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Using Grid-Forming Inverters to Improve Transient Stability of Dynamic Distribution Systems

Wei Du
Senior Research Engineer
Electricity & Infrastructure Group
Pacific Northwest National Laboratory
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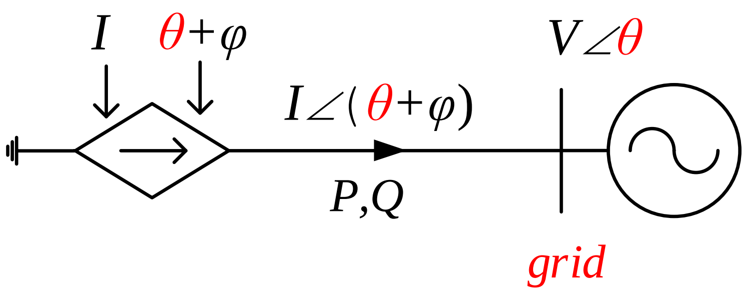
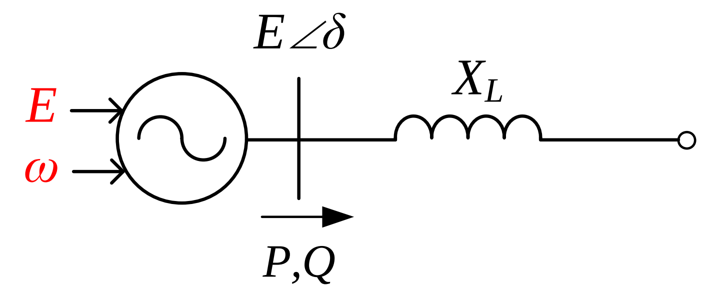
OUTLINE

- Grid-Forming Inverter & Grid-Following Inverter
- Inverter Modeling Work at PNNL & Model Validation against CERTS/AEP Microgrid Field Test Results
- Transient Stability Study of Large-Scale Distribution Systems with High Penetration of PV Grid-Forming Inverters

Inverter Control

Grid-Following vs. Grid-Forming





Grid-Following (Current Source)

+ Current Control (PLL+ Current loop)
+ Control P & Q

- Do not control voltage & frequency
- 'Negative Load' to Power System
- Reduce System Inertia

Most grid-connected sources (PV, fuel cells) use grid-following control

Grid-Forming (Voltage Source)

+ Voltage & Frequency Control
+ Autonomous Load Tracking

- No Direct Control of Current
- Overload Issues

Grid-forming source is crucial for islanded microgrid operation

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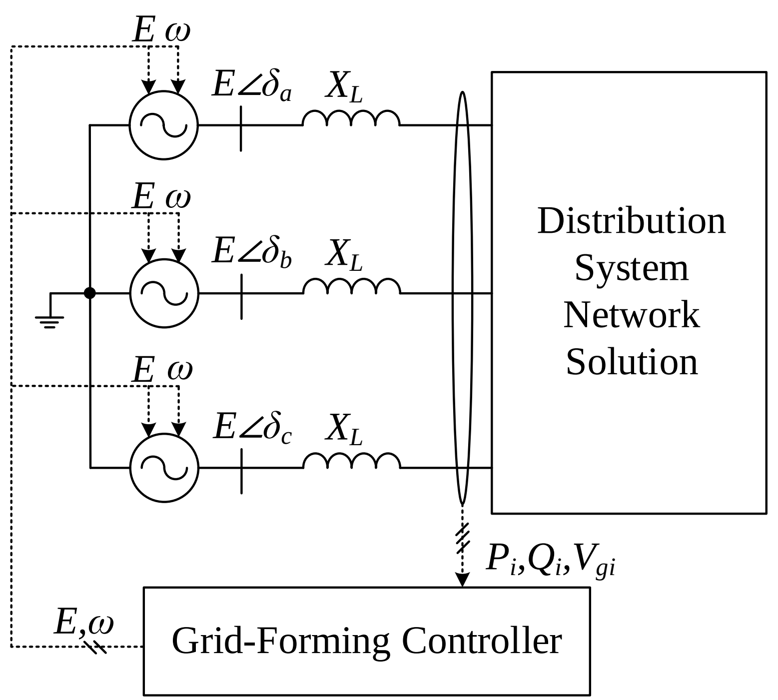
GridLAB-D

How do thousands of grid-forming/grid-following inverters impact the transient stability of large-scale distribution systems?

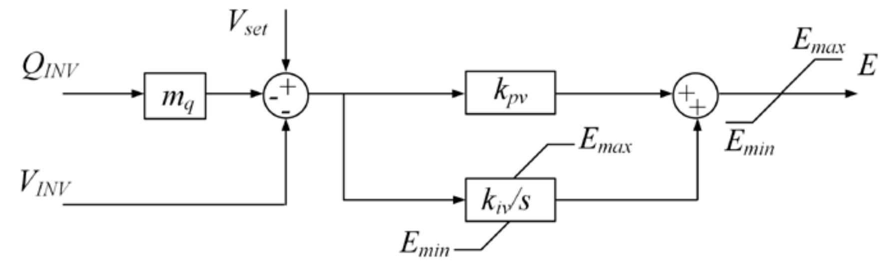
- **Challenges in simulation**: Neither the electromagnetic simulation nor the positive sequence-based transient stability simulation works for large-scale, three-phase, unbalanced distribution systems simulation
- **Solutions**: PNNL developed an open-source software—**GridLAB-D**, which can conduct three-phased transient stability simulations for distribution systems. Dynamic models include:
  - Synchronous generators
  - Motors
  - Grid-Forming/Grid-Following inverters
  - …

Modeling of Grid-Forming Inverters in GridLAB-D

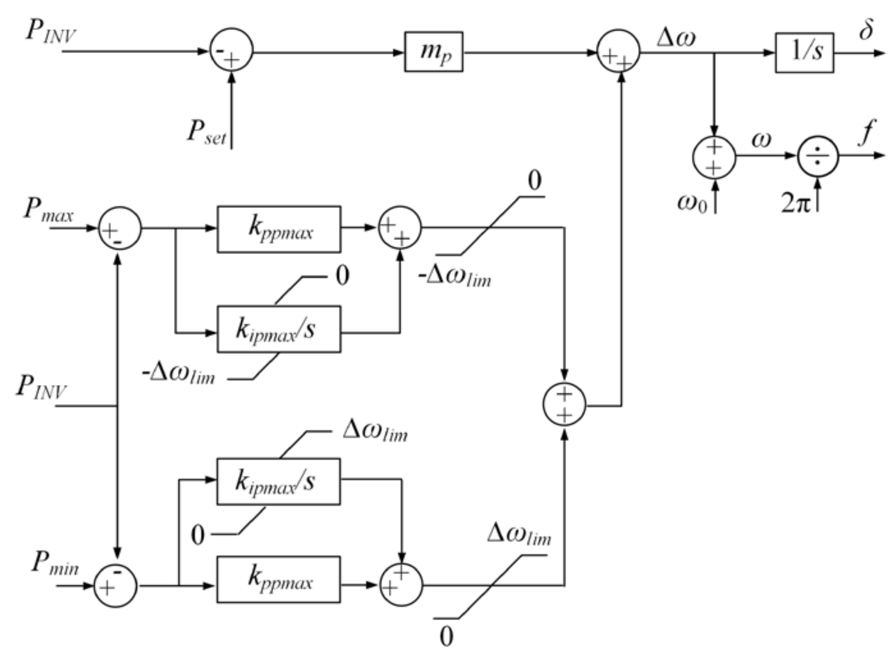
- **Grid-Forming Inverter:** Three-phase balanced voltage source behind X_L & Controller
- **Network Solution**: Extension of Current Injection Method, which allows three-phase power flow calculation



Inverter model and the interface to the distribution system



Q-V Droop



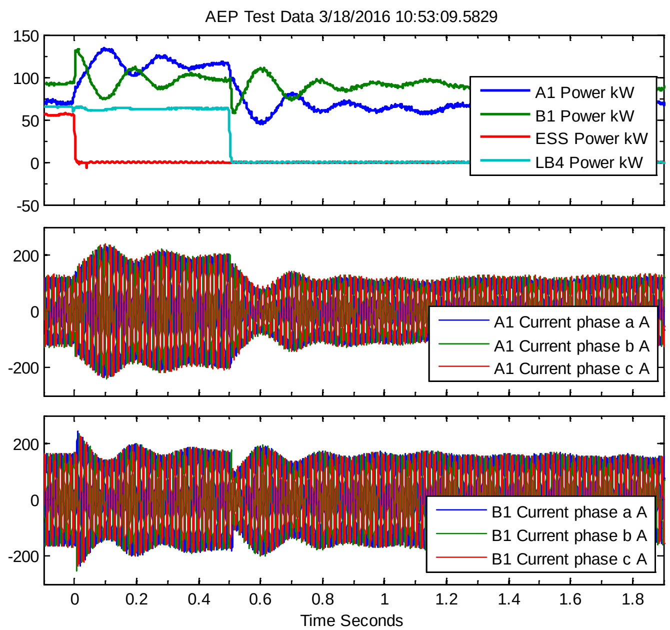
P-f Droop and Overload Mitigation

GridLAB-D

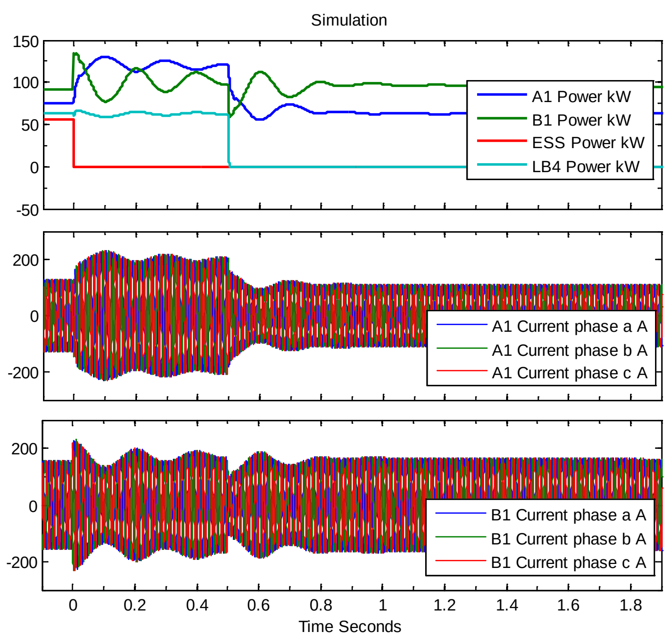
CERTS CONSORTIUM for ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

