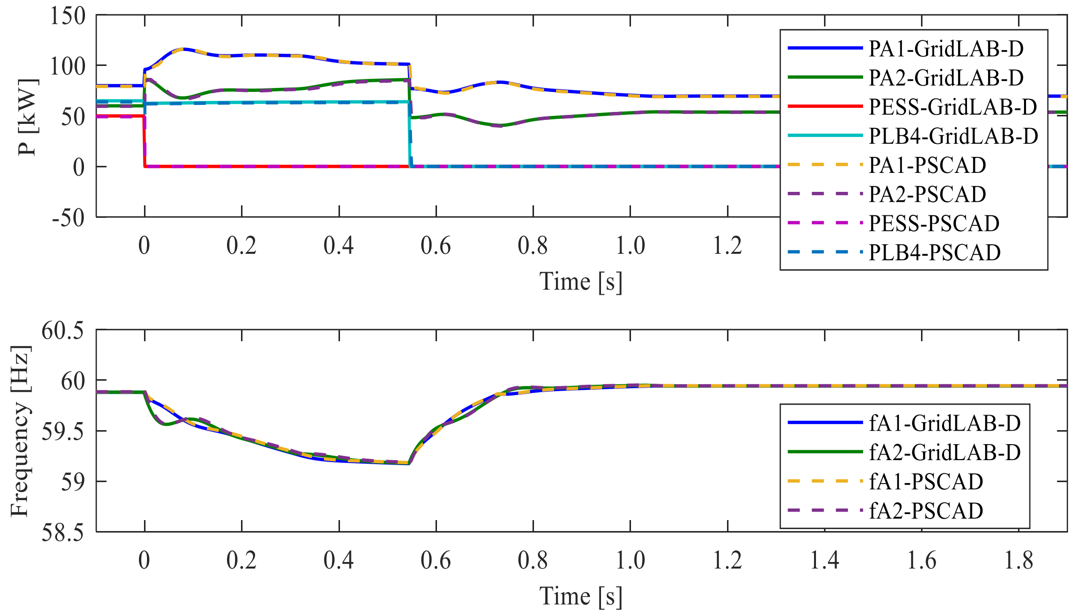
CERTS/AEP Test Site



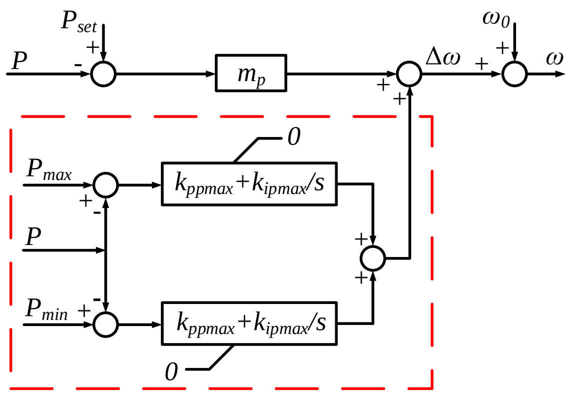
- After loss of the 58 kW ESS, the total 220 kW load exceeds the 193 kW maximum generation of A1 and B1
- Load Bank 4 is tripped in 0.5 s by the frequency relay
- The overload mitigation control helps to trigger under-frequency load shedding when the entire system is overloaded



Field test results from CERTS/AEP testbed



EMT and phasor simulation results



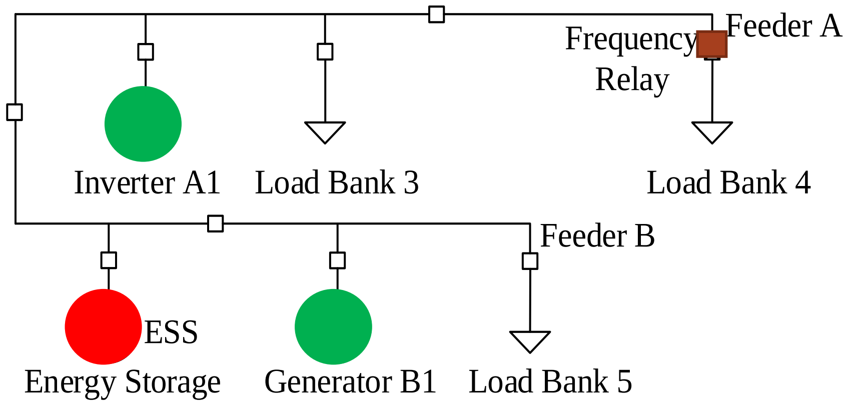
----EMT

——Phasor

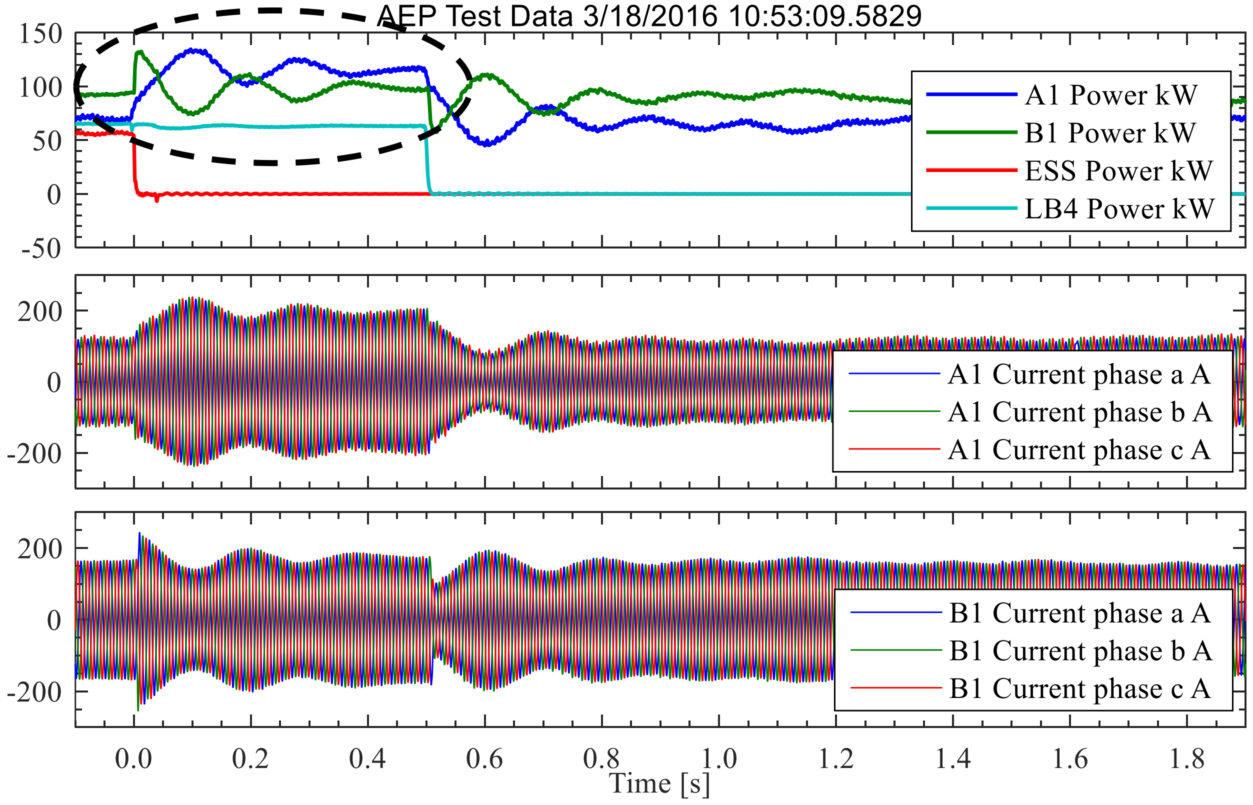
[1] Wei Du, Francis K. Tuffner, Kevin P. Schneider, Robert Lasseter, et al., “Modeling of Grid-Forming and Grid-Following Inverters for Dynamic Simulation of Large-Scale Distribution Systems”. IEEE Transactions on Power Delivery, 2020.

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

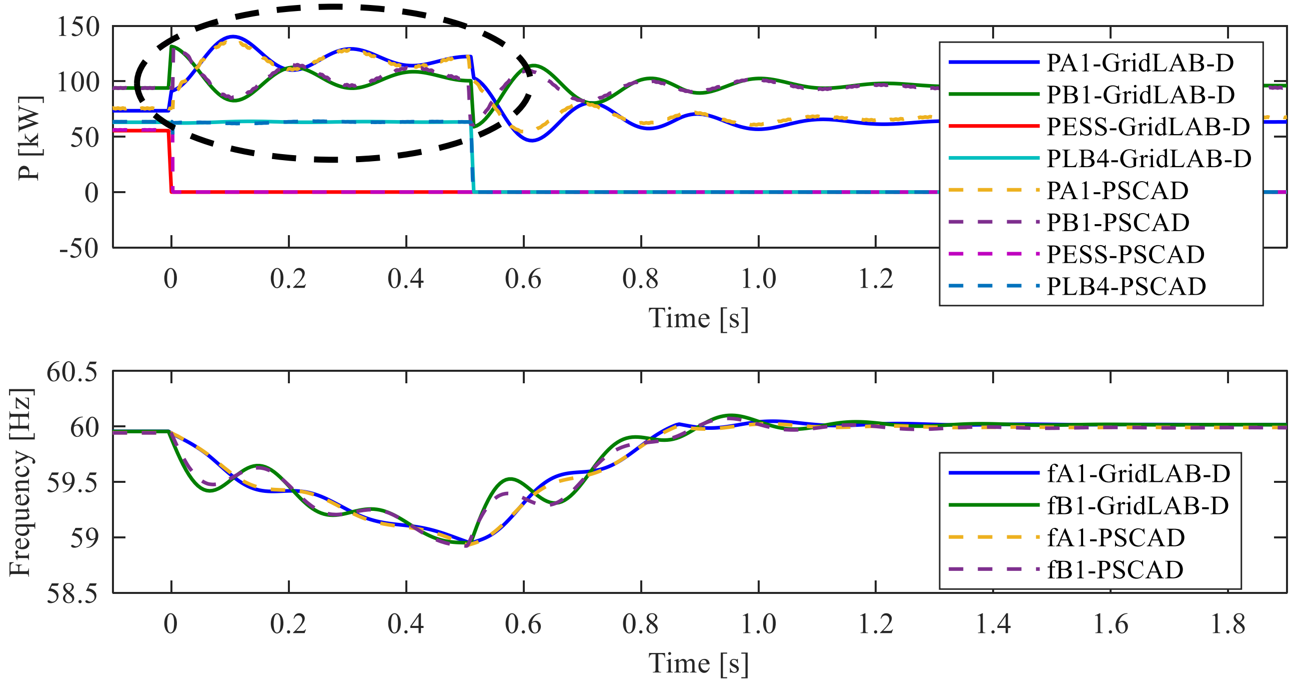
- The loss of ESS results in the overload of the entire microgrid
- Droop curve becomes vertical because of P_{max} control, triggering under-frequency load shedding
- GridLAB-D simulation, PSCAD simulation, and field test results match well with each other



CERTS/AEP Testbed



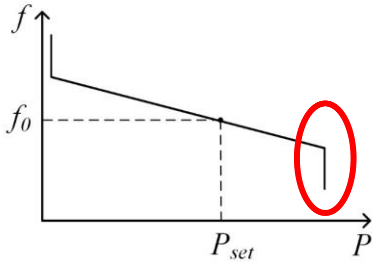
Field test results from CERTS/AEP testbed



