Sandia National Laboratories

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Bulk Power System Dynamics with Varying Levels of Synchronous Generators and Grid-Forming Power Inverters

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ENERGY NNSA

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Outline

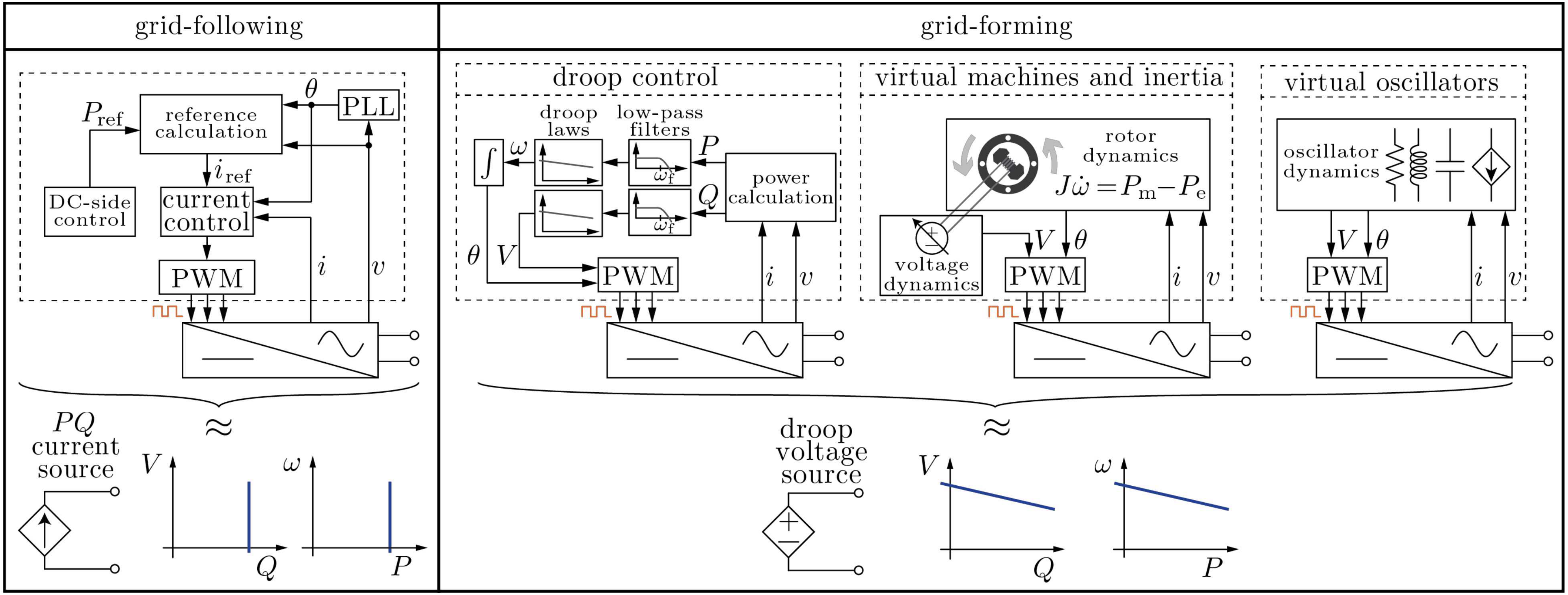
1. Overview of grid-following vs. grid-forming control models
2. Grid-forming virtual oscillator control (VOC) and droop control models
3. Positive sequence version of these models developed for PSLF
4. Simulation results of 50% VOC, 50% droop, vs. 100% synchronous on IEEE 39-bus system and MicroWECC system.
5. Conclusions and future work

Grid-following vs. grid-forming control

- Two fundamental types of voltage sourced inverter controls

Grid Following Control (GFL)	Grid Forming Control (GFM)
Controls current and phase angle	Controls voltage magnitude and frequency
Controls active & reactive power as well as fault currents	Instantaneously balances loads without coordination controls
Cannot operate standalone	Can operate standalone
Cannot achieve 100% penetration	Can achieve 100% penetration