Validation against CERTS/AEP Microgrid Test Results

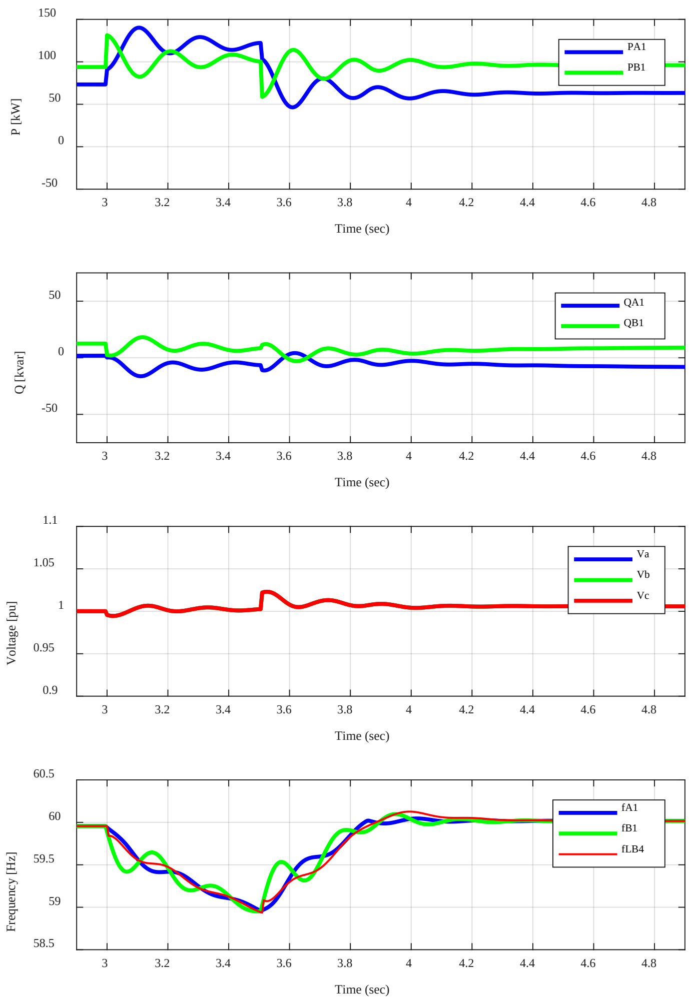
Under-Frequency Load Shedding: Generator vs. Inverter

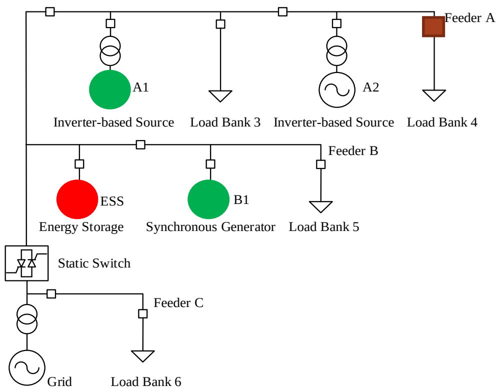


Field Test Results



PSCAD Simulation, Time Step = 50 μs





CERTS/AEP Microgrid

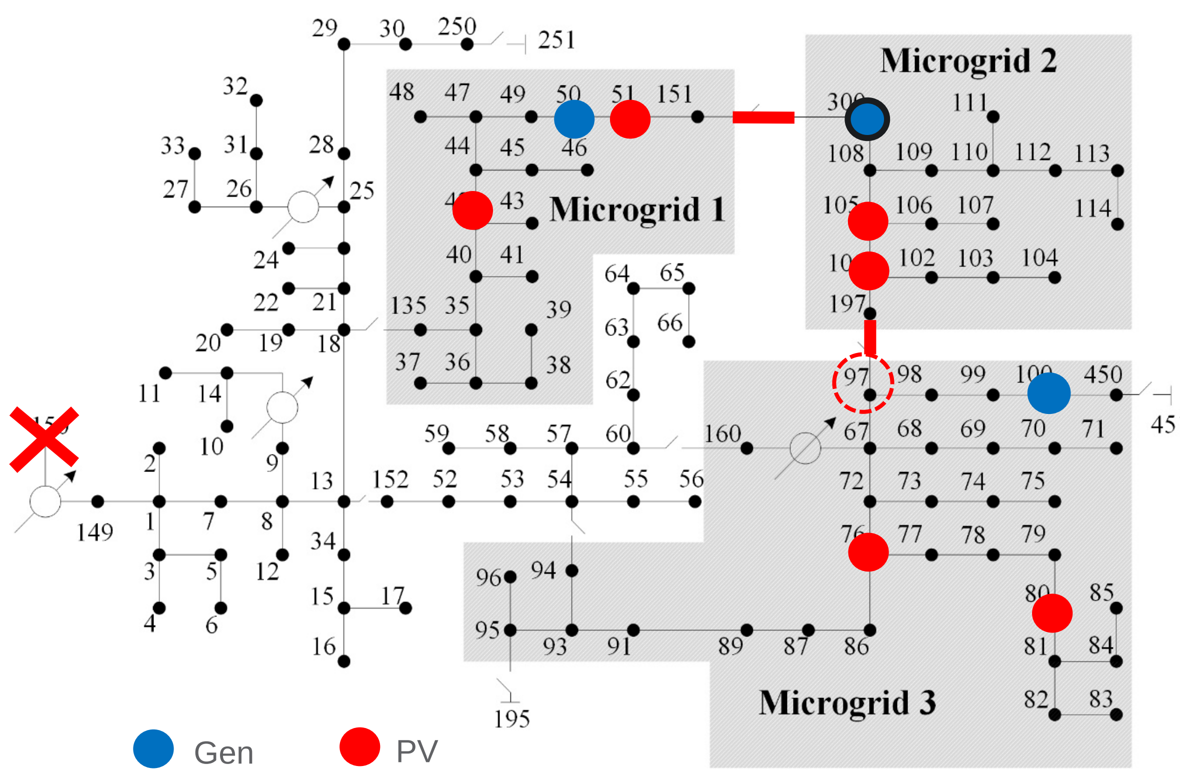
Time Step = 5 ms

- In most microgrids, load shedding is achieved through fast communication. The CERTS microgrid can do under-frequency load shedding.
- By ignoring electromagnetic transients, GridLAB-D is able to conduct transient analysis of large-scale, three-phase, unbalanced distribution systems

Simulation on a Modified IEEE 123-Node Test Feeder

- Substation voltage is lost due to extreme weather events, three microgrids work as an islanded networked microgrid
- Contingency: Loss of Generator 3

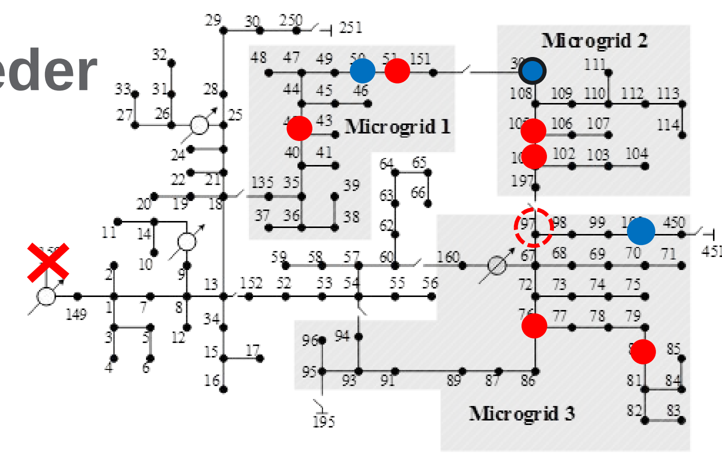
- Synchronous Generators: 3*600 kW
- 6 Distributed PV Inverters: 1400 kW
- Peak Load: 2150 kW + 490 kvar
- PV Penetration: 65% (compared to peak load)