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

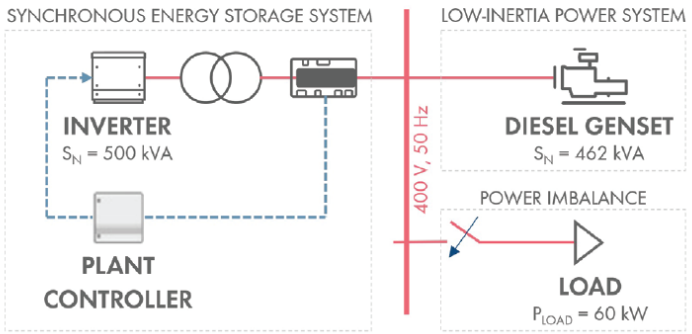
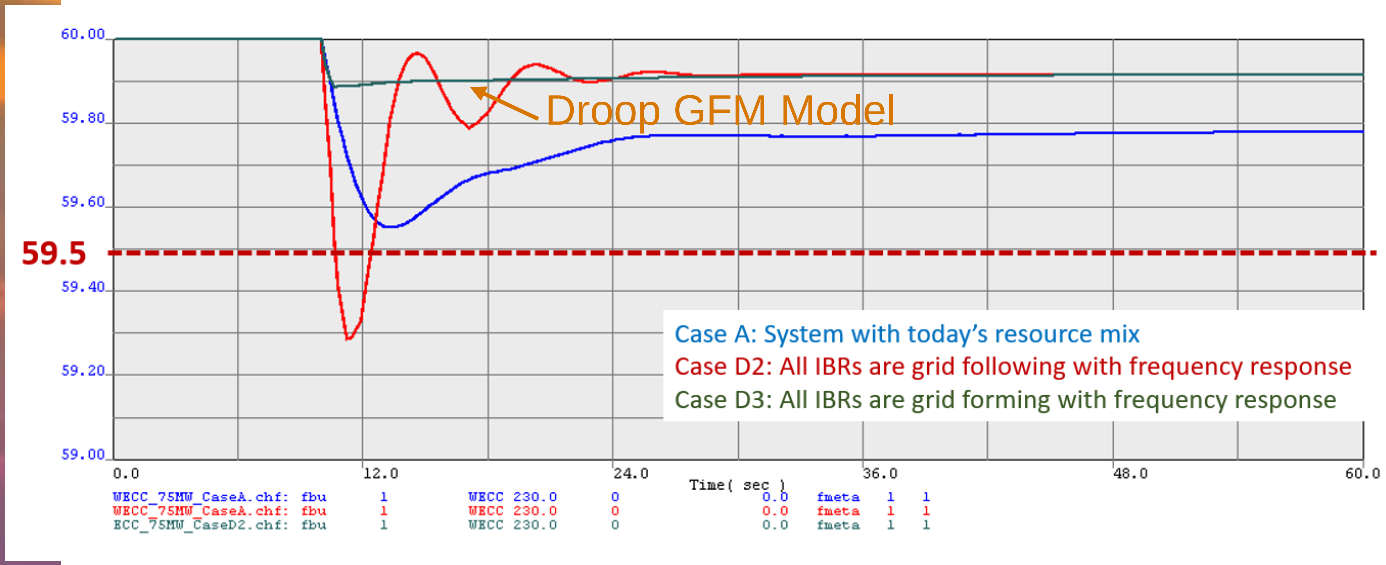
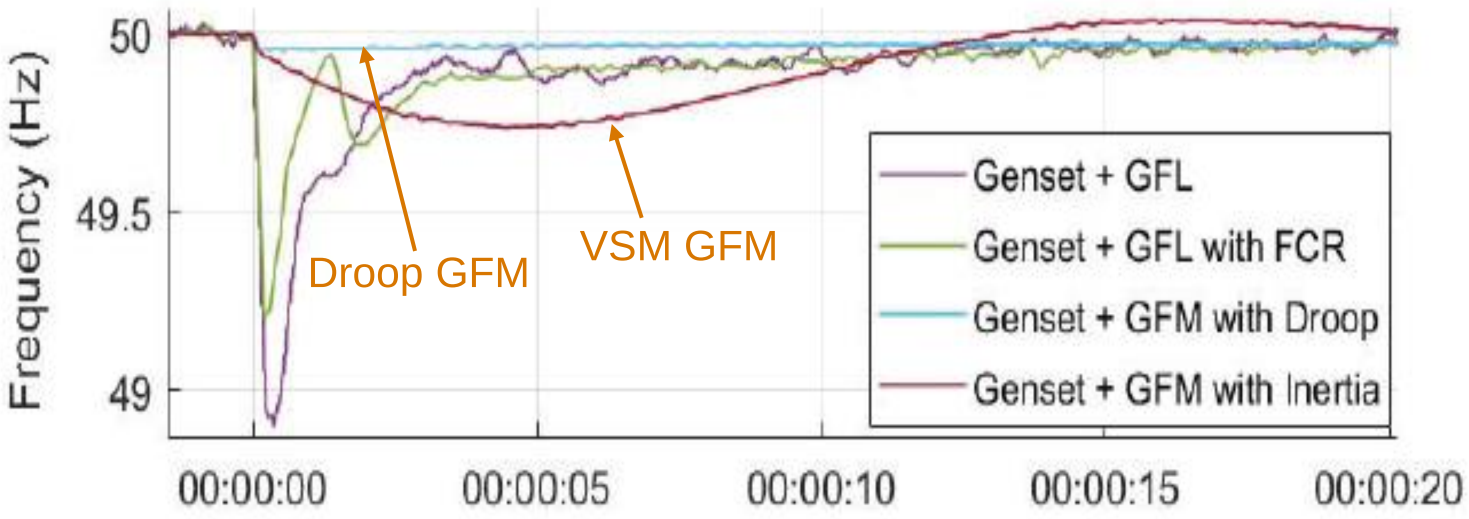


Fig. 7: Laboratory setup for demonstration of SESS control capabilities

73% penetration of GFMs in the micro-WECC system



SMA Hardware Test Results on a Small System[1]



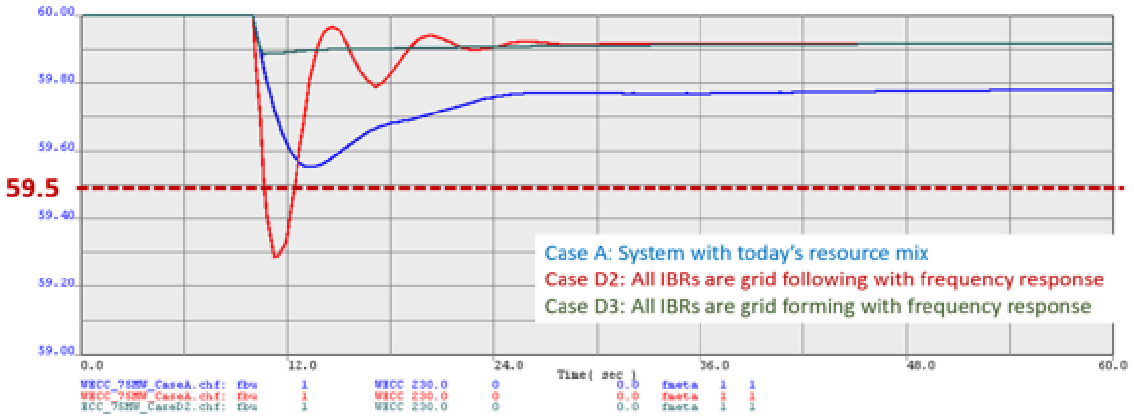
(Simulation credit: Dmitry, BPA)

[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

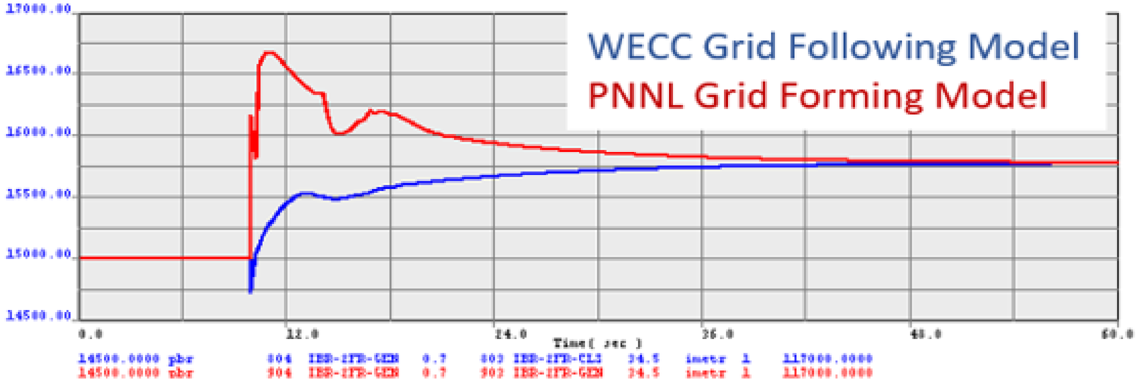
- The GFM unit behaves as a controllable voltage source behind impedance, so it increases the output power almost instantaneously after the disturbance
- The synchronous generator’s output power is clamped so its speed does not change too much

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)

IBRs on Frequency Response



SMA Hardware Test Results on a Microgrid[1]

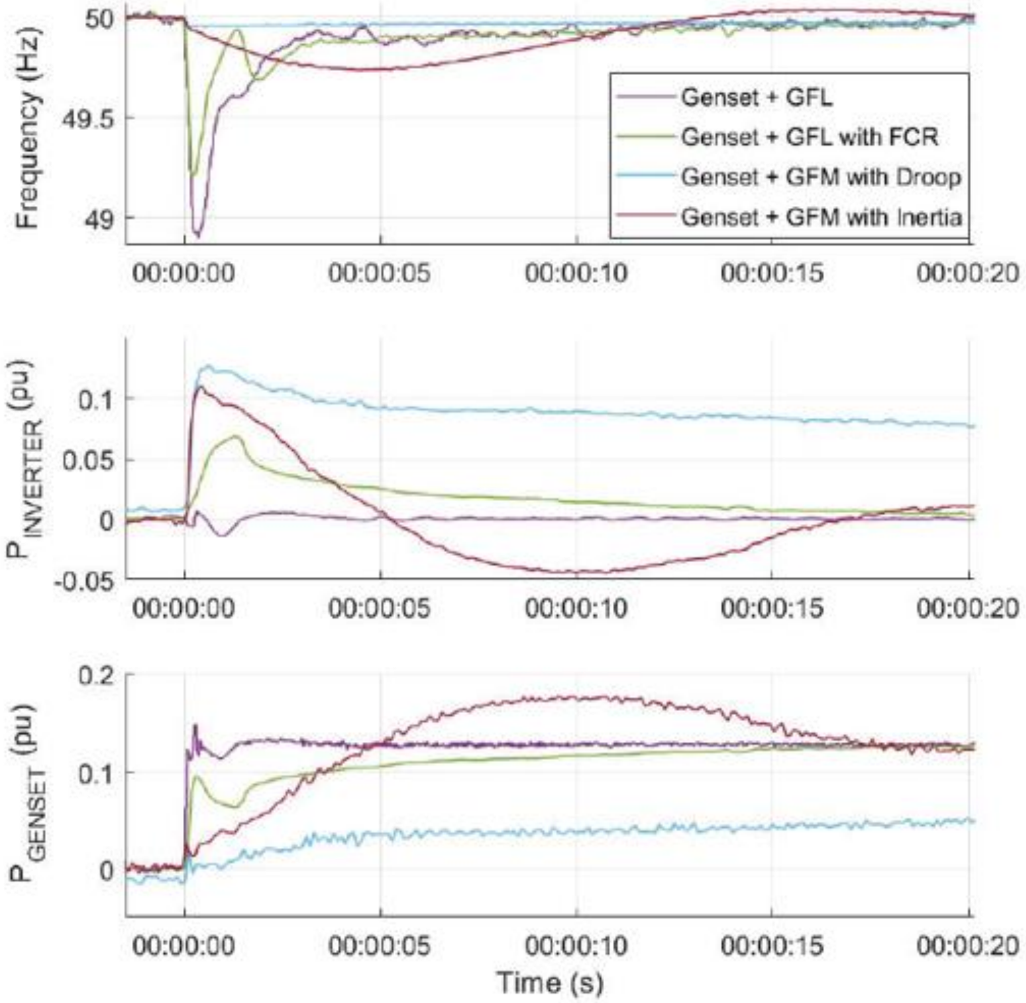
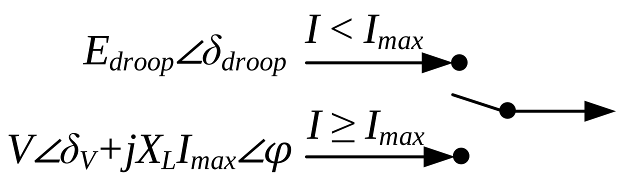