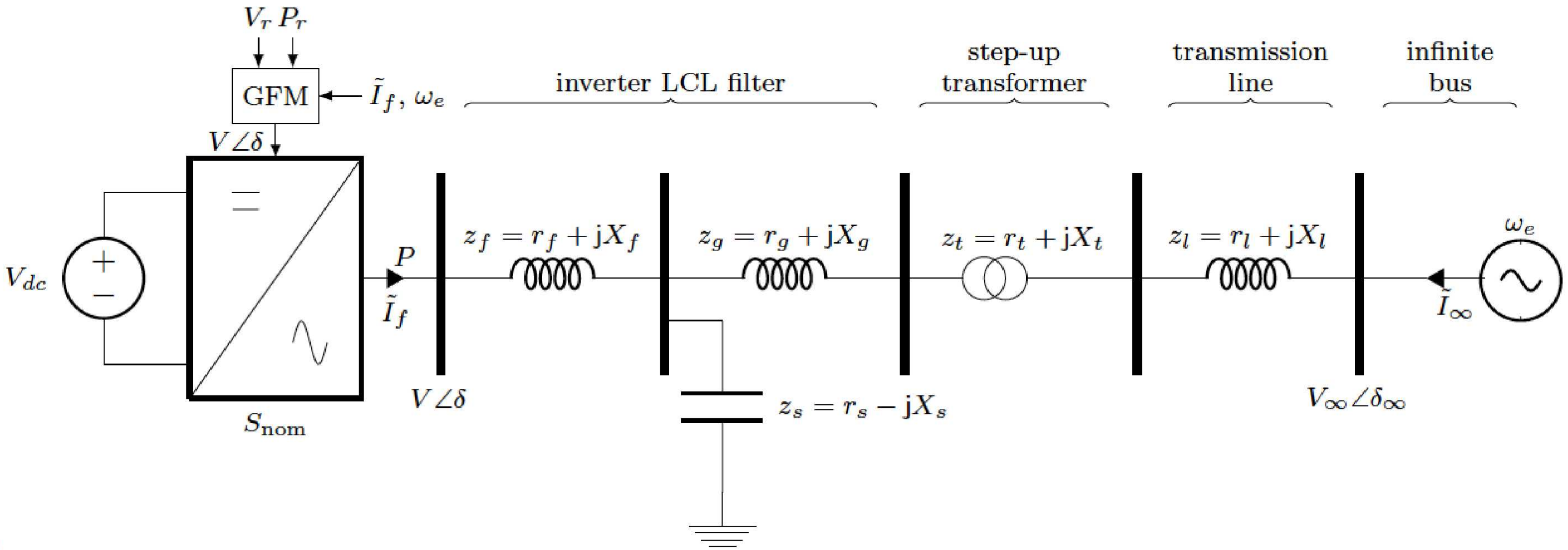
Grid-following vs. grid-forming



Grid-forming controls model

Grid-forming inverter control can:

1. autonomously generate terminal voltages cycling at a common synchronous speed,
2. regulate system voltage magnitudes, and
3. meet a power system demand in a shared manner without communication.



Virtual oscillator control (VOC) and Droop grid-forming models

- Overall, the droop model, defined by (14)–(18), has significant resemblance to the VOC model defined by (8)–(13), albeit originating from different technologies.
- Both models have the ability to set parameters to allow for specific droop percentages (e.g. 5% frequency-droop, 2% voltage-droop). Although the VOC is non-linear and therefore will not match exactly.
- Both models are in a way trying to mimic synchronous machine dynamics and can share load changes throughout the system without communication.

Positive sequence VOC model	
$\frac{d}{dt}V = \frac{1}{2\tau_V}V(V_r^2 - V^2) - \kappa_q \frac{Q}{V}$	(8)
$\frac{d}{dt}\delta = \omega_b(\omega - \omega_e)$	(9)
$\omega = 1 - \frac{\kappa_P}{V^2}(P - P_r)$	(10)
$P = V\, i_{df}$	(11)
$i_{df} + j i_{qf} = e^{-j\delta}\tilde{I}_f$	(12)
$Q = -V\, i_{qf}.$	(13)