An Islanded IEEE 123-Node Test Feeder with High Penetration of PVs

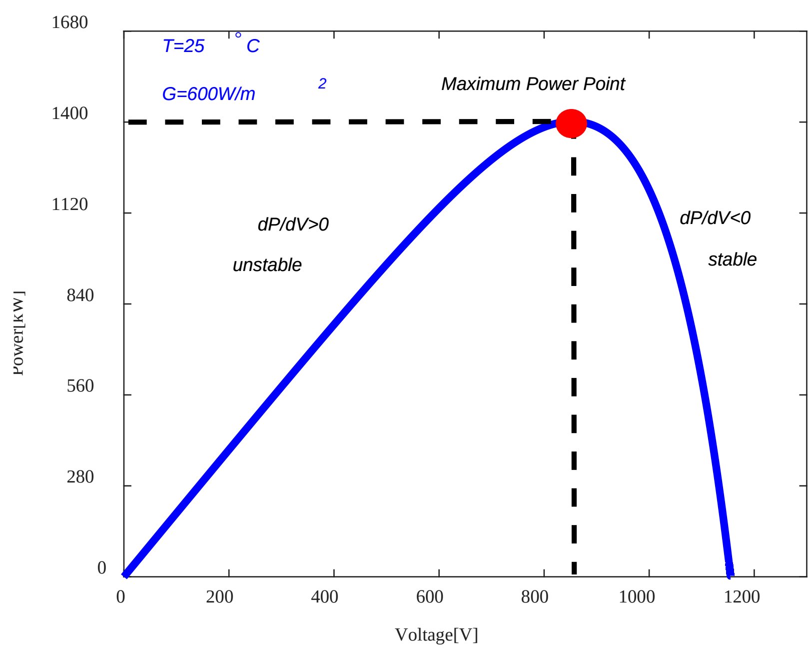
GridLAB-D

Simulation on a Modified IEEE 123-Node Test Feeder

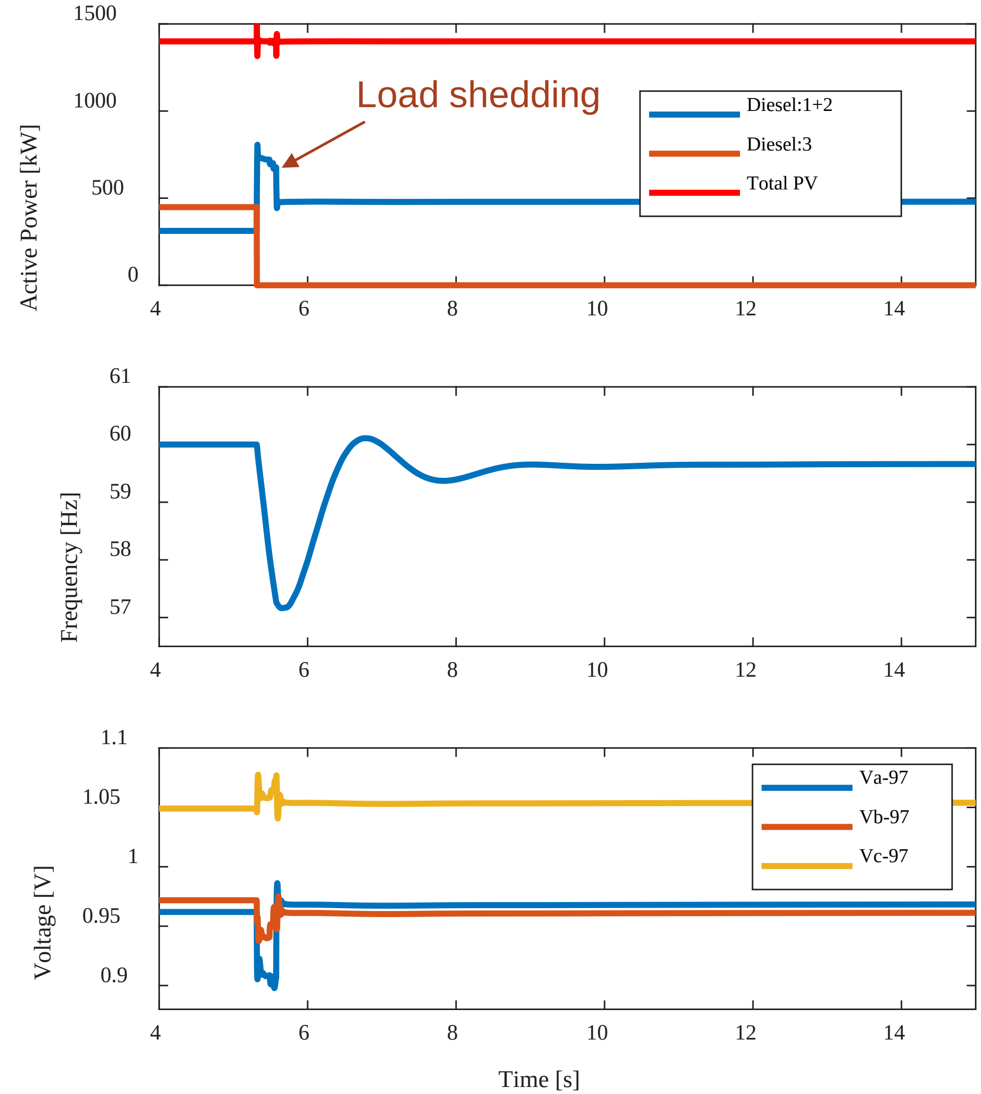


- PV operates at Maximum Power Point
- Contingency: Loss of Generator 3
- Frequency drops fast due to the low inertia, 12% Loads are tripped

PV: Grid-Following controlled at MPP



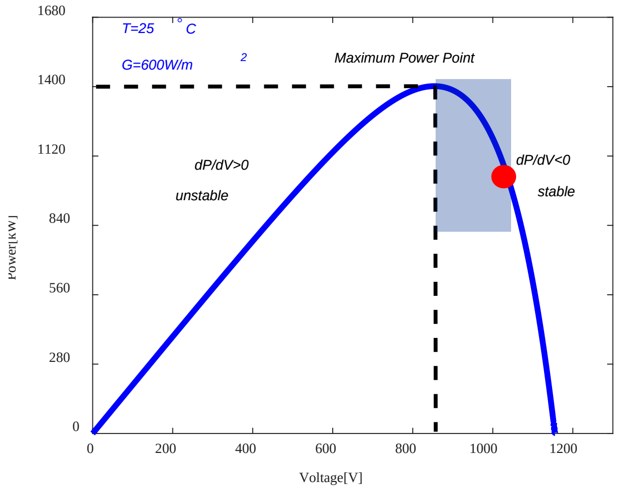
GridLAB-D Simulation



GridLAB-D

Simulation on a Modified IEEE 123-Node Test Feeder

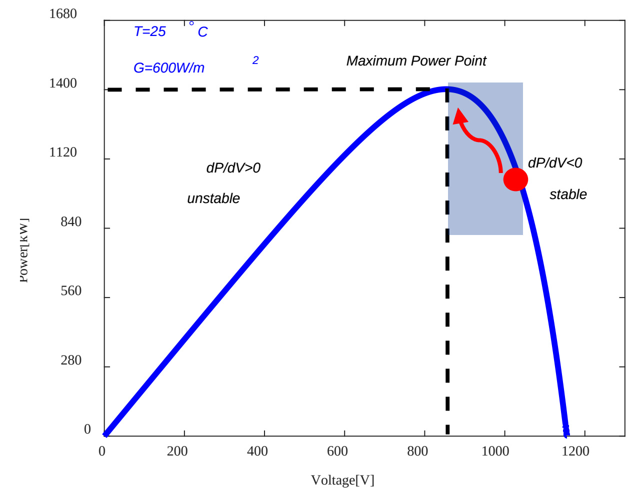
- As the penetration of PVs continues increasing, dynamic reserve of PVs has the potential to improve the transient stability
- How do we use this reserve?



33% Reserve

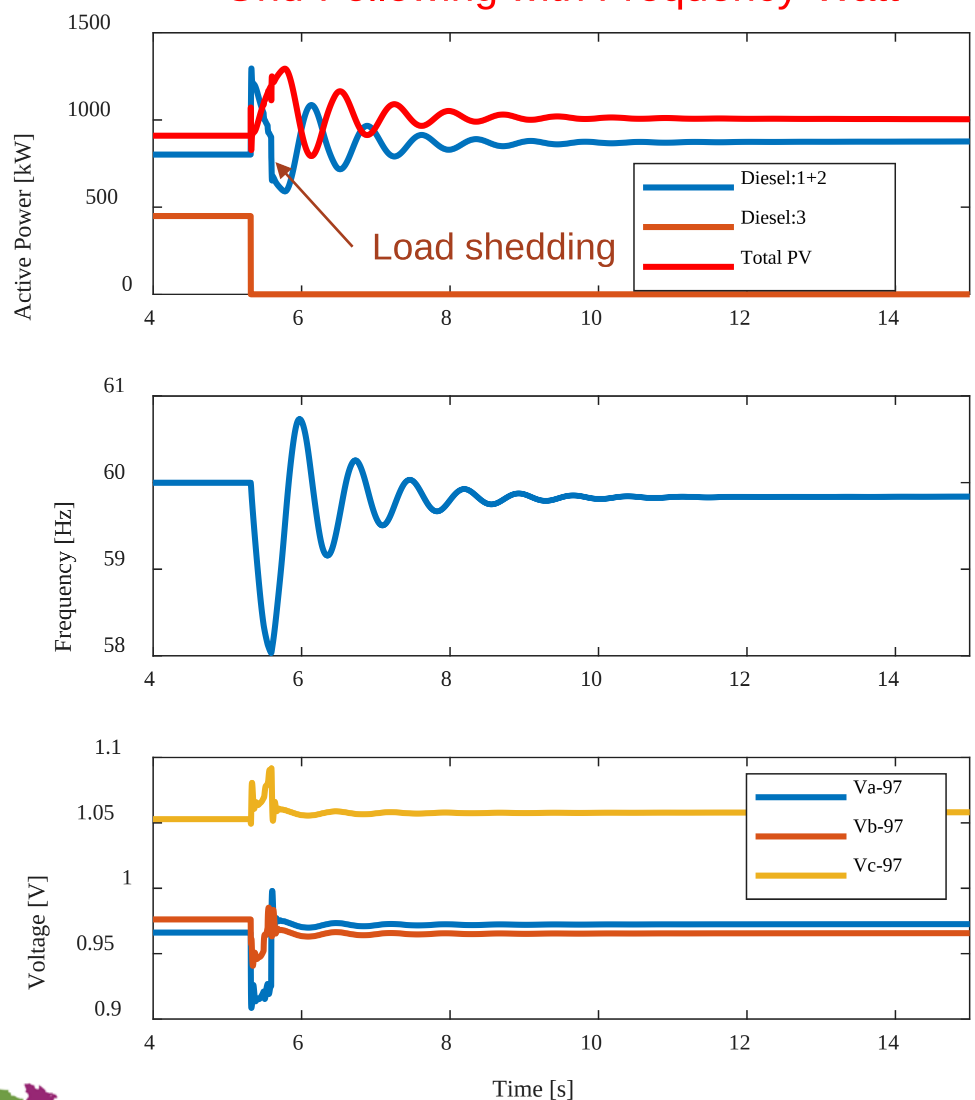
Simulation on a Modified IEEE 123-Node Test Feeder

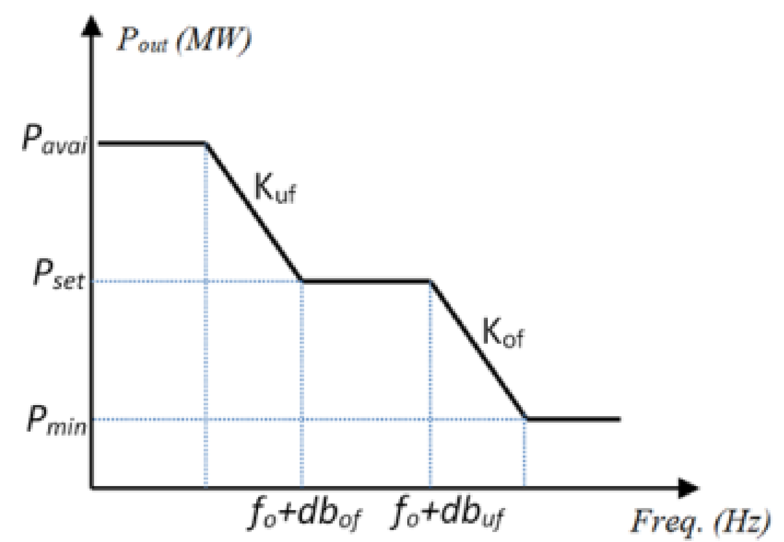
- PV: Grid-Following with Frequency-Watt
- Not only reduces the system inertia, but also results in oscillations between generators and inverters
- Loads are still tripped