Fig. 8: Impact of different inverter system control modes on the frequency of a downscaled low-inertia power system at a power imbalance event

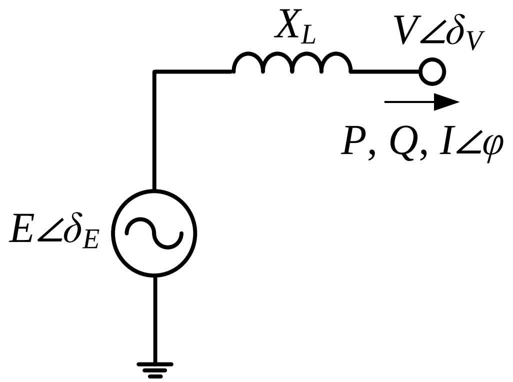
REGFM_A1 Model Benchmarking Results

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

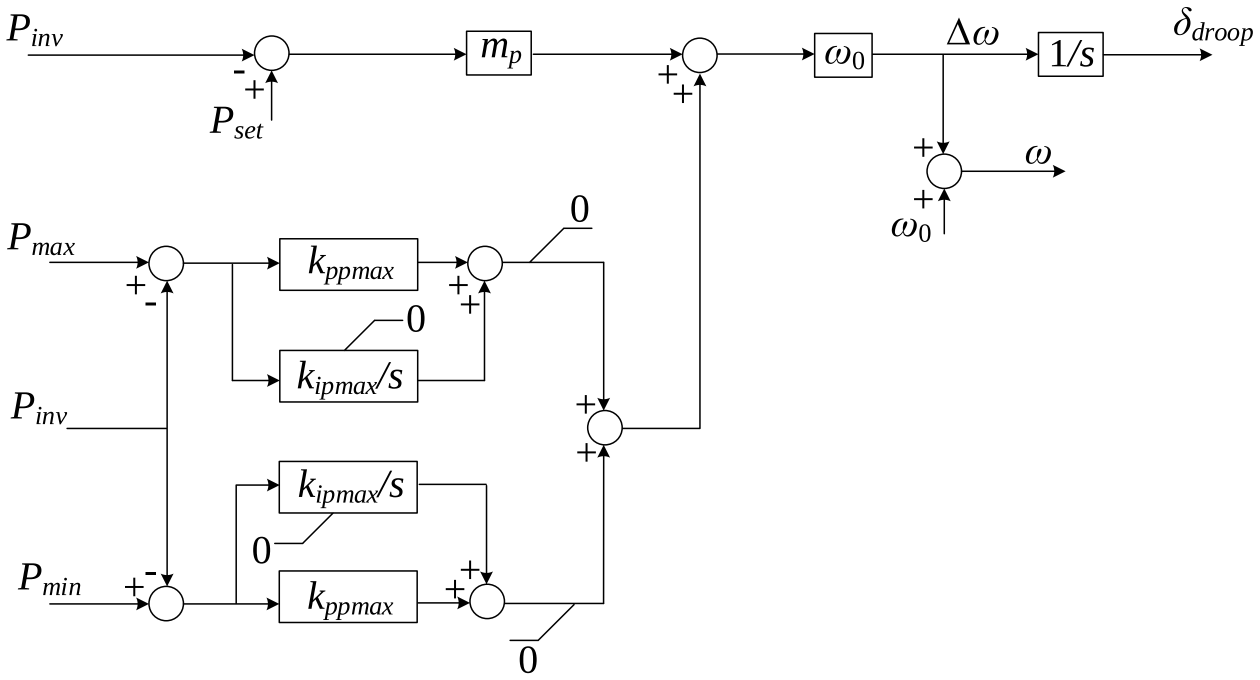
- The model includes the voltage source representation, *P-f* and *Q-V* droop control, *P/Q* limiting, and fault current limiting
- Most of the control blocks came from the CERTS Microgrid Project[1,2]
- SMA suggested to add the Q_{max}/Q_{min} control block, and the Vflag=0 option



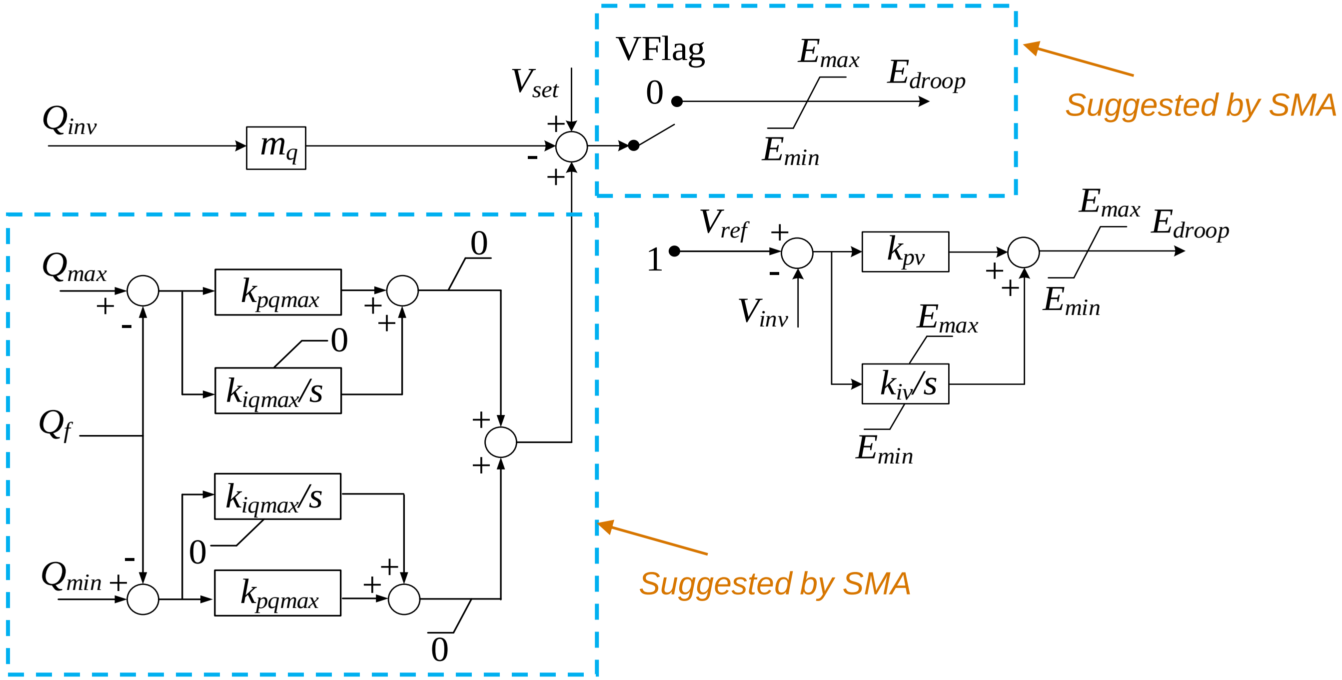
Fault current limiting



Voltage source behind impedance



P-f droop and P Limiting

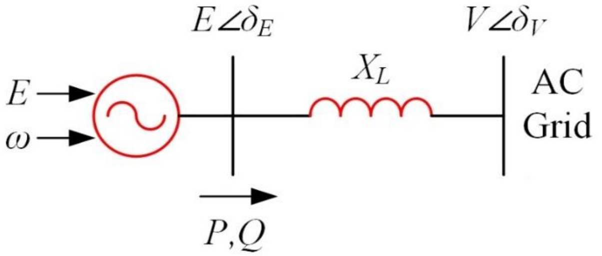


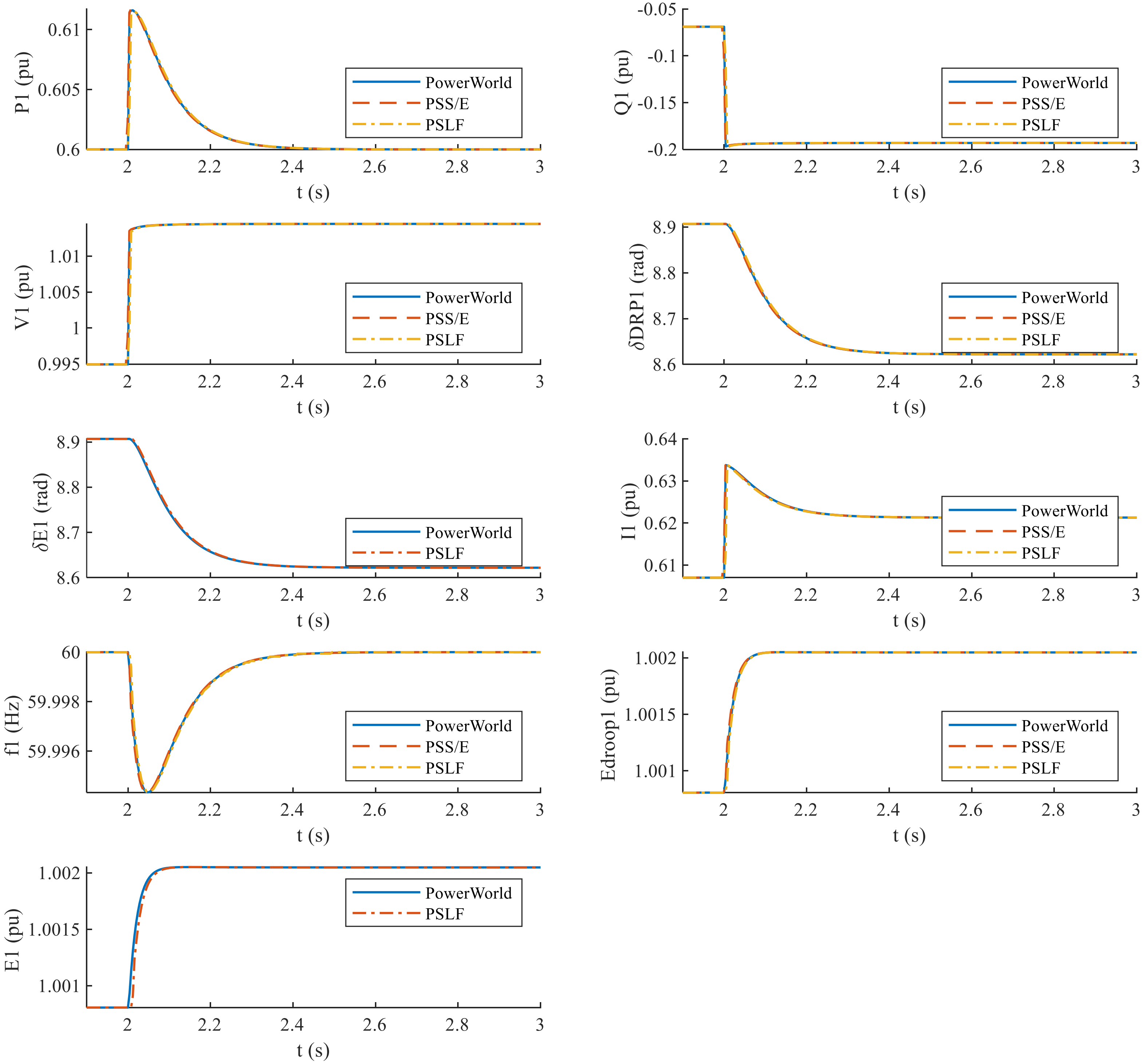
Q-V droop and Q Limiting

[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.