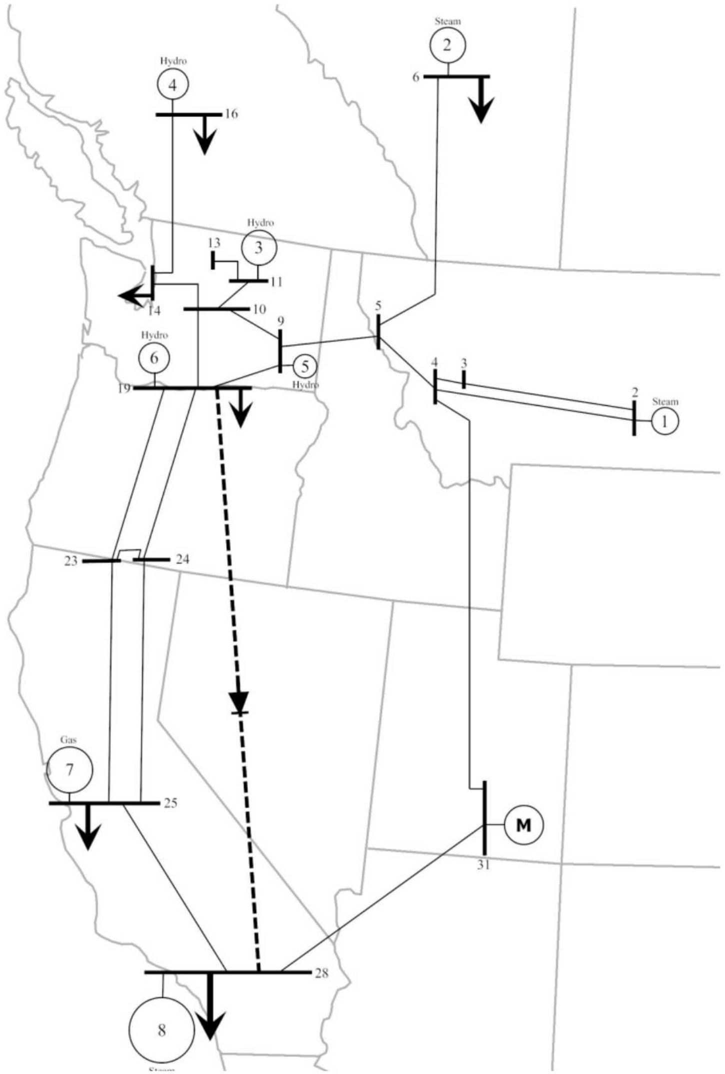
Positive sequence Droop model	
$\frac{d}{dt}V = \frac{1}{\tau_V}\left(V_r - V - \kappa_Q Q\right)$	(14)
$\frac{d}{dt}\delta = \omega_b(\omega - \omega_e).$	(15)
$\omega = 1 - \kappa_P(P - P_r)$	(16)
$\frac{d}{dt}Q = \frac{1}{\tau_S}\left(-Q - V\, i_{qf}\right)$	(17)
$\frac{d}{dt}P = \frac{1}{\tau_S}\left(-P + V\, i_{df}\right)$	(18)

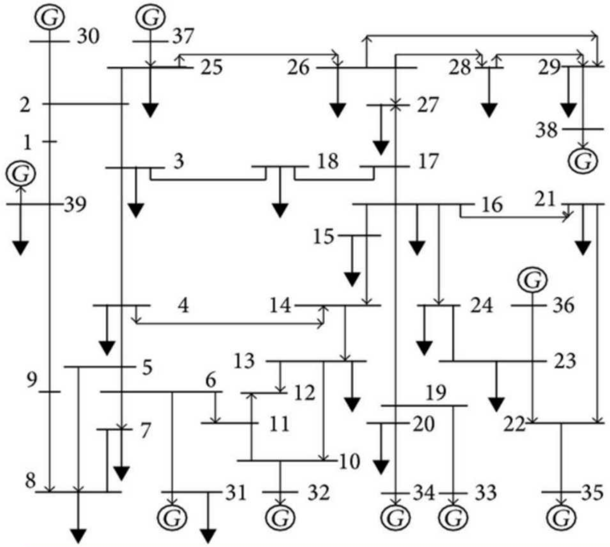
Test systems to realize grid-forming PV impacts

MicroWECC system

- Scaled down version of the North American Western Interconnection (developed by Montana Tech)
- Prone to a significant frequency Nadir
- Prone to oscillations

- 32 buses
- 8 generators
- 9 loads
- 21 lines





IEEE 39-bus system

- Built from part of the U.S. eastern interconnection
- Has a "Lazy L" frequency
- Overall very stable