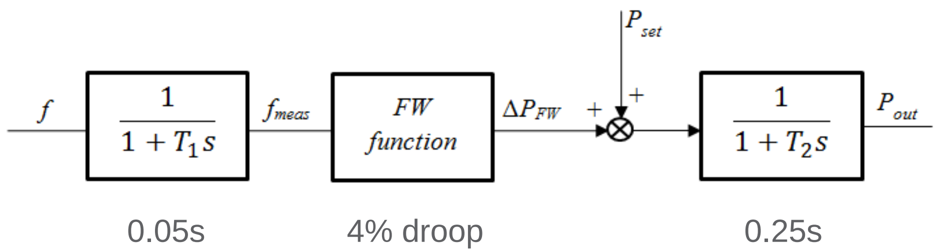


33% Reserve

Grid-Following with Frequency-Watt





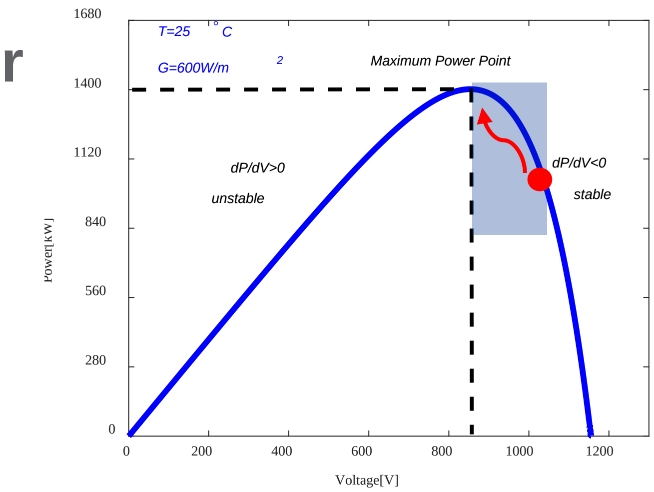


Frequency-Watt Control

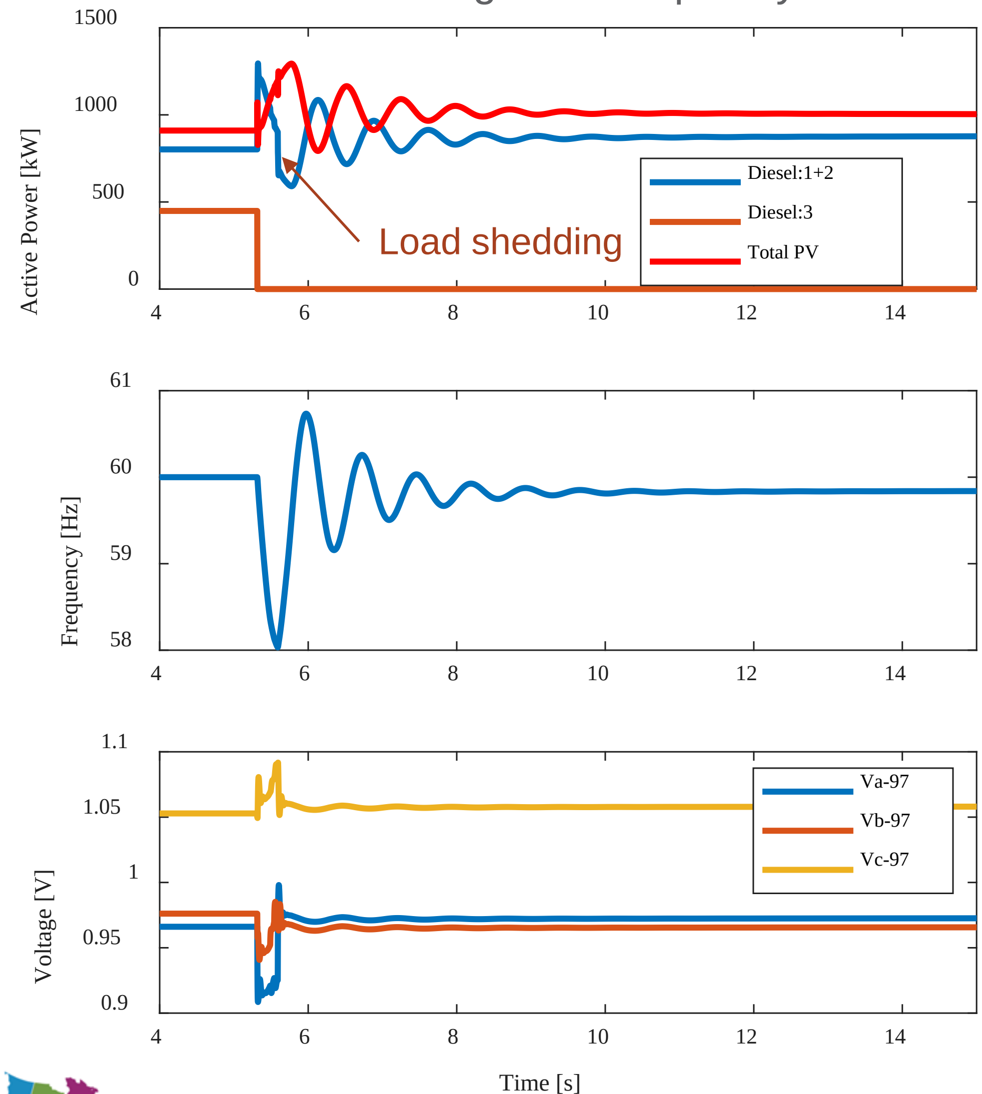
GridLAB-D

Simulation on a Modified IEEE 123-Node Test Feeder

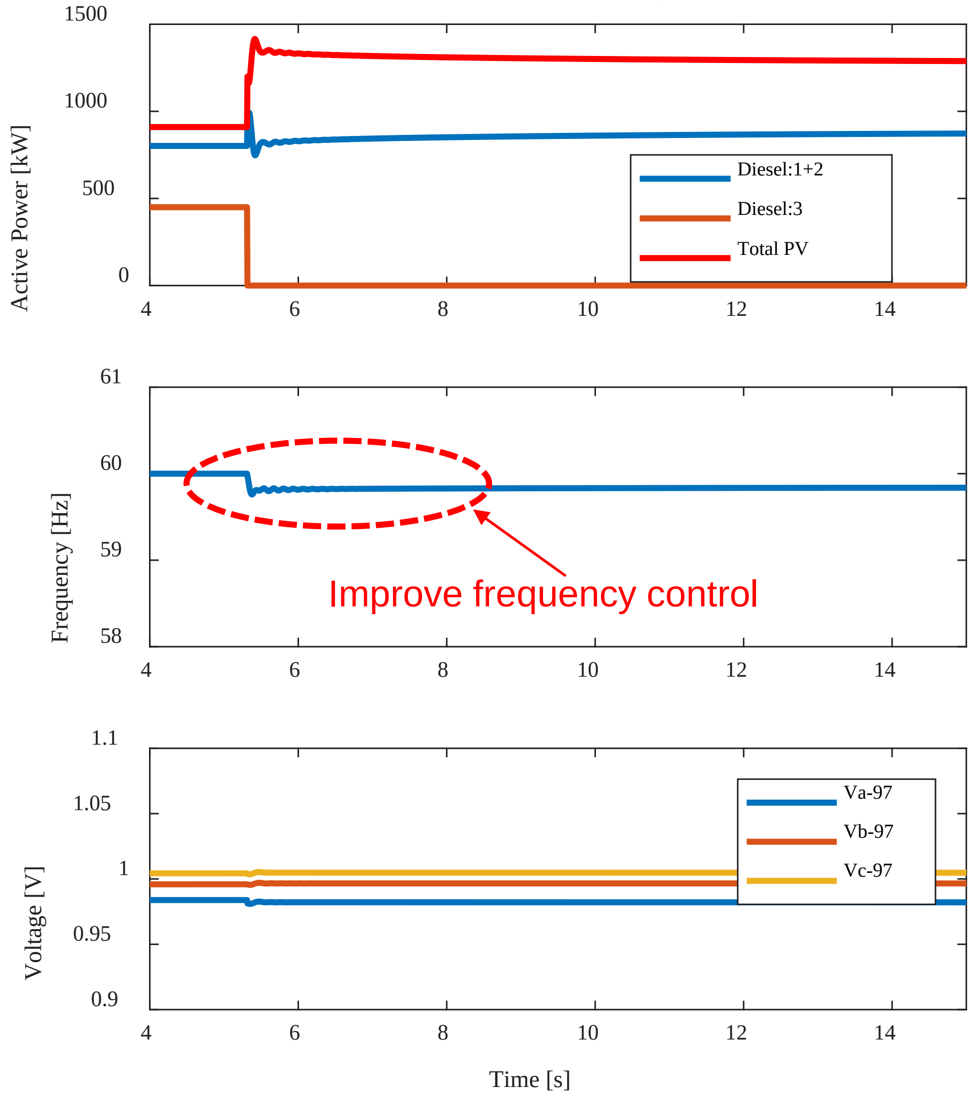
- Grid-Forming PV with dynamic reserve can improve frequency stability, load shedding is avoided
- Grid-forming inverters response to load changes instantaneously