Single-GFM-Infinite-Bus System

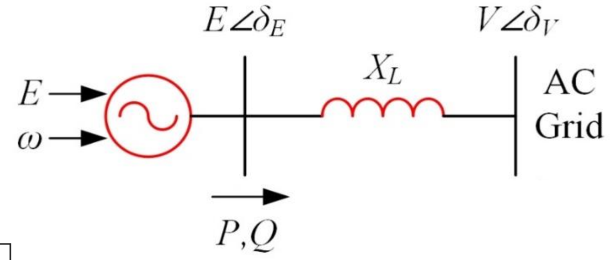
- 0.05 pu Step Increase in Voltage
  - VFlag=0

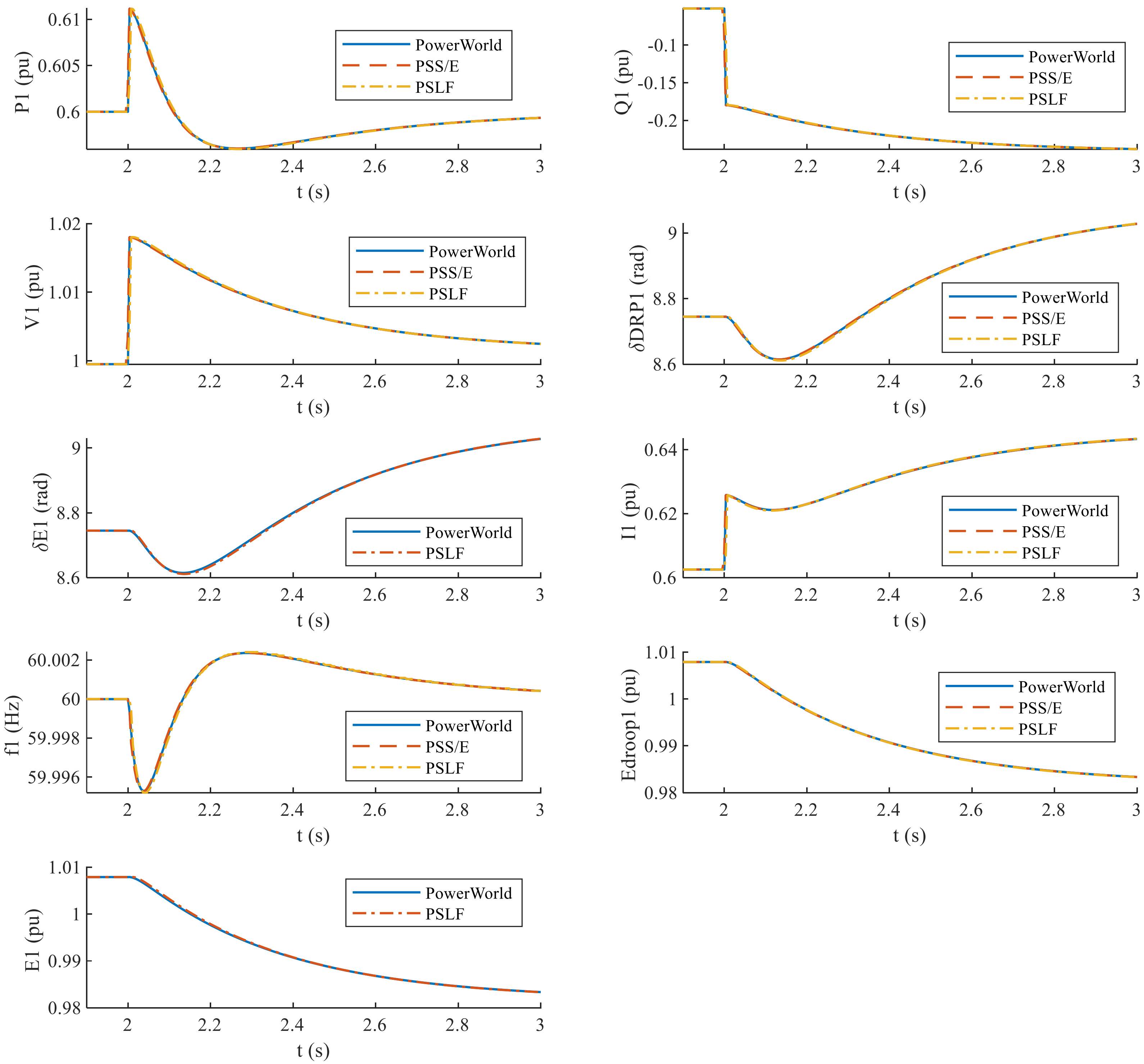




Single-GFM-Infinite-Bus System

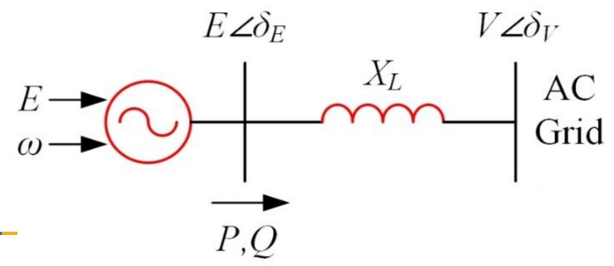
- 0.05 pu Step Increase in Voltage
  - VFlag=1

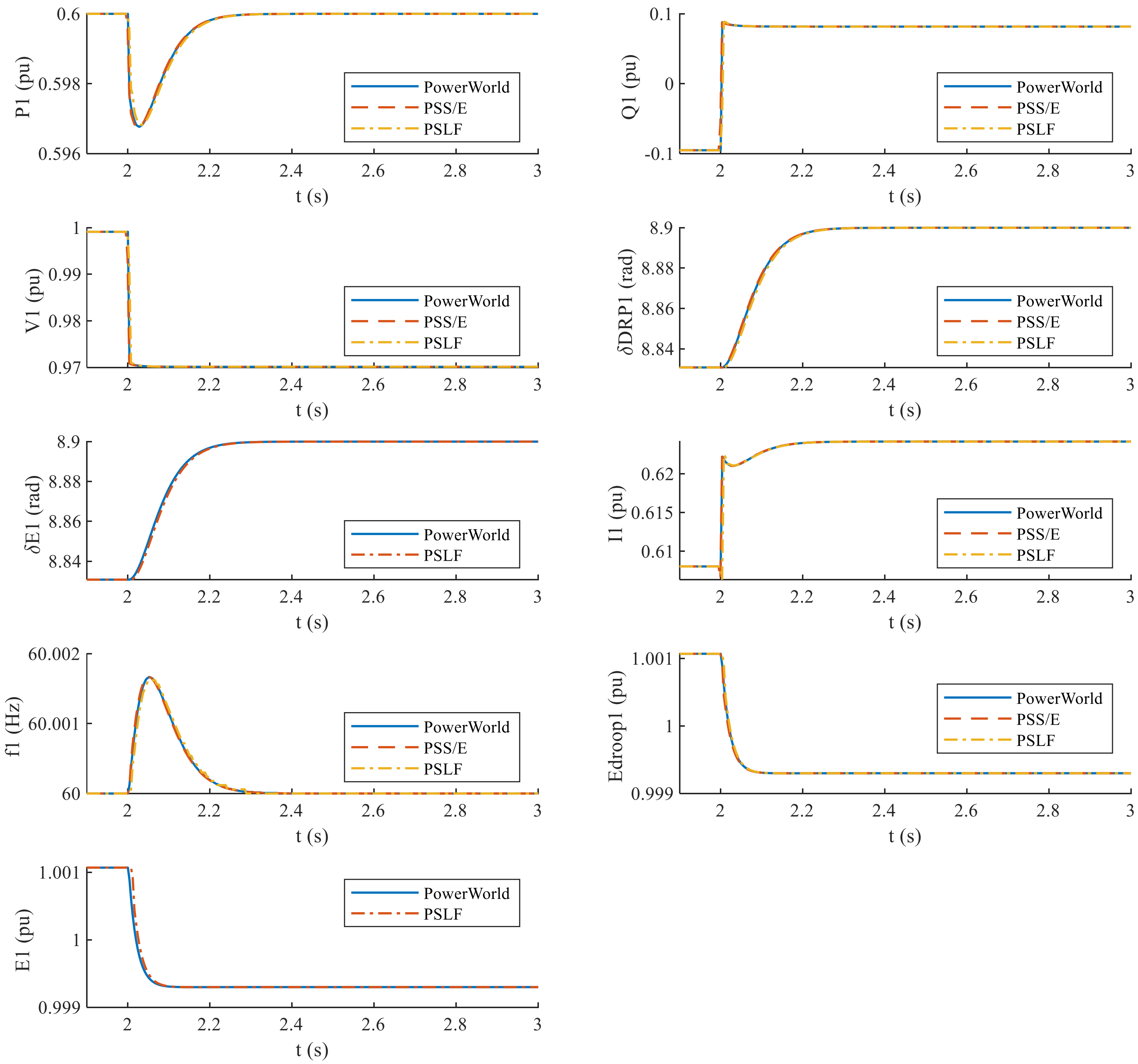




Single-GFM-Infinite-Bus System

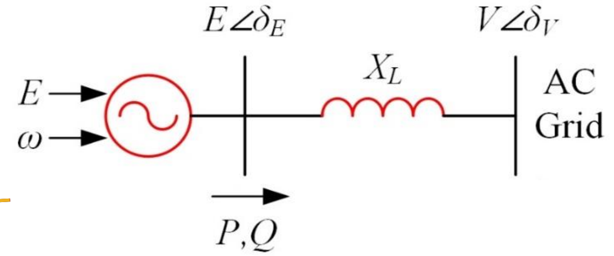
- 0.05 pu Step Decrease in Voltage
  - VFlag=0