- 39 buses
- 10 generators
- 19 loads
- 34 lines

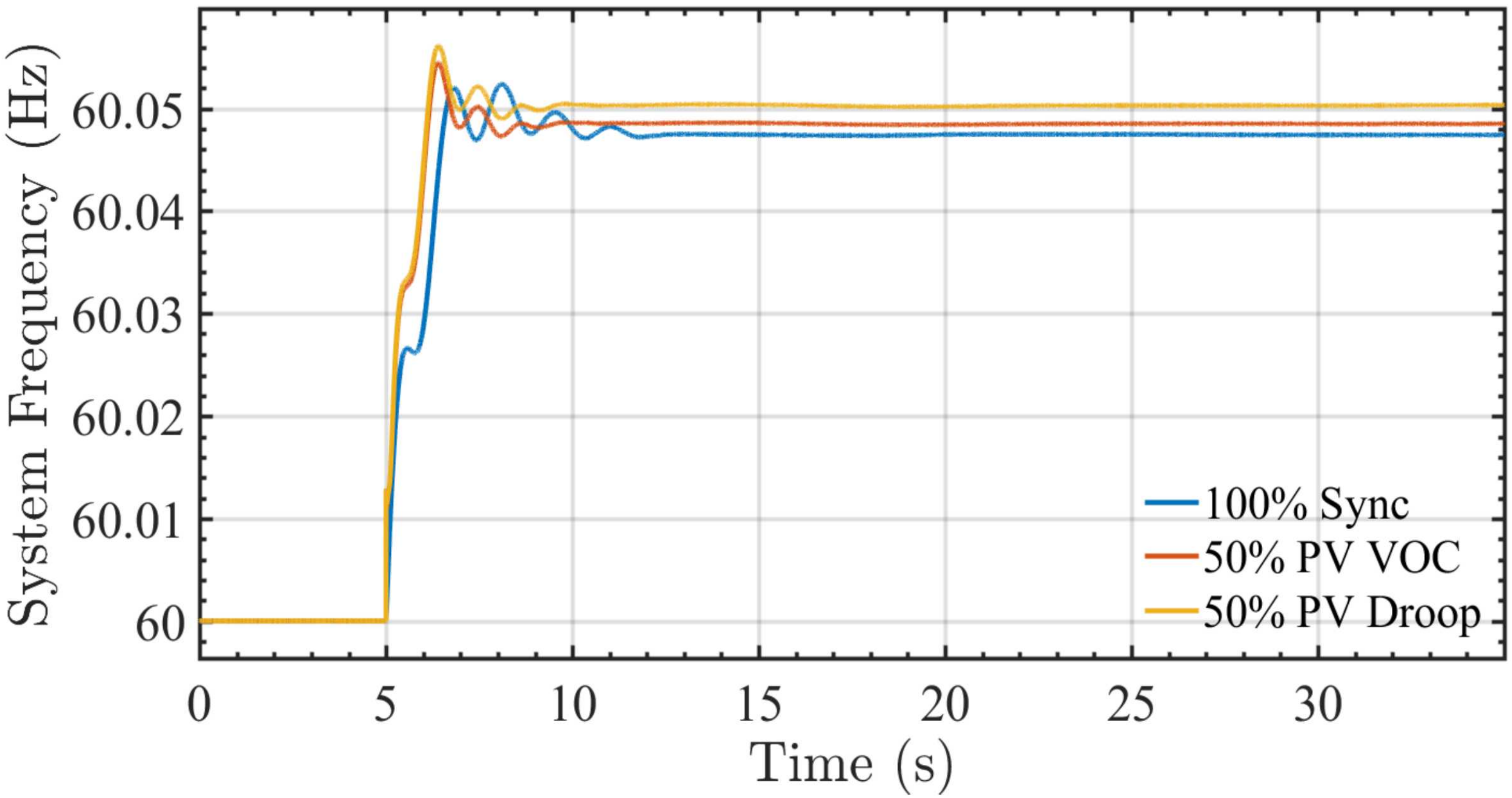
Test system modifications

- Governors for all generators set to 5% droop
- Modern exciters added with 2% voltage droop
- All generator buses split into two parallel generator buses with 50% PV and 50% conventional synchronous generation.
- PV generation set to either Droop model or VOC model with parameters of 5% frequency-droop and 2% voltage-droop (match synchronous generation for apples-to-apples comparison).
- Updated load models on the IEEE 39-bus system to modern models.

Brian J. Pierre, et al., "Bulk Power System Dynamics with Varying Levels of Synchronous Generators and Grid-Forming Power Inverters"

Load trip event on IEEE 39-bus system

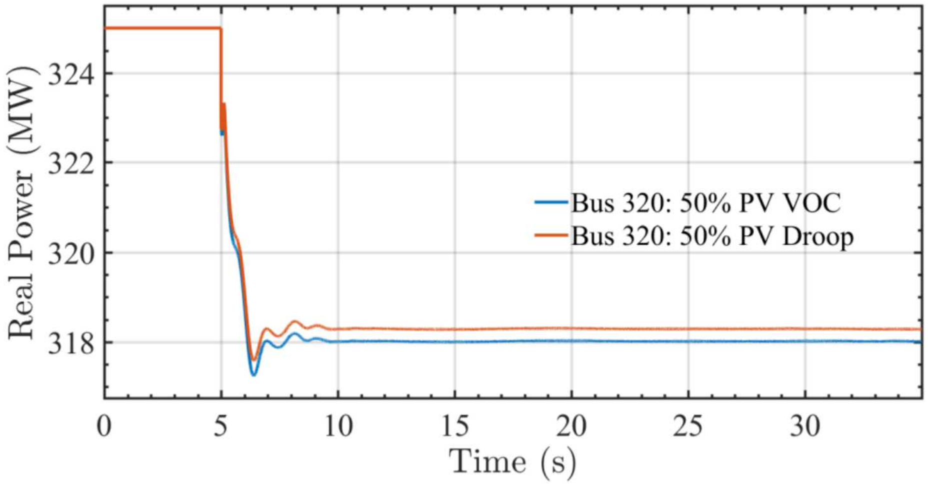
- The settling frequency of the 50% PV cases is effectively the same as in the 100% synchronous case.
- This indicates that the droop characteristic programmed into the inverter-based generation controls matches the setting of the synchronous generator turbine governors.
- The settling frequency in the VOC case deviates slightly from the droop case because its dynamics do not precisely correspond to a linear droop characteristic.