Grid-Following with Frequency-Watt



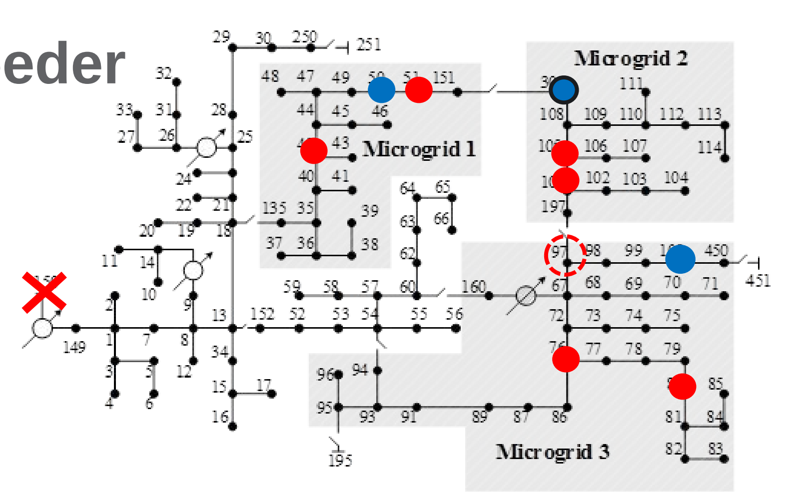
Grid-Forming



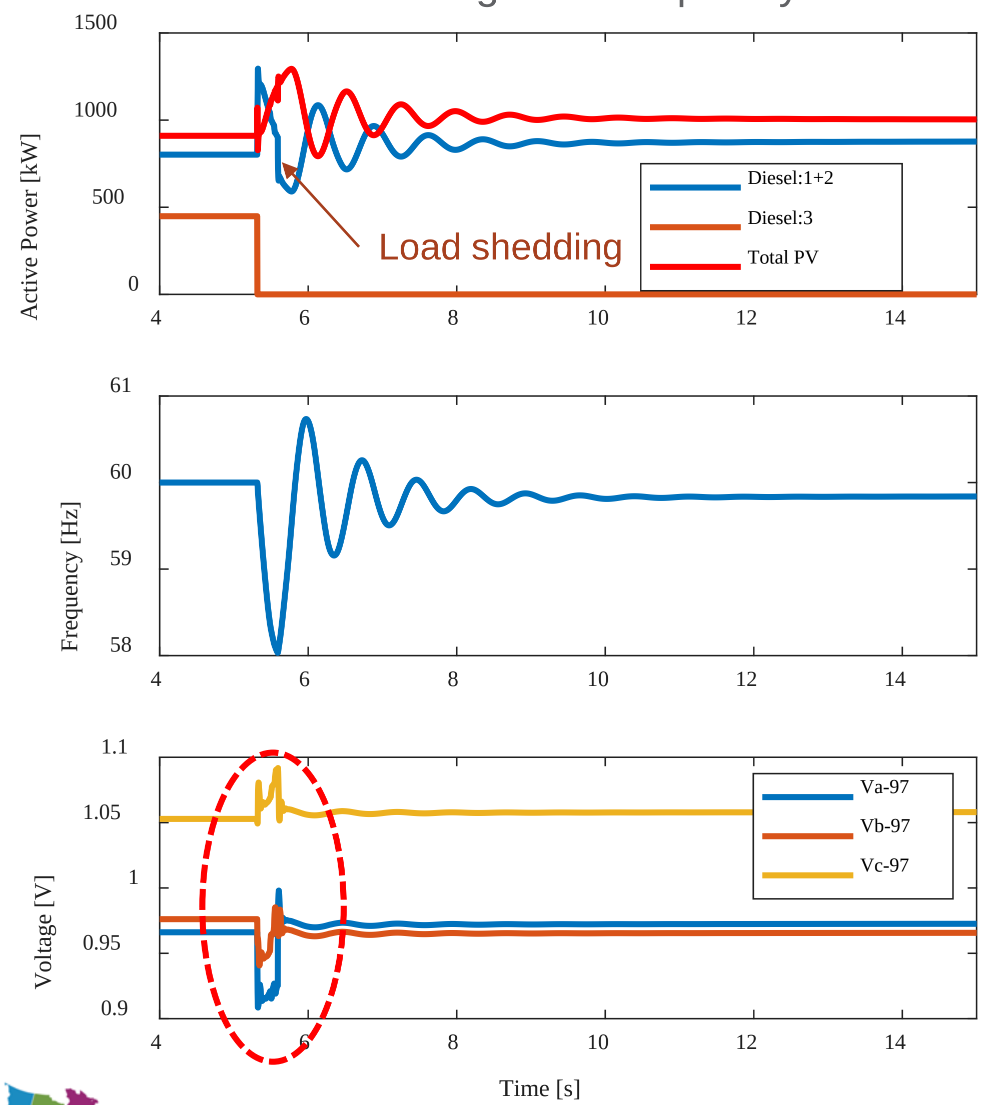
GridLAB-D

Simulation on a Modified IEEE 123-Node Test Feeder

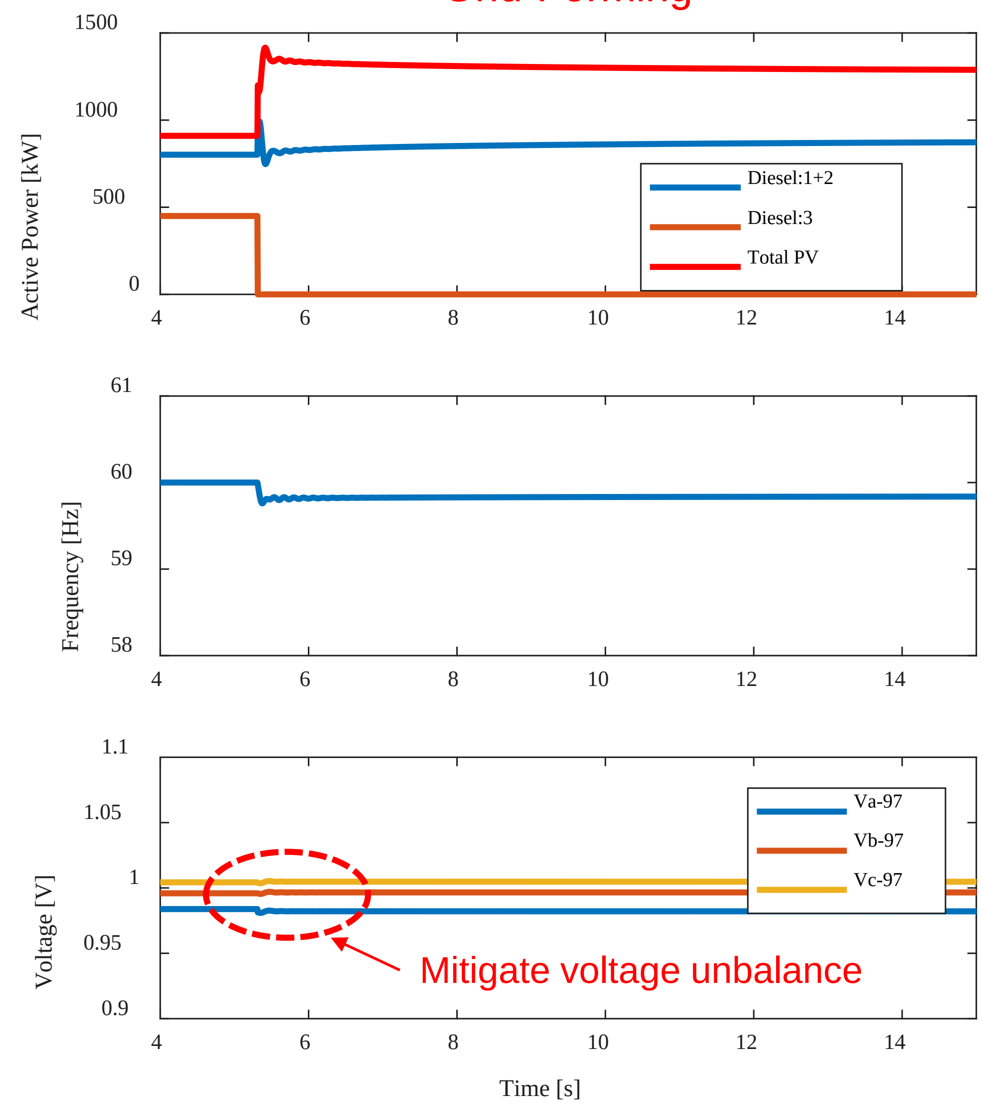
- Grid-Forming inverters can improve voltage control, voltage unbalance is mitigated
- All PV inverters become three-phase, balanced voltage source behind X_L, system is stiffer



Grid-Following with Frequency-Watt



Grid-Forming



GridLAB-D

Conclusion

- A three-phase, electromechanical modelling approach is proposed to model Grid-Forming/Grid-Following inverters for large-scale distribution system study
- The developed Grid-Forming inverter model in GridLAB-D is validated against CERTS Microgrid test results
- PV Grid-Forming inverters with dynamic reserve can improve Frequency & Voltage stability of distribution systems

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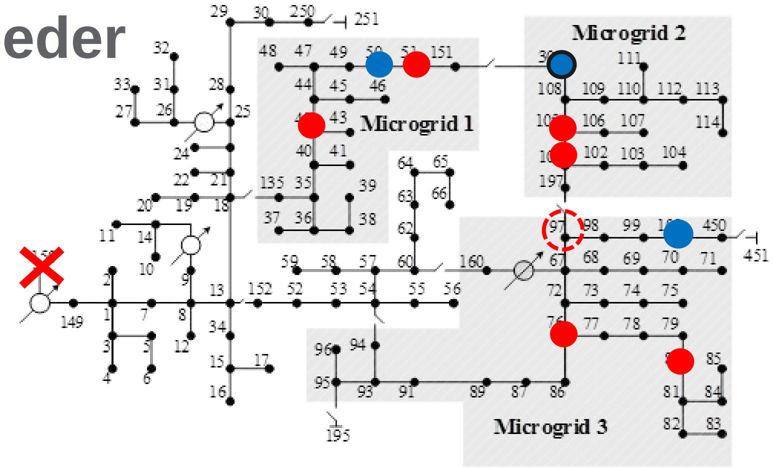
Thank you

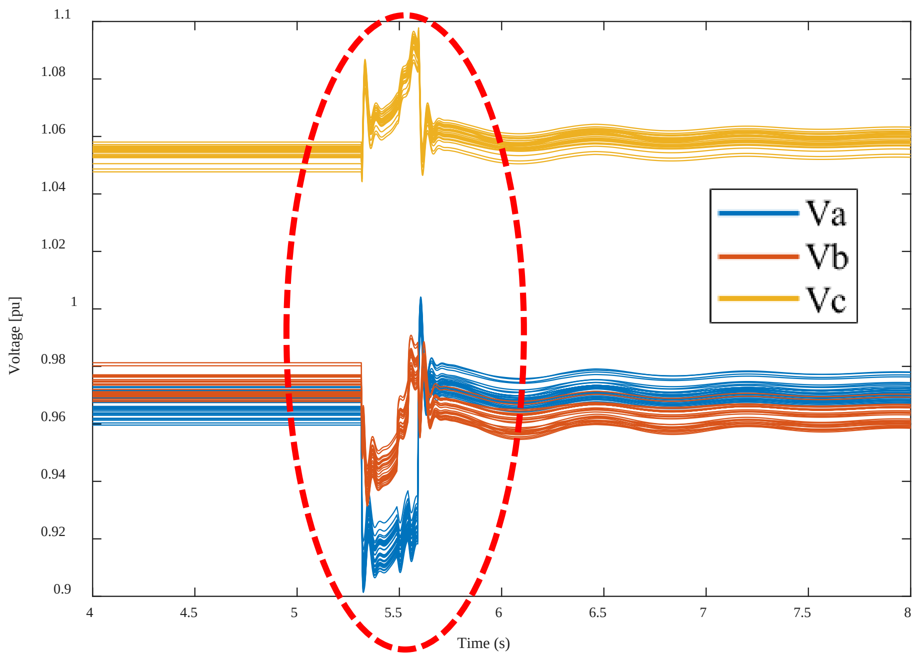
Backup Slides

Simulation on a Modified IEEE 123-Node Test Feeder

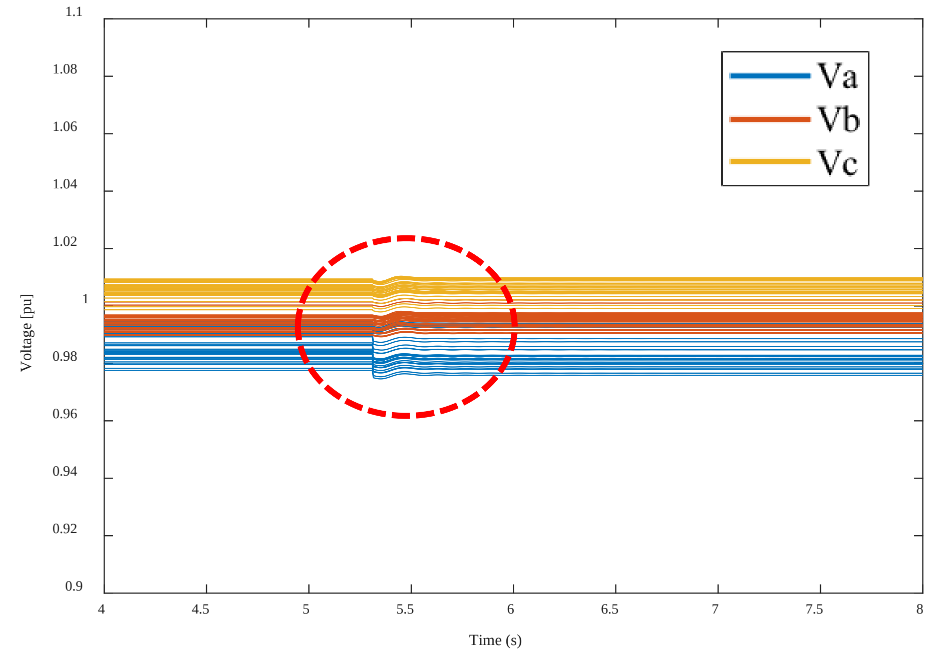


- The voltage profile of the entire distribution feeder is significantly improved
- The three-phase unbalanced characteristic cannot be easily reflected by positive-sequence-based simulation