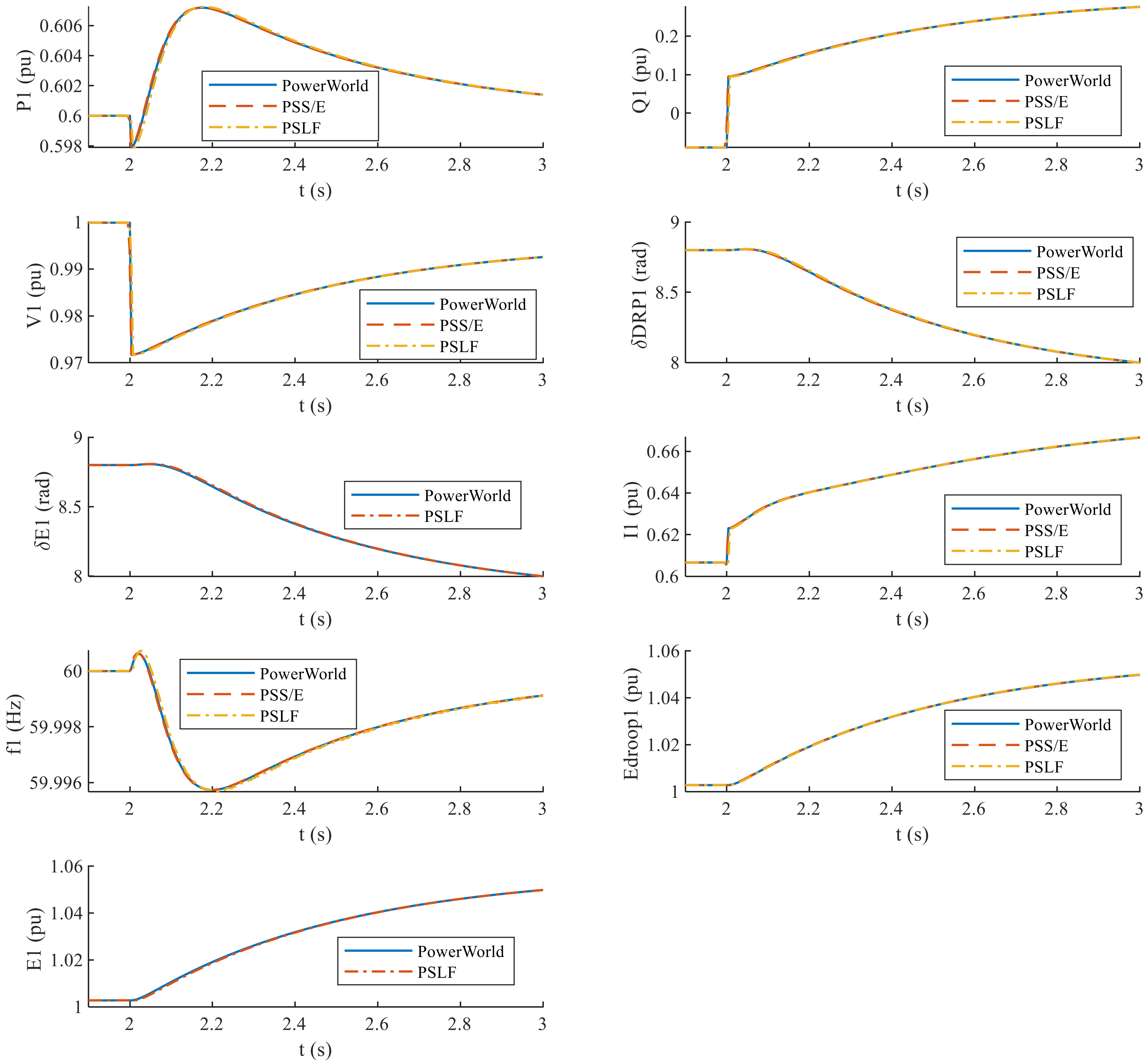




Single-GFM-Infinite-Bus System

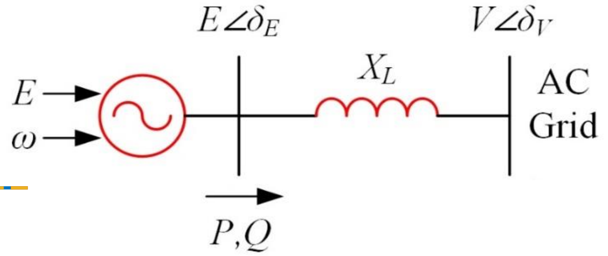
- 0.05 pu Step Decrease in Voltage
  - VFlag=1

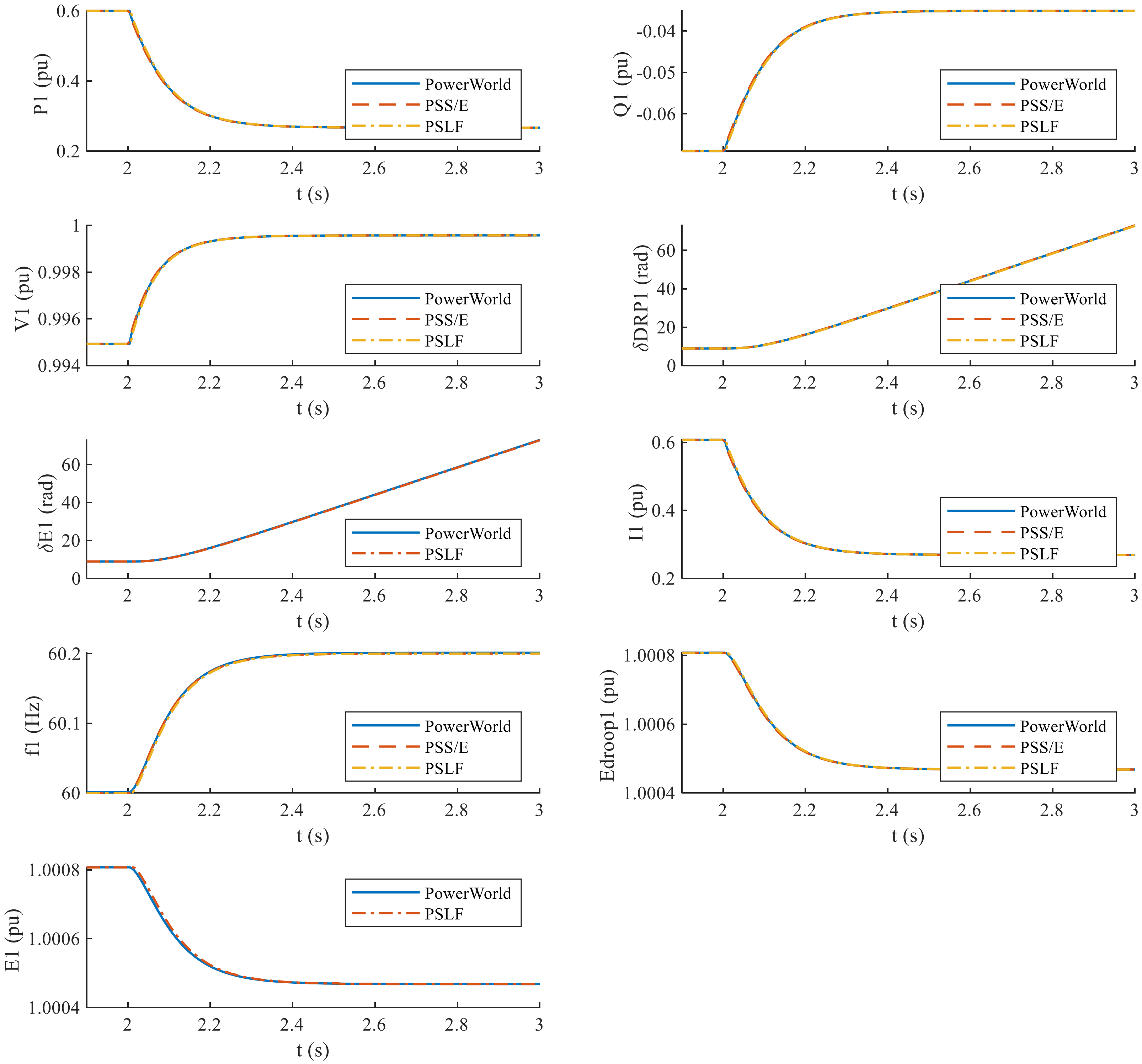




Single-GFM-Infinite-Bus System

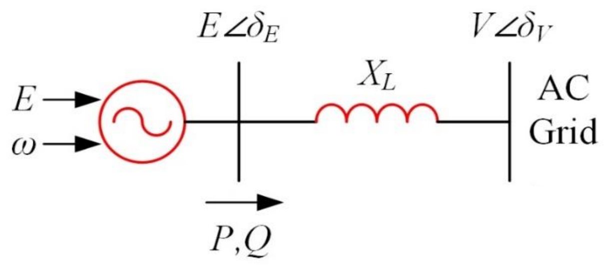
- Frequency step up from 60 Hz to 60.2 Hz
  - VFlag=0

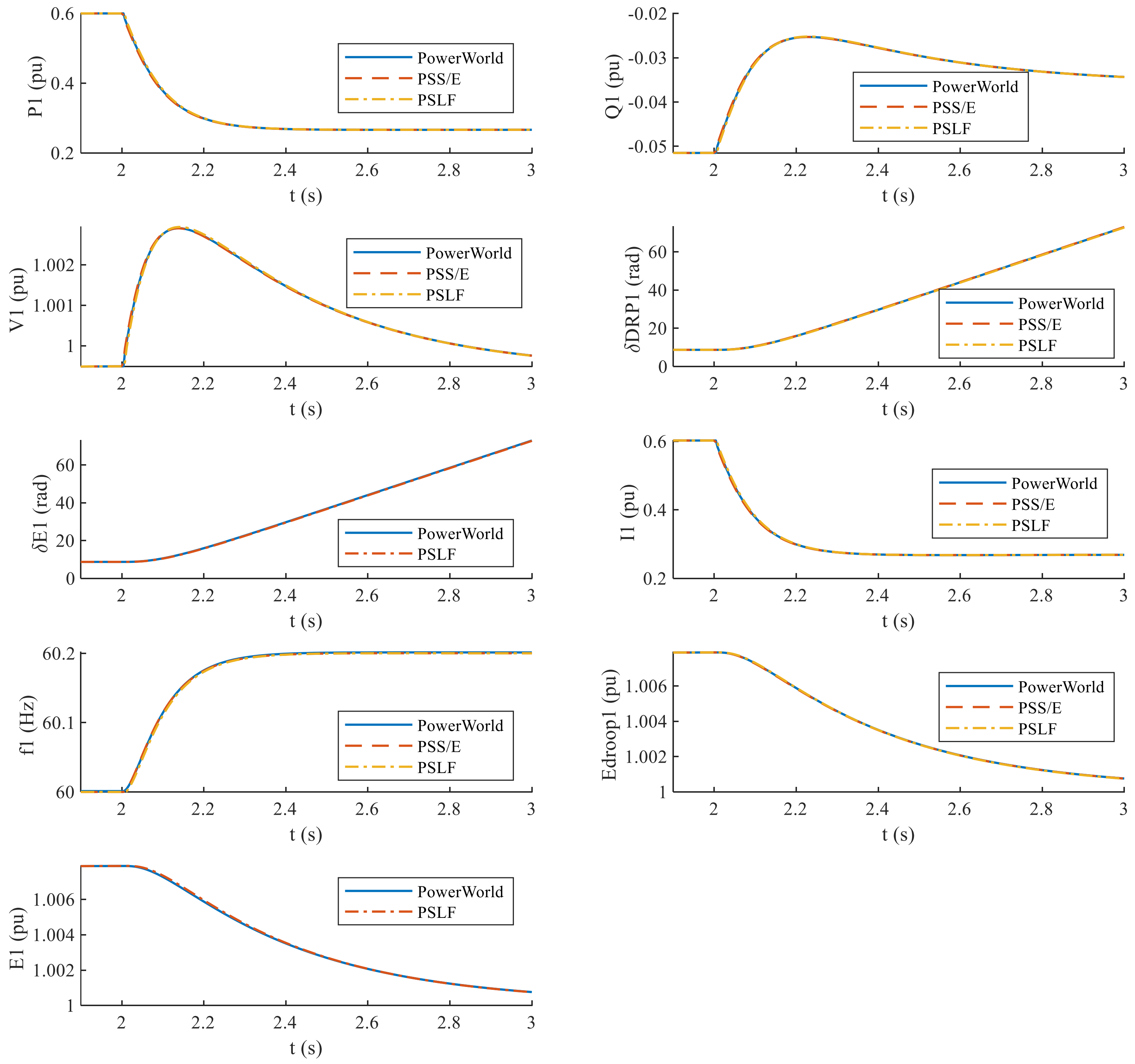




Single-GFM-Infinite-Bus System

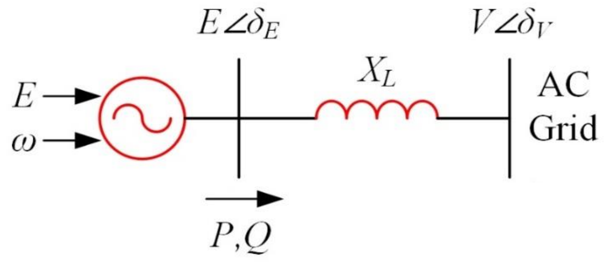
- Frequency step up from 60 Hz to 60.2 Hz
  - VFlag=1