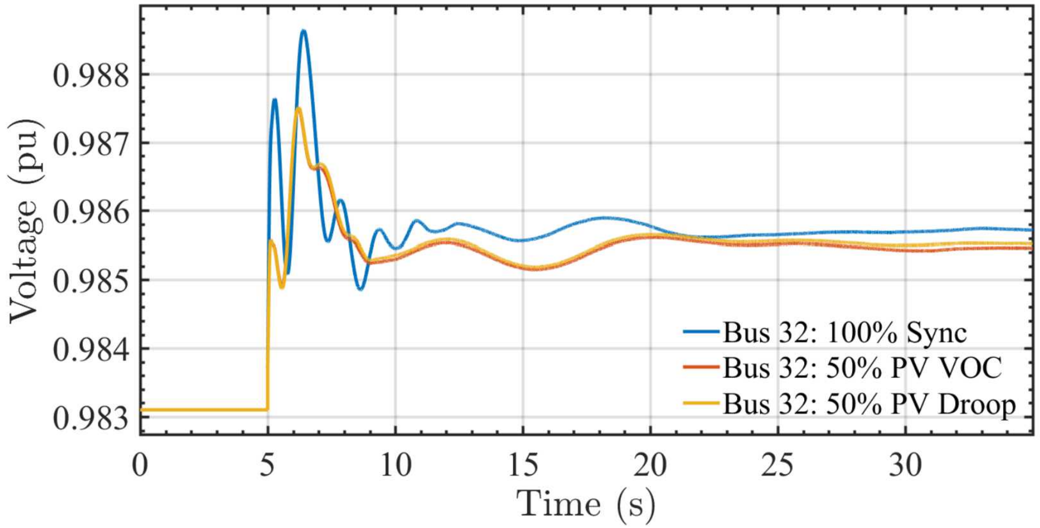


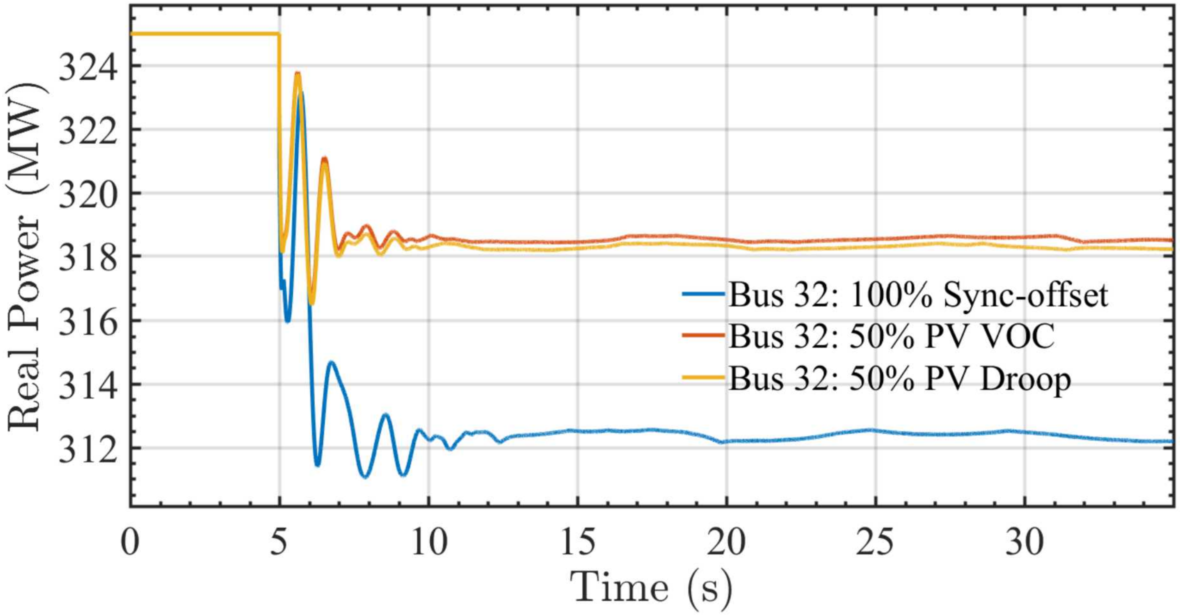
- Note, the IEEE 39-bus case exhibits the "Lazy L" frequency response.