Grid-Following

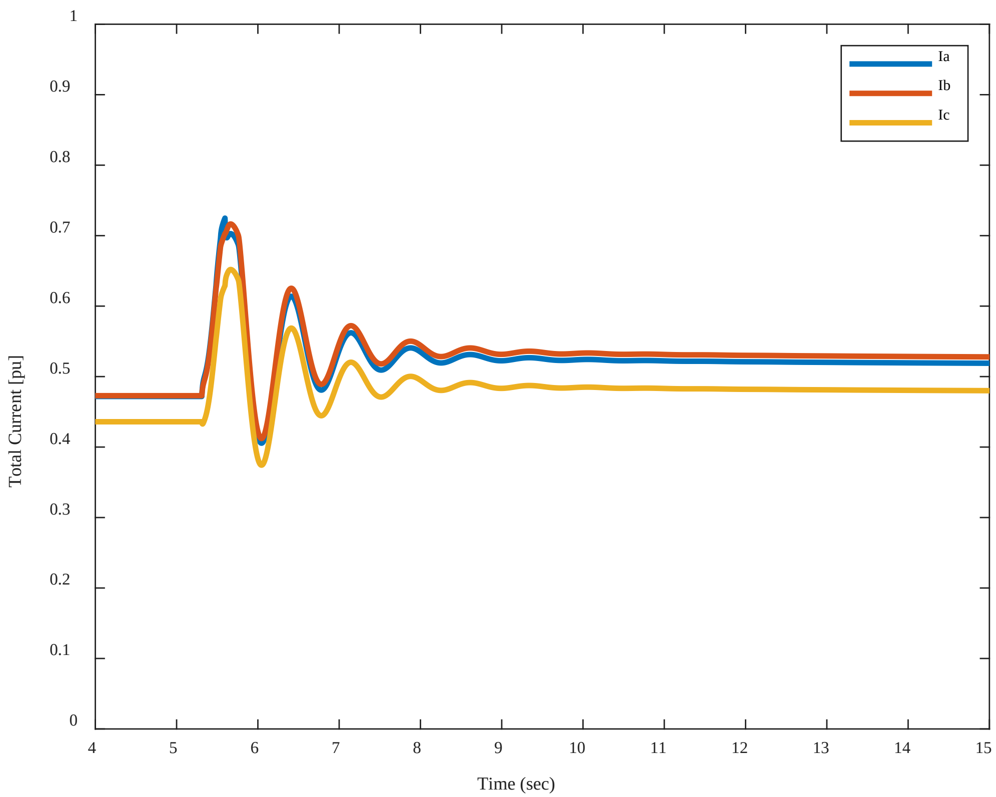


Grid-Forming



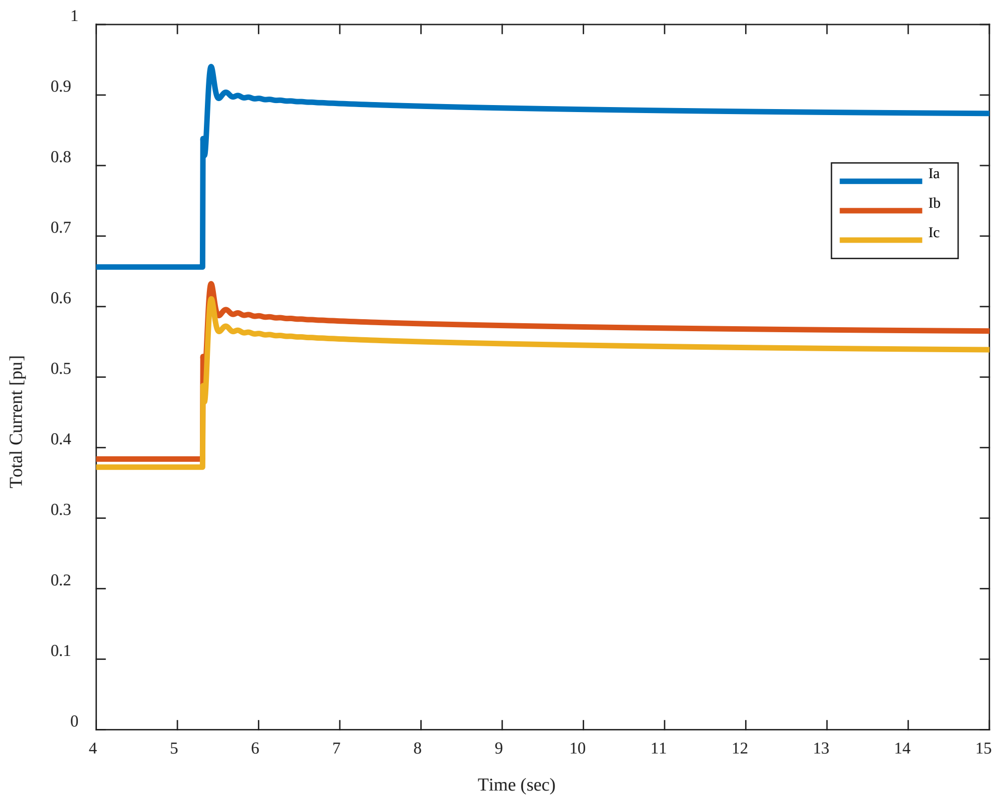
- Grid-Forming inverters provide larger currents than grid-following inverters, because they need to provide reactive power to support the voltage

Grid-Following with Frequency-Watt



Currents

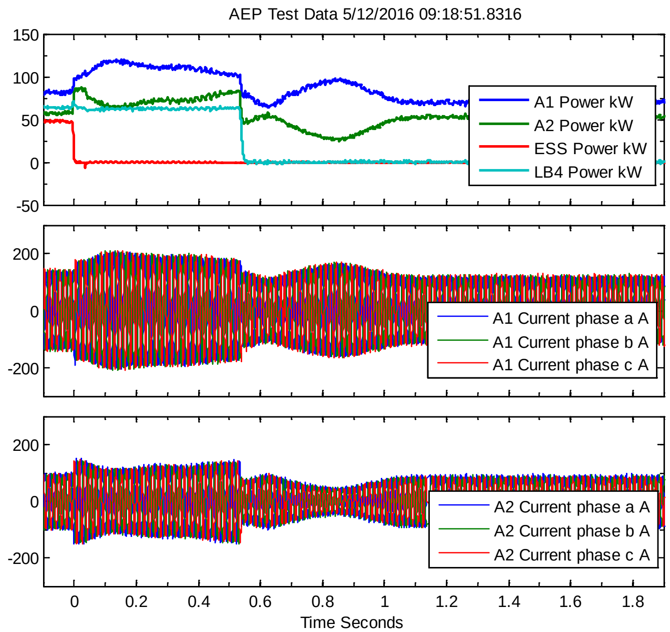
Grid-Forming



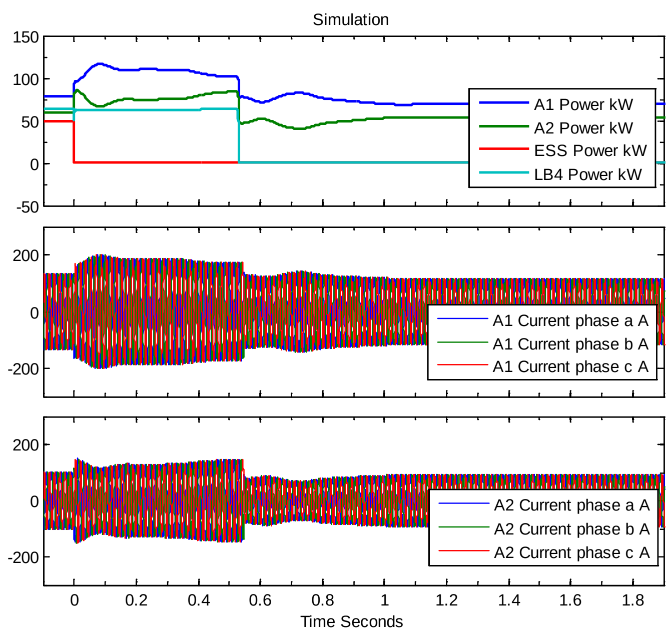
Currents

Validation against CERTS/AEP Microgrid Test Results

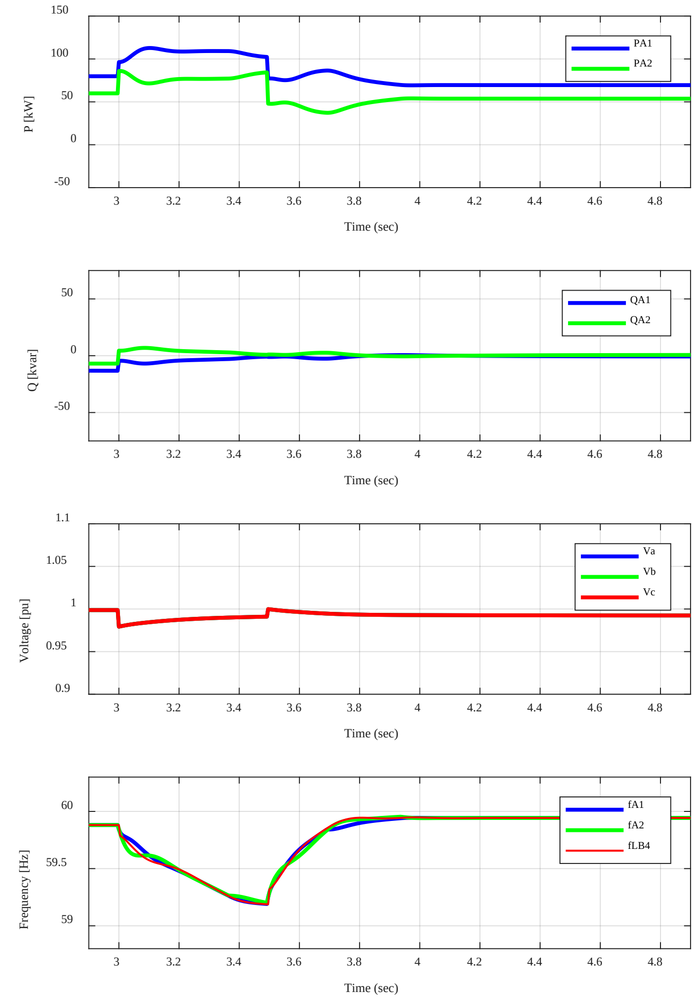
Under-Frequency Load Shedding: Inverter vs. Inverter