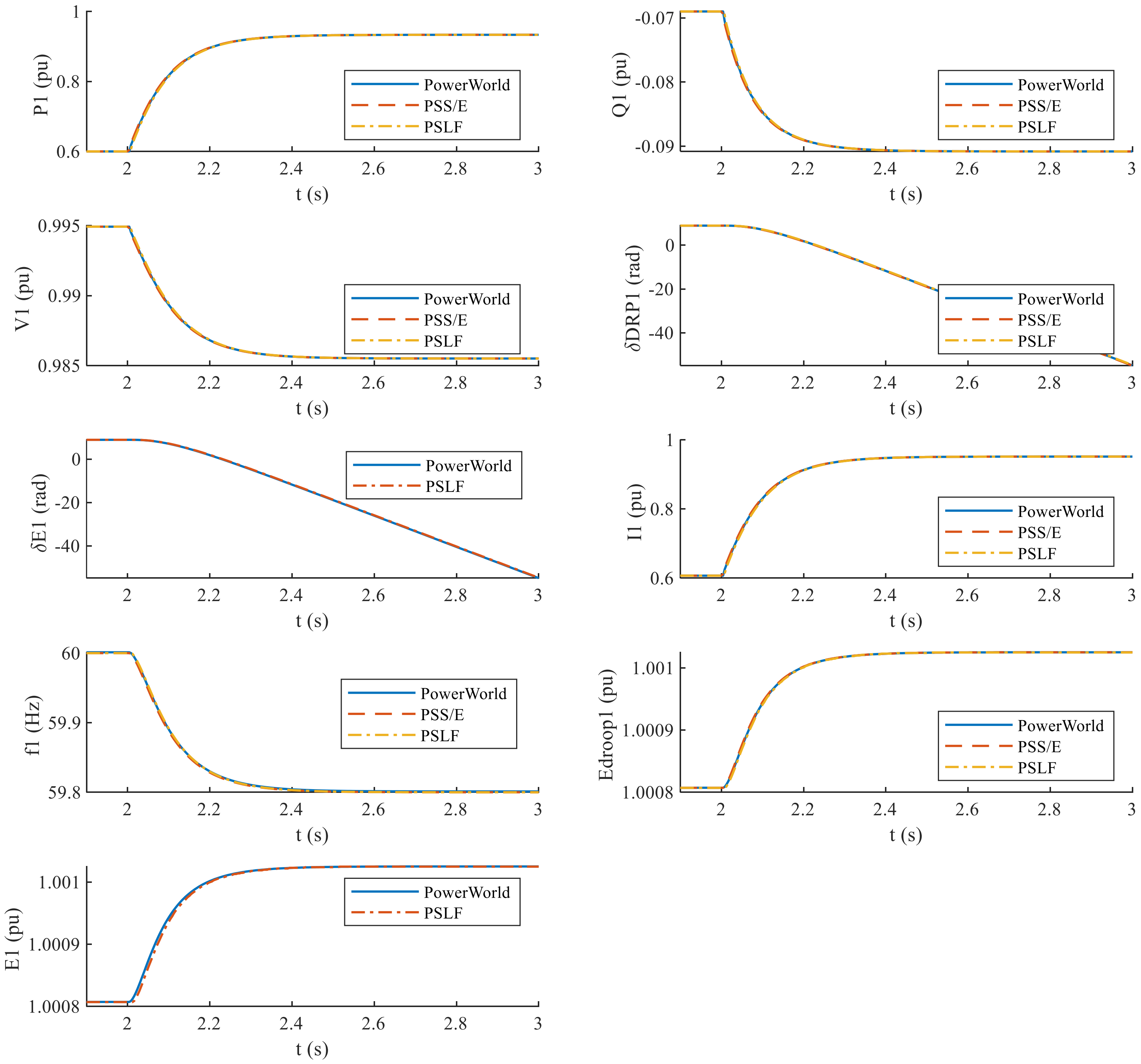




Single-GFM-Infinite-Bus System

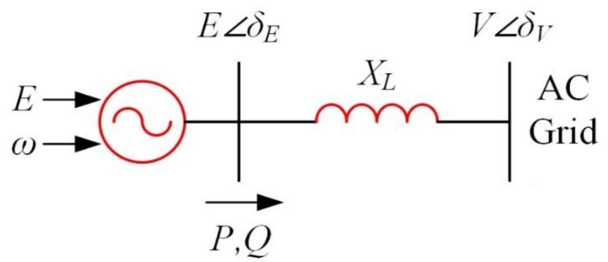
- Frequency step down from 60 Hz to 59.8 Hz
  - VFlag=0

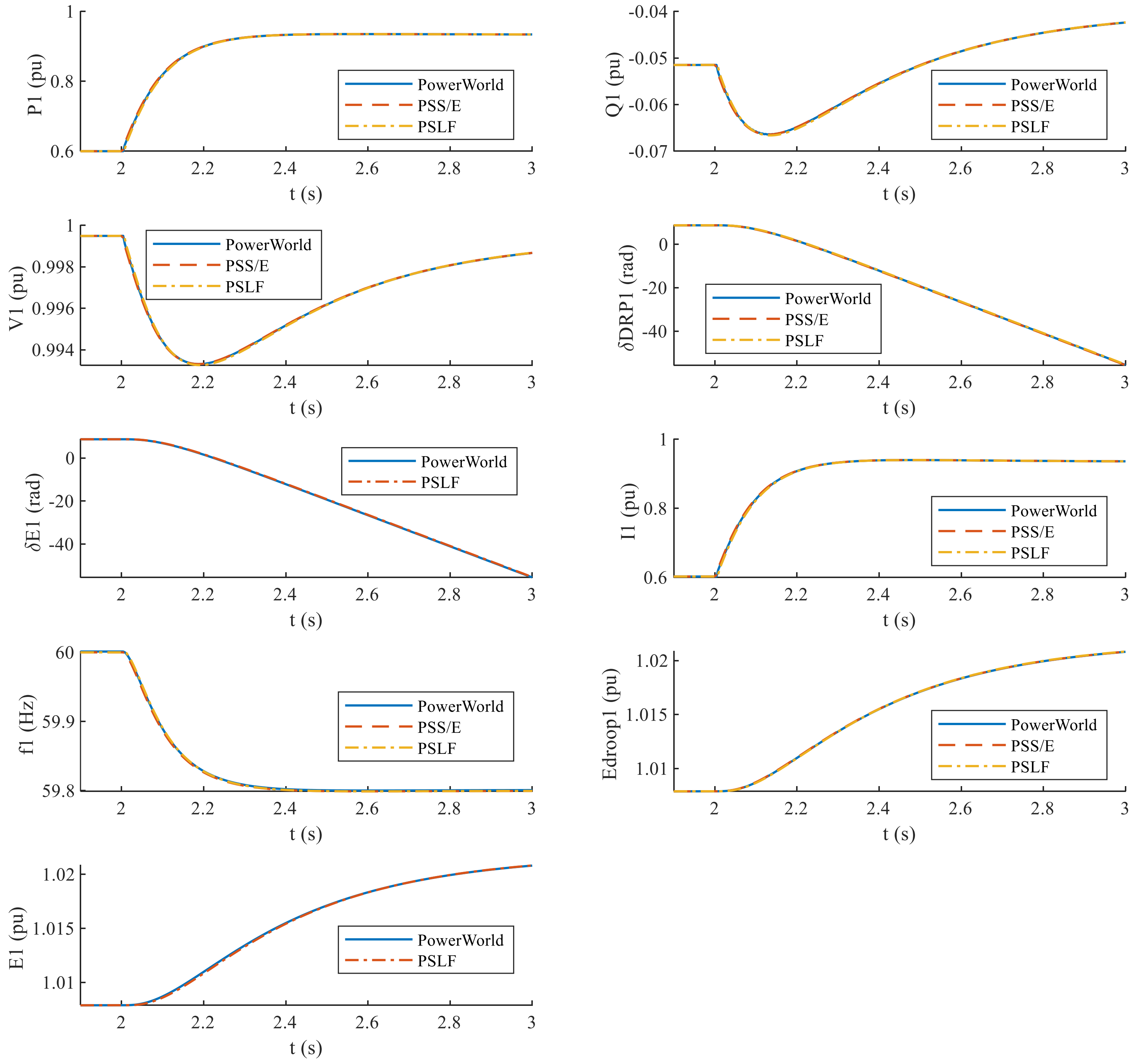




Single-GFM-Infinite-Bus System

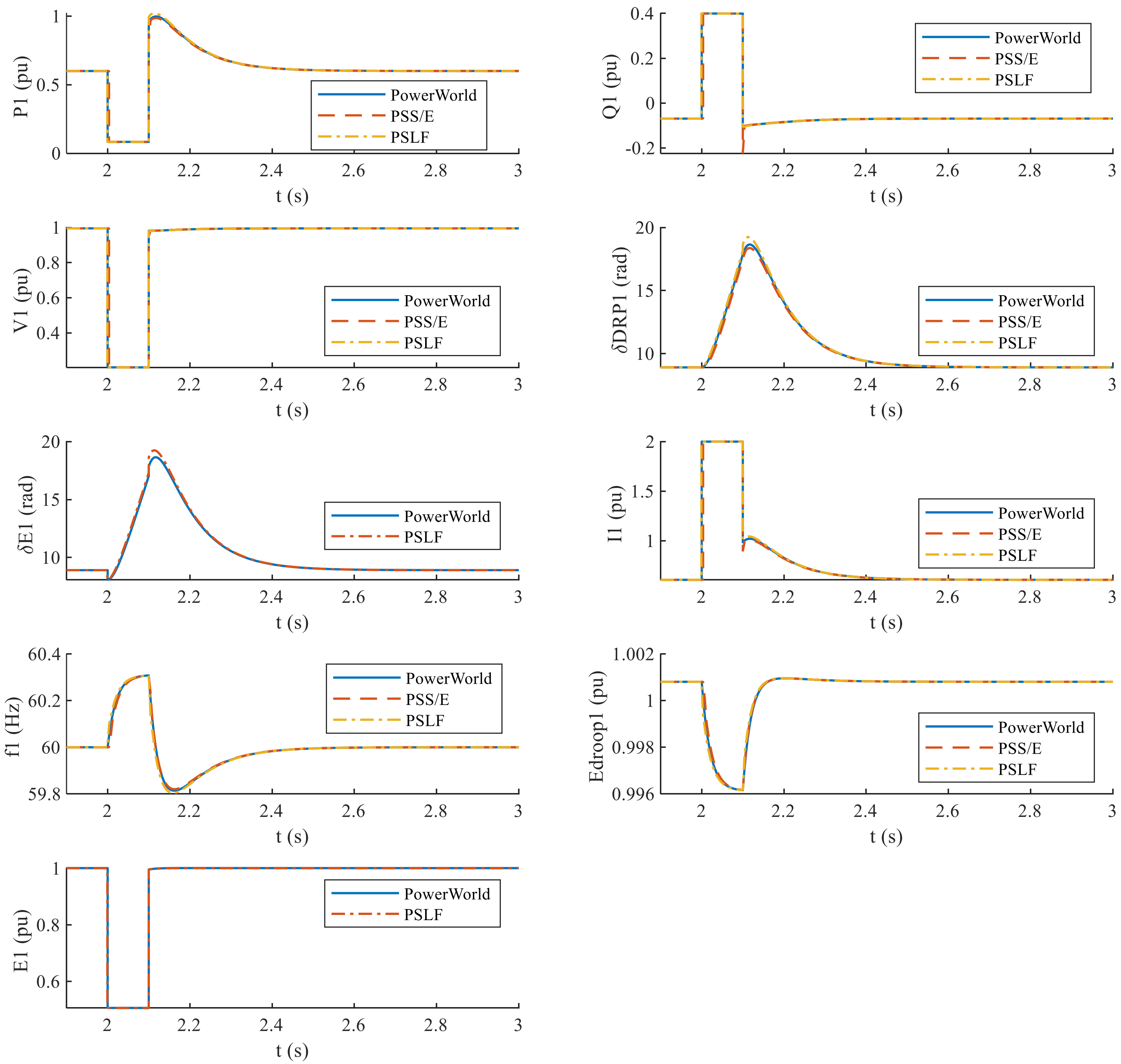
- Frequency step down from 60 Hz to 59.8 Hz
  - VFlag=1