Load trip event on IEEE 39-bus system

- The voltage plot compares the voltage regulation achieved purely using the automatic voltage regulator (AVR) and excitation system of the synchronous machine with that achieved by the combined efforts of the synchronous and inverter-based generator controls.
- The results indicate similar transients in all three cases, with perhaps slightly better damping in the 50% PV cases.
- The change in power output in the PV cases is half that of the synchronous case, because of the change in generation percentages (100% sync to 50% sync)

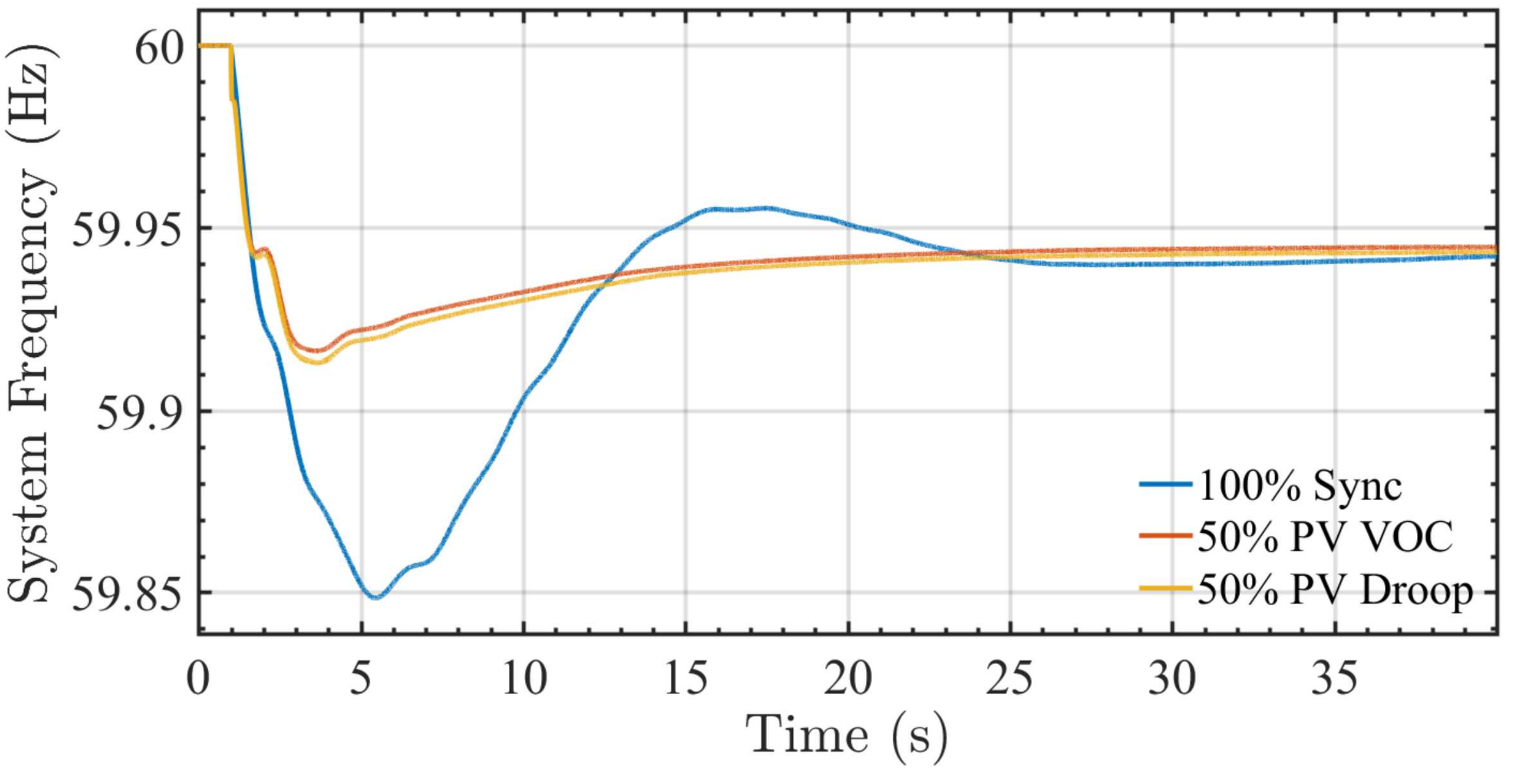