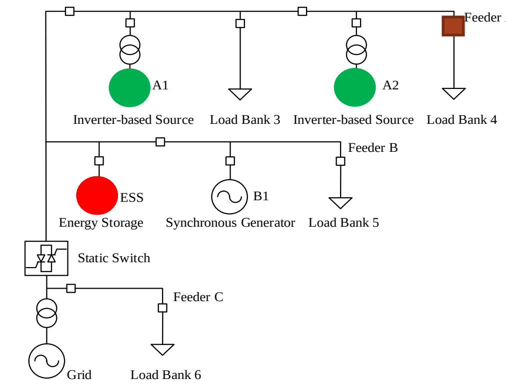
CERTS Field Test Results



PSCAD Simulation, Time Step = 50 μs



GridLAB-D Time Step = 5 ms



CERTS/AEP Microgrid

By ignoring electromagnetic transients, GridLAB-D is able to conduct transient analysis of large-scale, three-phase, unbalanced distribution systems

CERTS Microgrid Laboratory Test Bed

R. H. Lasseter, *Fellow, IEEE*, J. H. Eto, *Member, IEEE*, B. Schenkman, J. Stevens, *Member, IEEE*, H. Vollkommer, *Member, IEEE*, D. Klapp, E. Linton, H. Hurtado, and J. Roy

Tecogen's response to fault

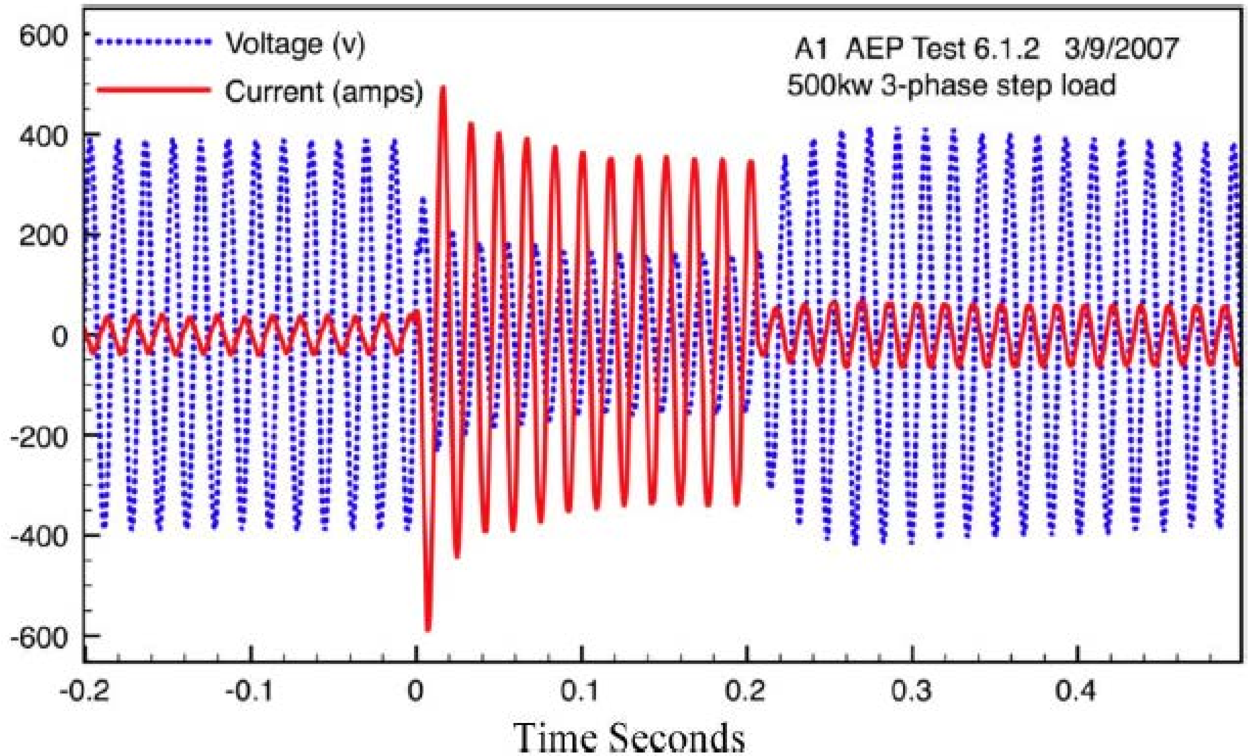
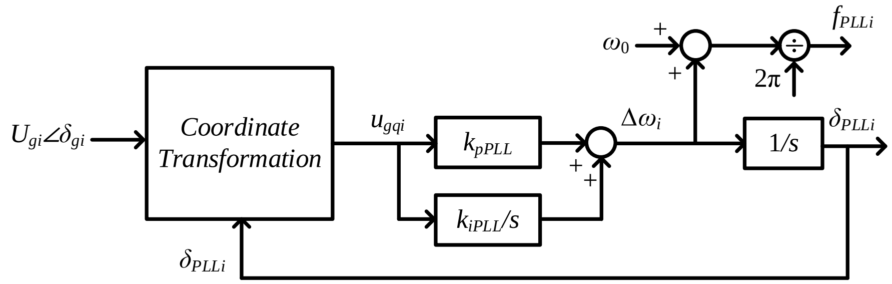
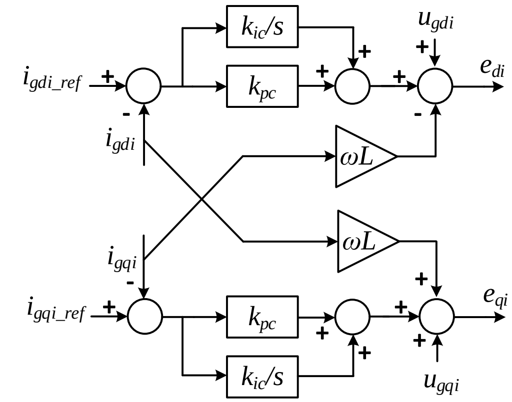


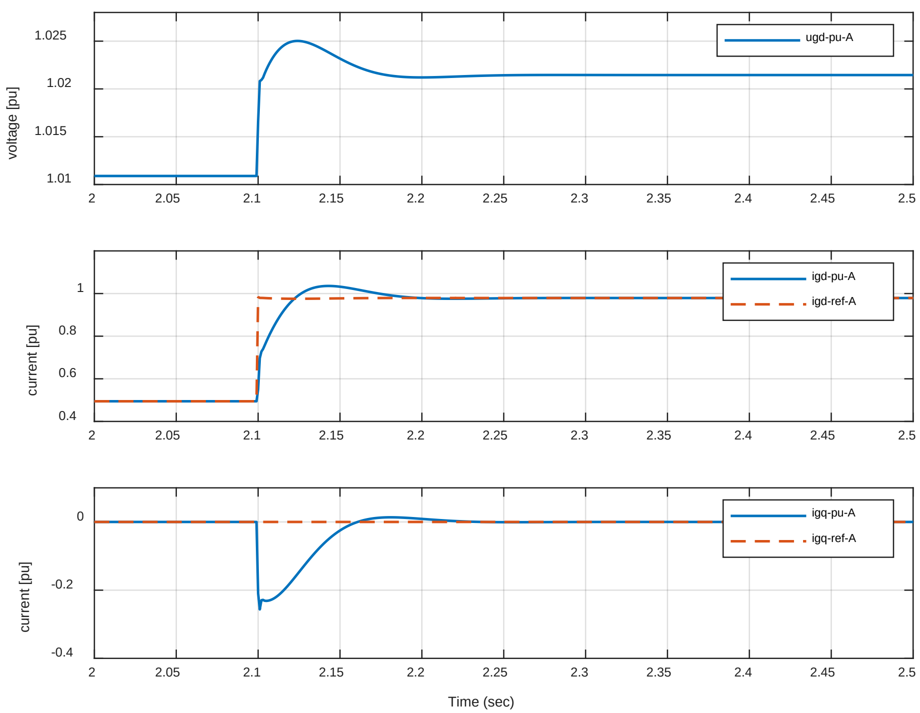
Fig. 9. Response to 500 kW step load.