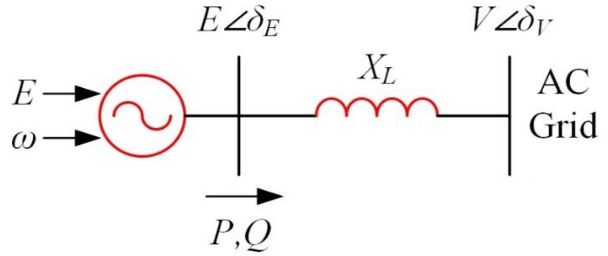




Single-GFM-Infinite-Bus System

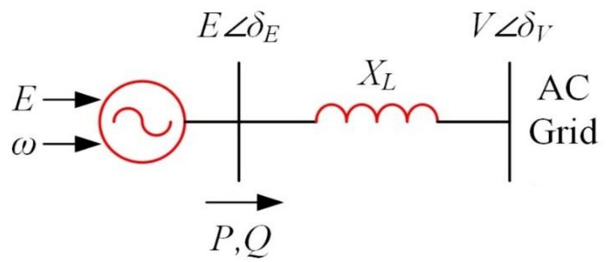
- 0.1 s Short-Circuit Fault
  - VFlag=0

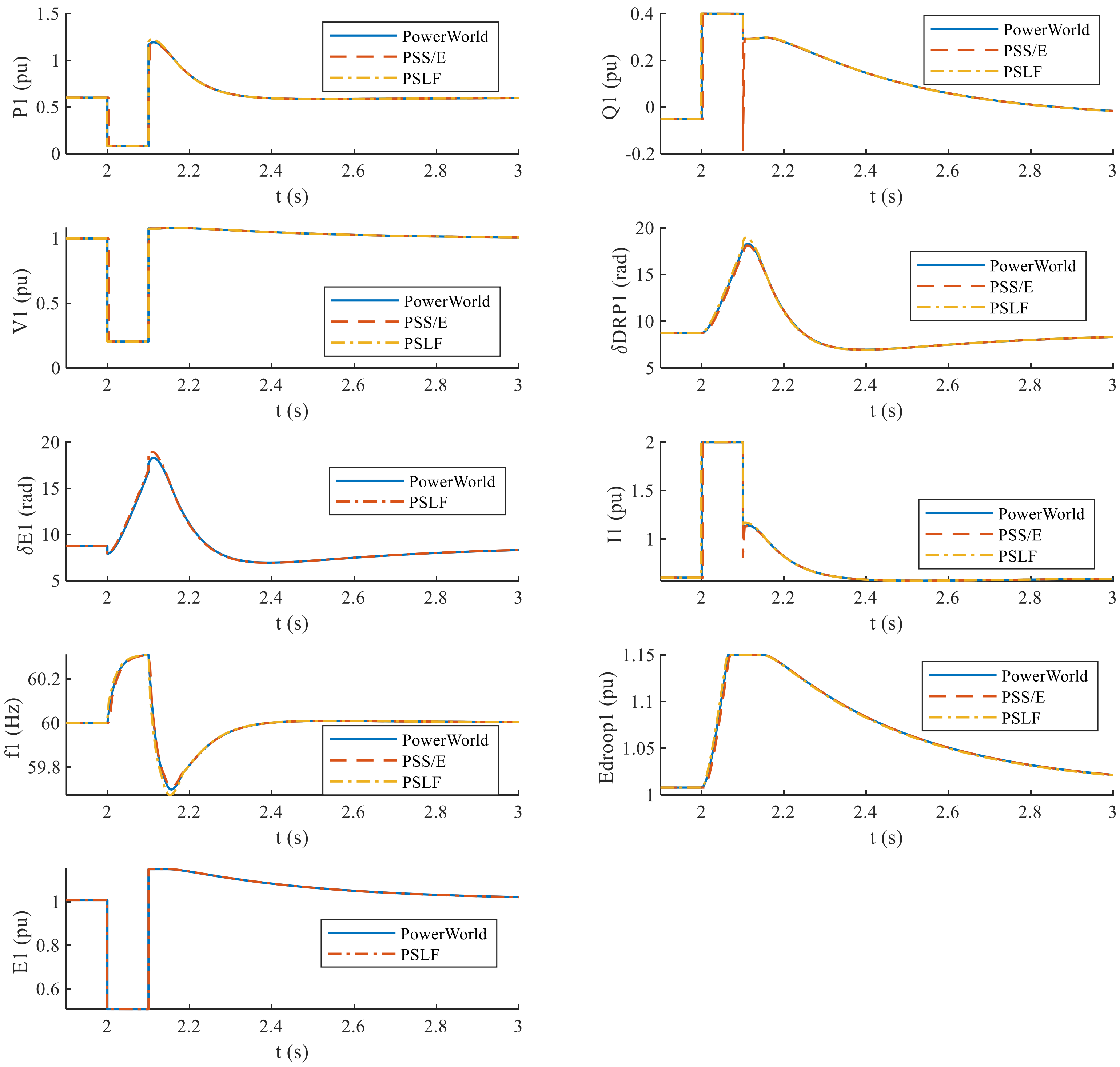




Single-GFM-Infinite-Bus System

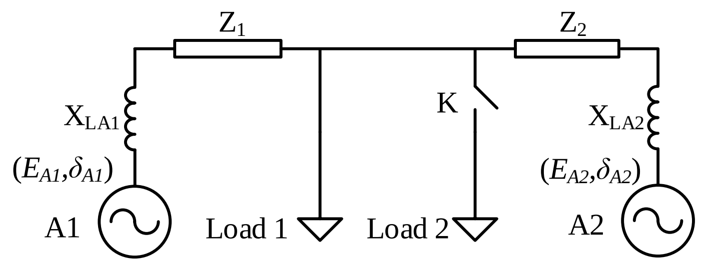
- 0.1 s Short-Circuit Fault
  - VFlag=1



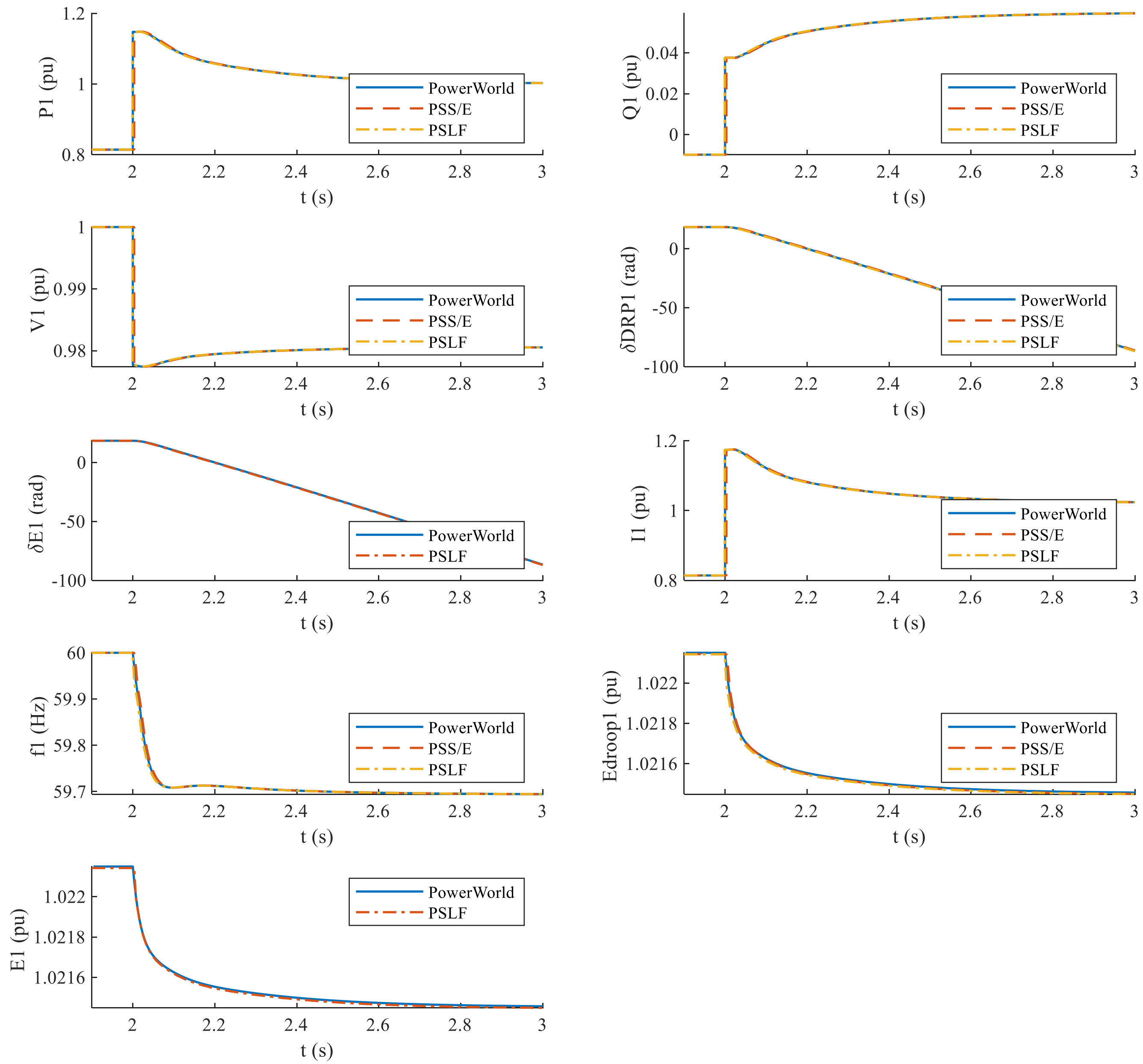


Two-GFM Islanded System