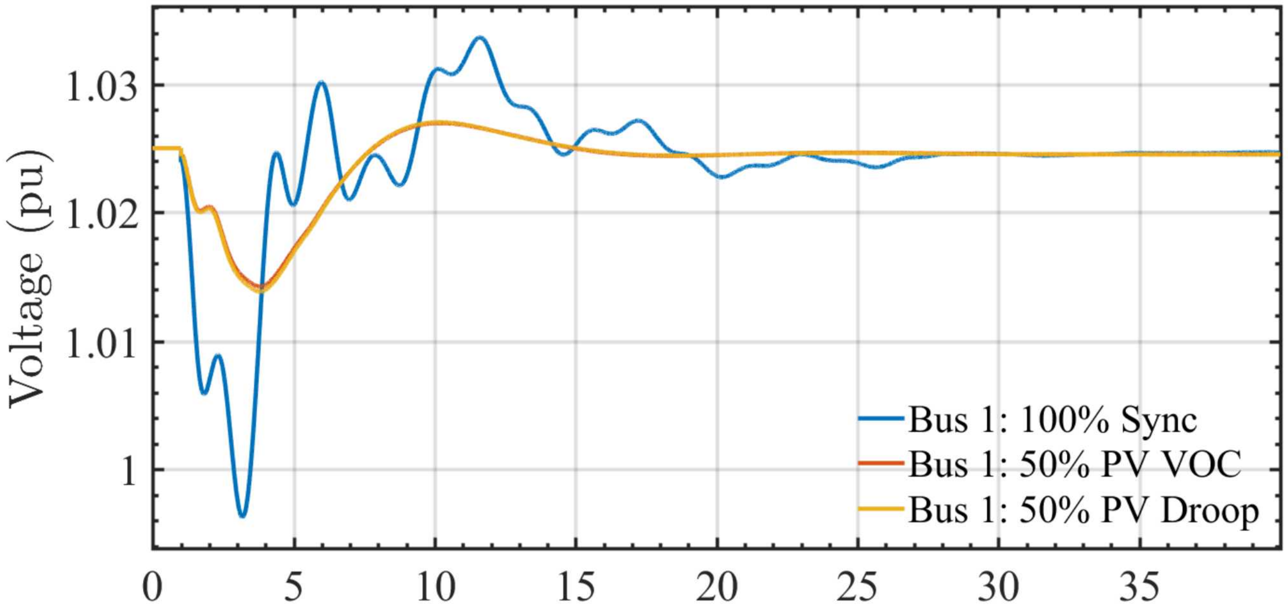
Generator trip event on MicroWECC system

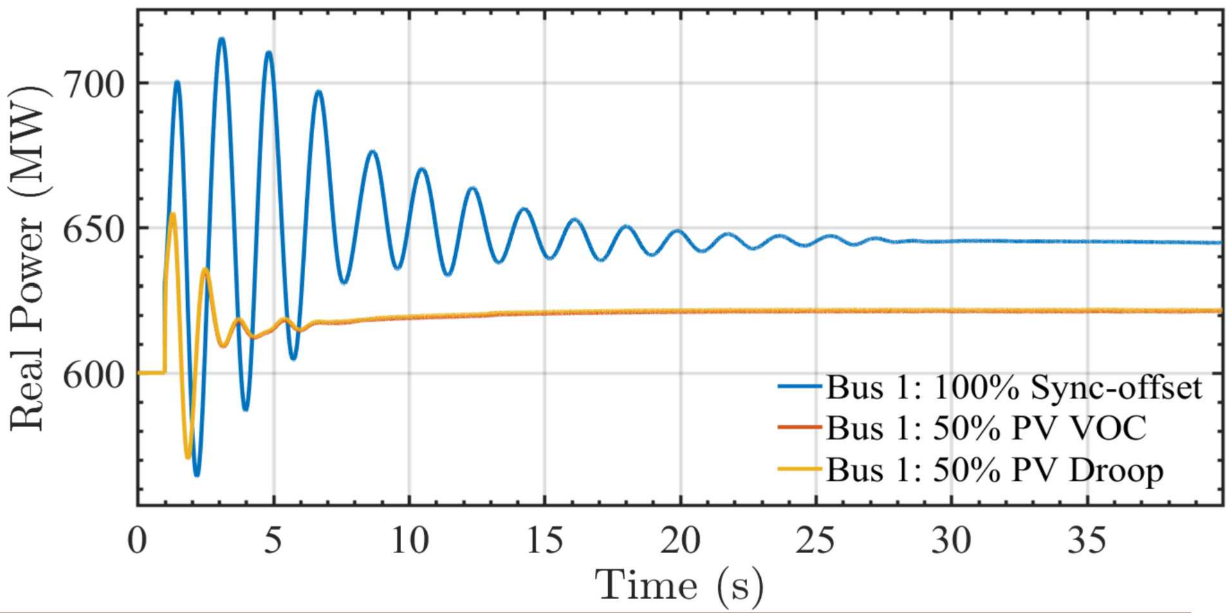
- The microWECC system was utilized due to being prone to a large frequency Nadir and oscillations.
- Assumption there is adequate headroom to increase PV output during the event (PV is curtailed or energy storage exists).
- The settling frequency of the 50% PV cases is effectively the same as in the 100% synchronous case as expected.
- However, the PV cases show significantly less overshoot,
- this indicates that the addition of the inverter-based controls has a stabilizing effect on the frequency regulation mode