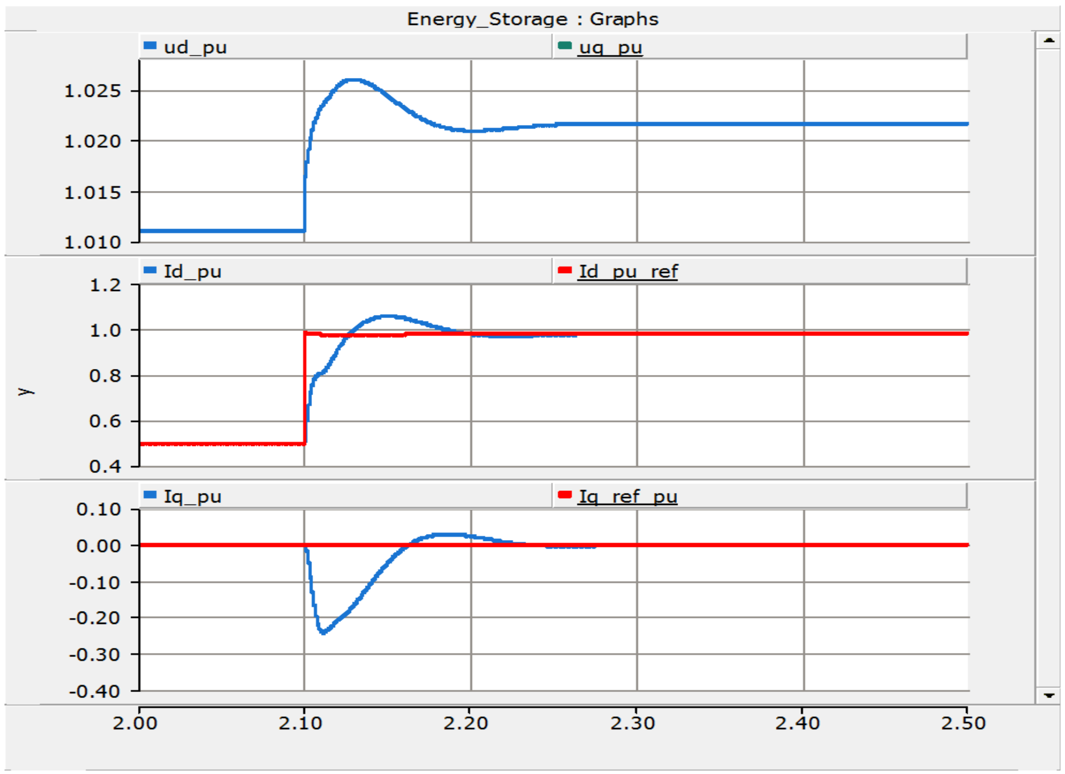
Grid-Following Inverters





P_{ref} changes from 0.5 pu to 1 pu at 2.1 s

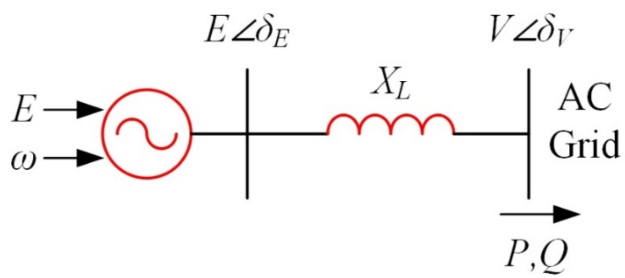




Current Loop PI gains: kp=0.05, ki=5, but with feedforward term F=0.3

Grid-Forming Inverter & Droop Control

- Grid-Forming inverter: voltage source behind a coupling reactance X_L
  - ➢ A well designed X_L is important for controller design: $P \propto \delta$, $Q \propto E$

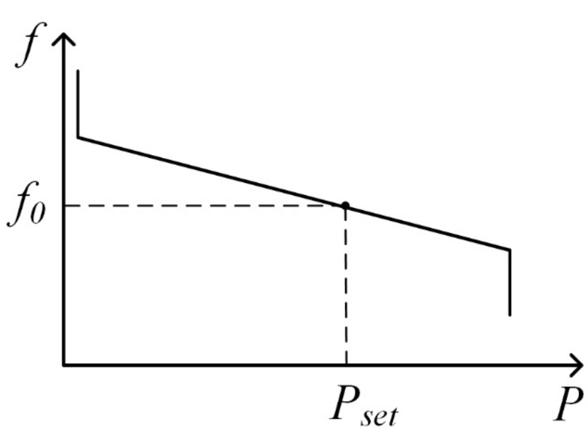


$$\delta_p = \delta_E - \delta_V$$

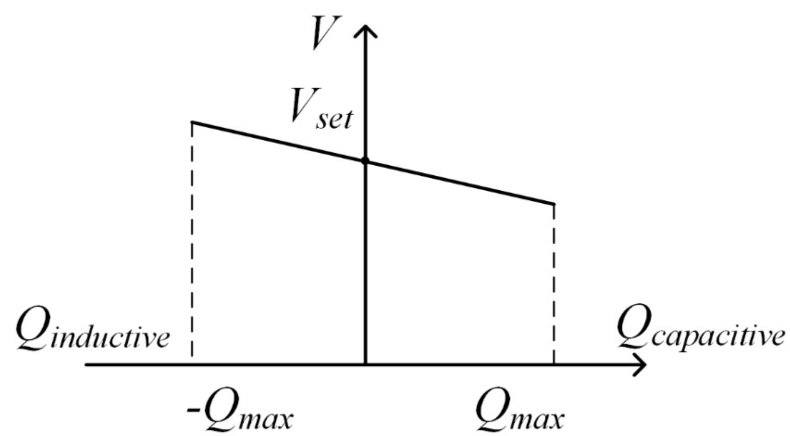
$$P = \frac{EV}{X_L}\sin\delta_p \approx \frac{EV}{X_L}\delta_p$$

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

- Droop Control: make multiple inverters work together in a microgrid
  - ➢ P vs. f droop ensure sources are synchronized
  - ➢ Q vs. V droop avoids large circulating reactive power between sources



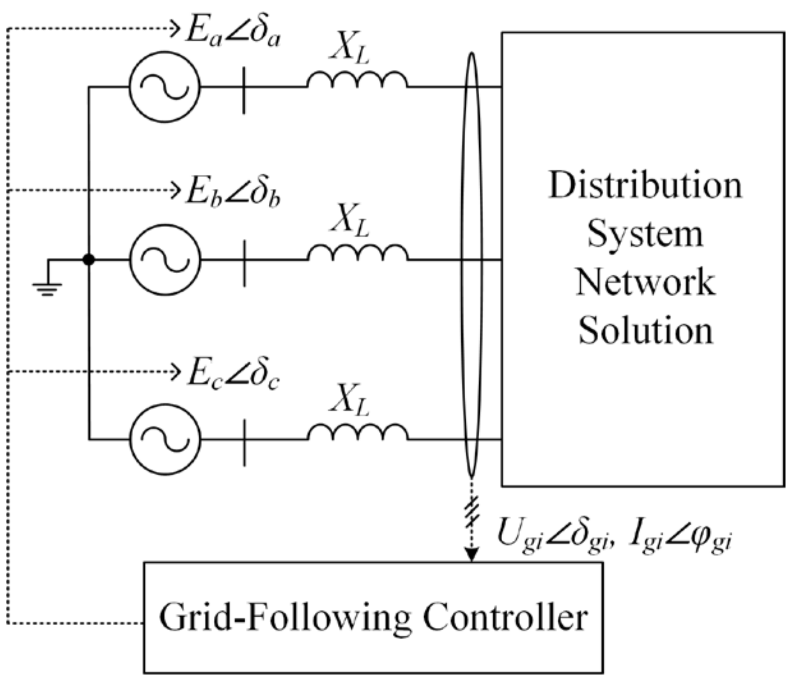
P vs. f droop



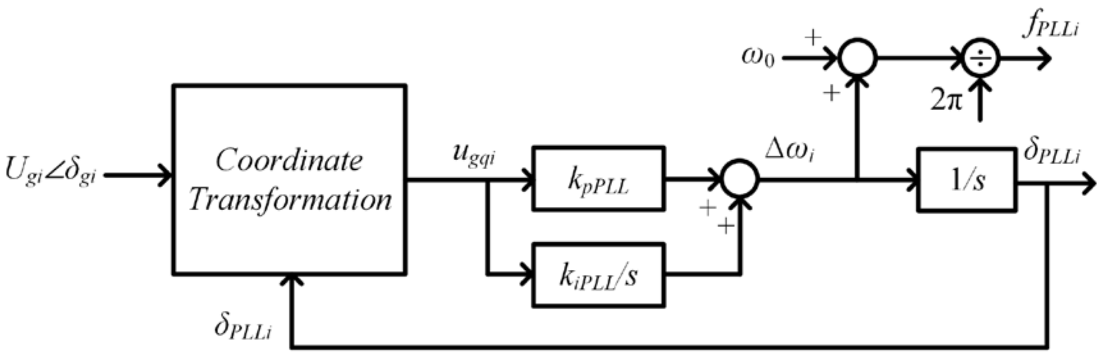
Q vs. V droop

Modeling of Grid-Following Inverters in GridLAB-D

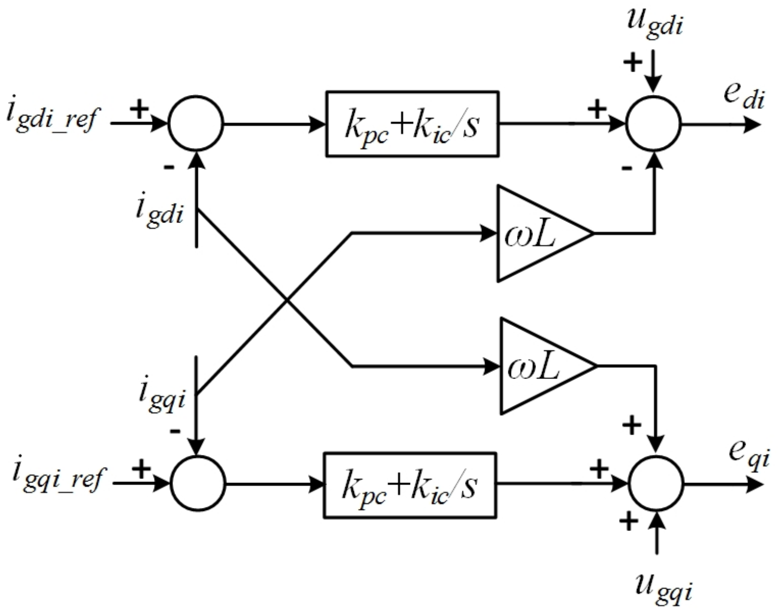
- Grid-Following inverters are usually modeled as **controllable PQ node** in traditional transient stability analysis software, PLL and current loops are ignored
- In GridLAB-D, they are modeled as controllable voltage sources, and detailed PLL and current loop are modeled



Inverter model and the interface to the distribution system



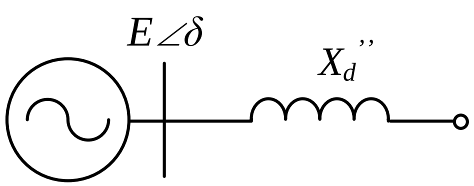
Phase-Lock Loop

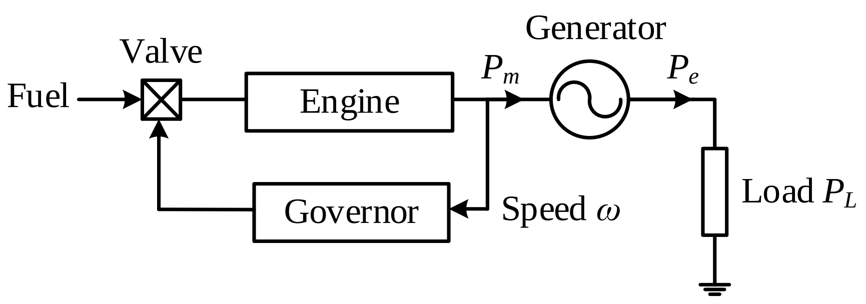


Current Loop

Synchronous Generator

- **Why synchronous generators need inertia?**
  - A synchronous generator behaves as a voltage source behind X_d'' in transient
  - P_e responses to load changes instantaneously
  - P_m from prime mover changes slowly
  - The unbalance between P_e and P_m results in the change of speed





$$2H\frac{d\omega}{dt} = P_m - P_e$$