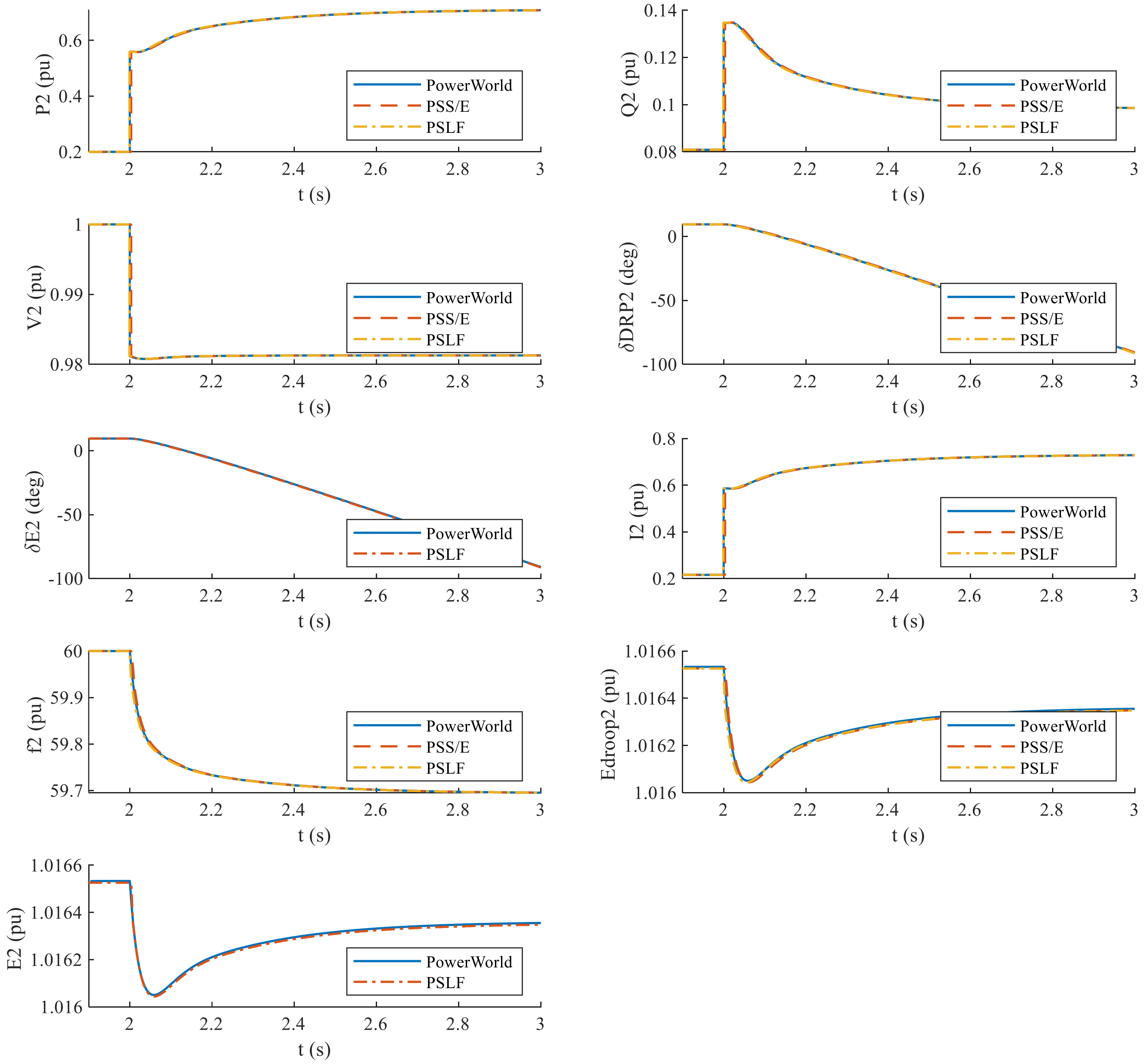
- Step Increase in Load
  - VFlag=0



A Two-GFM Islanded System



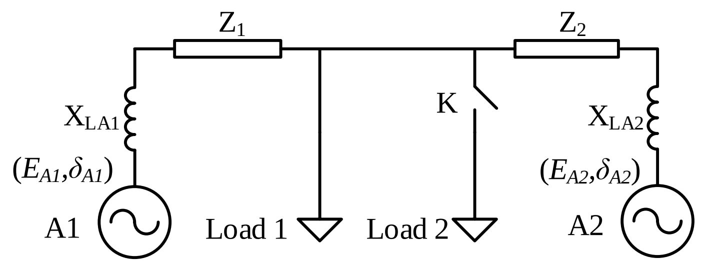
Response of GFM1



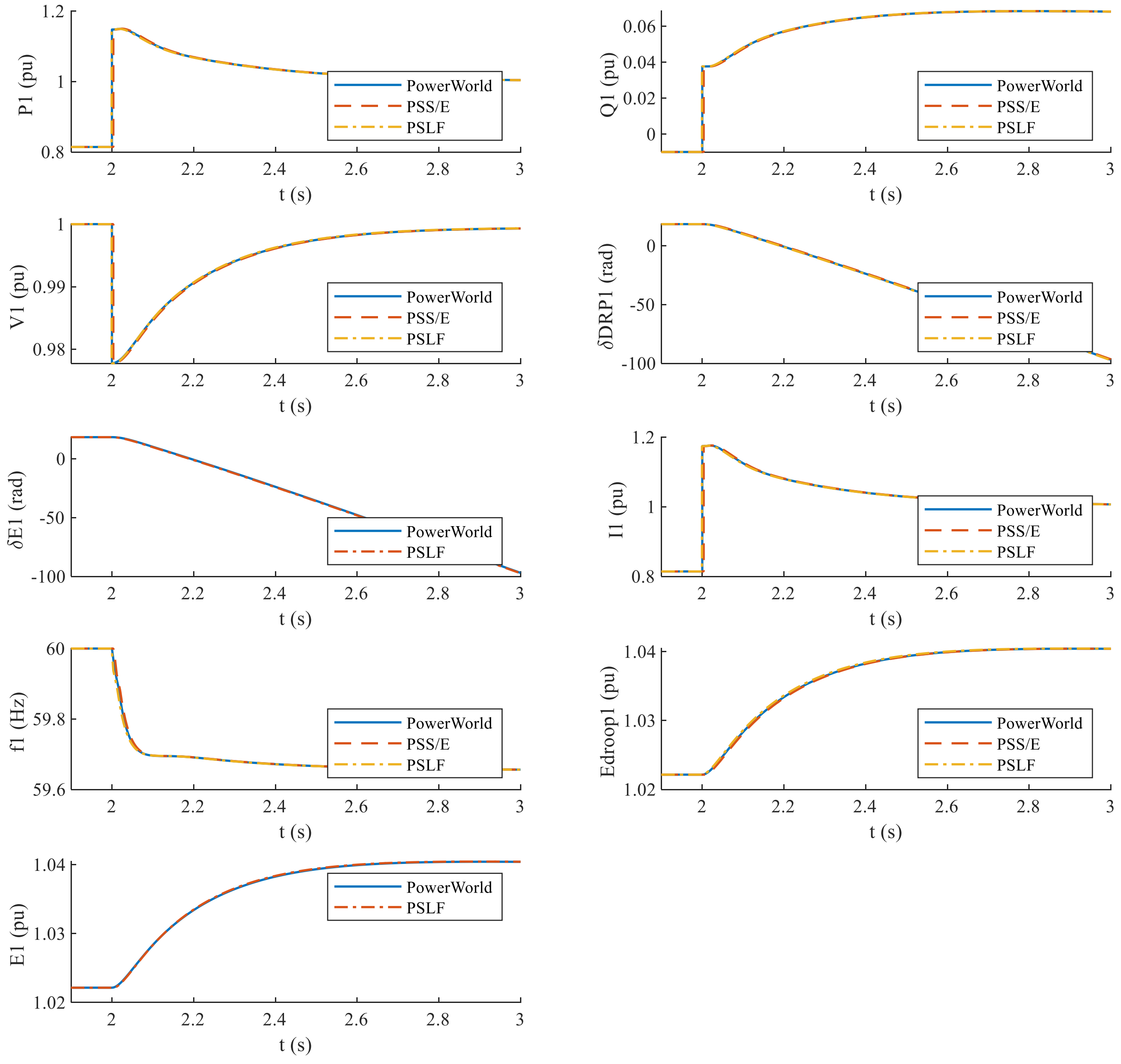
Response of GFM2

Two-GFM Islanded System

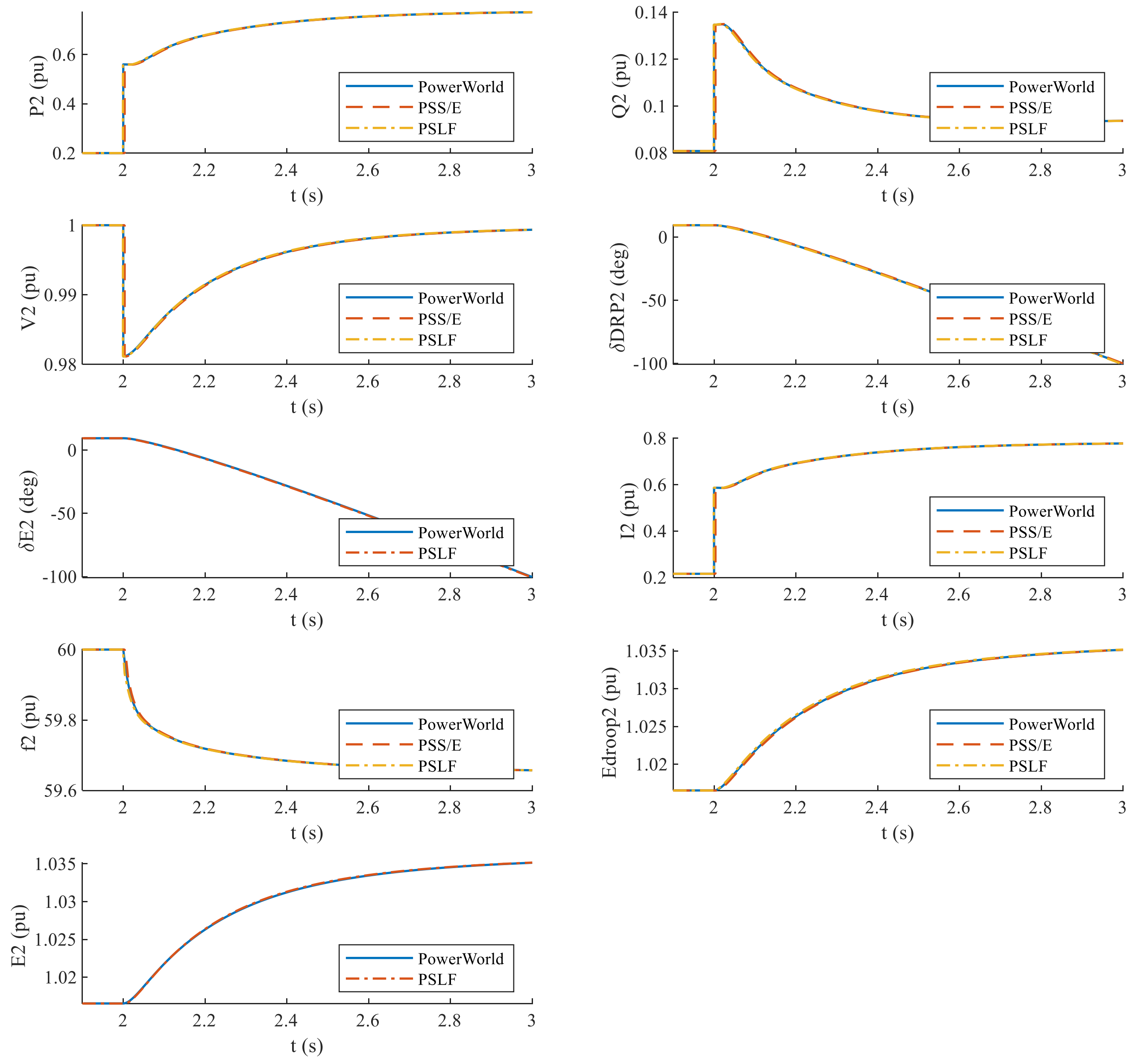
- Step Increase in Load
  - VFlag=1



A Two-GFM Islanded System



Response of GFM1



Response of GFM2