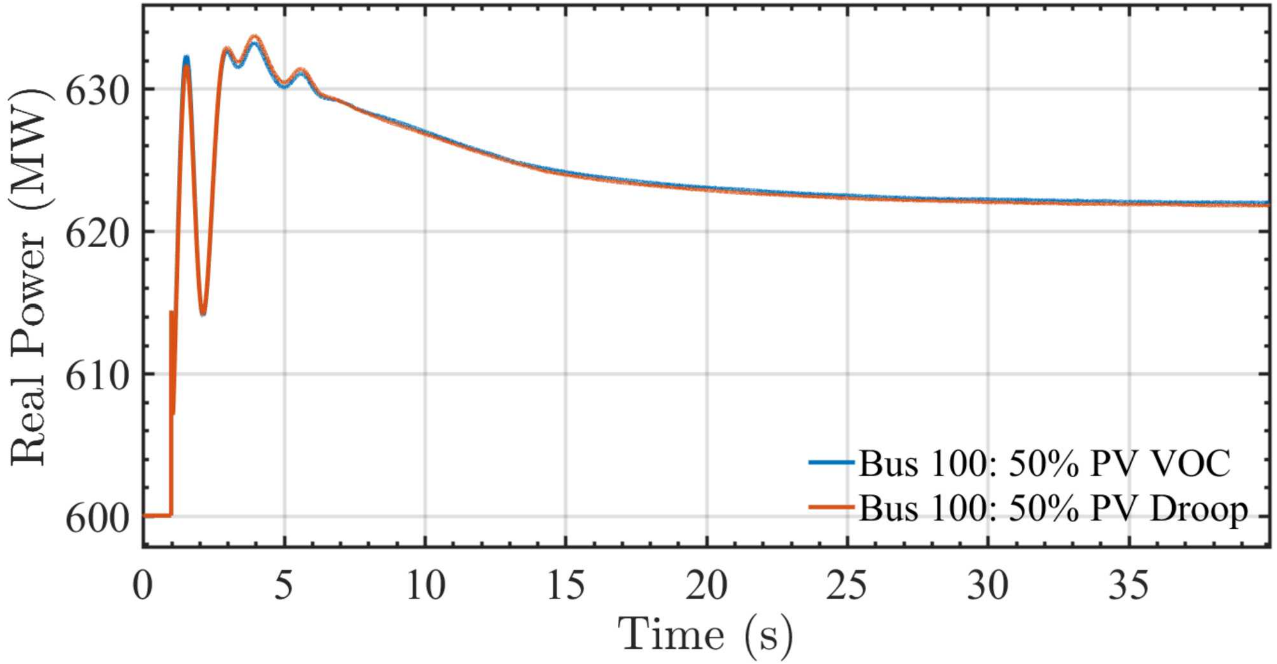


Generator trip event on MicroWECC system

- The cases with inverter-based generation controls exhibit markedly better damping than the 100% synchronous case for this contingency (note this is somewhat sensitive to how the PSSs are modeled in the system).
- The voltage at a synchronous generator bus indicates better stability in the PV cases.







Conclusions and future work

- The results from these simulations indicate that under typical contingencies, the grid-forming inverter models can have similar or better dynamic performance to traditional 100% synchronous generation if the parameters of the control schemes are chosen appropriately.

- The results are promising, but future work needs to continue research in this area, especially in fault analysis and protection for grid-forming inverters.