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Mitigation of MicroGrid Power Oscillations using PMU data

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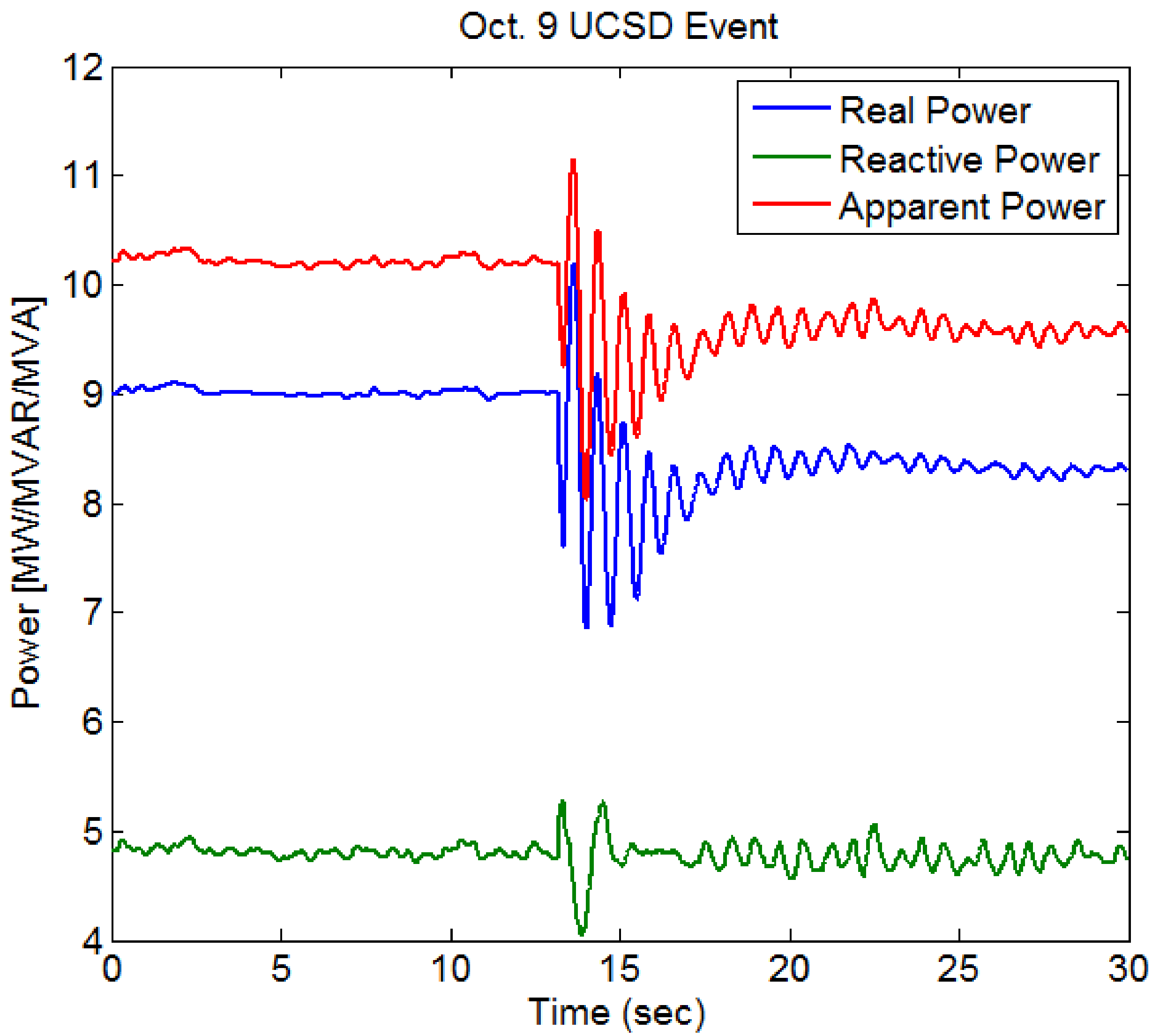
Motivation: microgrid events

Measurements from SEL breaker at 12kV

3 phase line (6.9kV phase to phase)

- RMS Voltage and Current of 3 phases
- Real Power
- Apparent Power



Outline

What can we do to mitigate (micro)grid events?

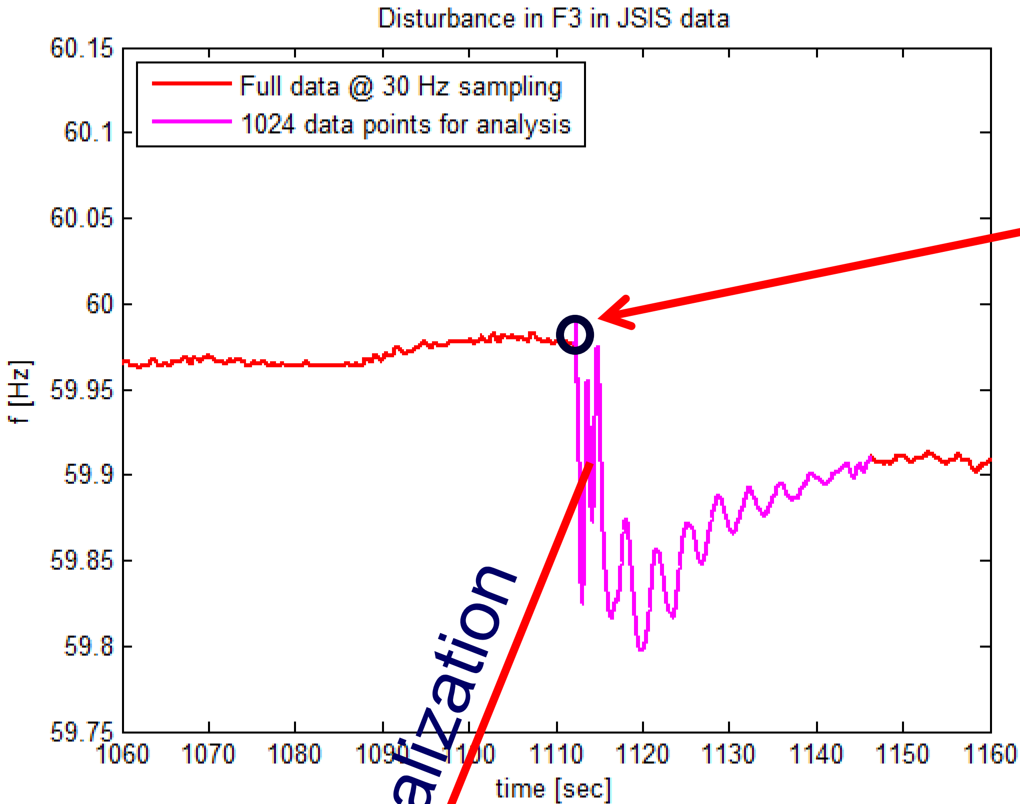
Events = excitation of grid:

- Measurement of this event (PMU data)
- Possibility to model dynamics
- Possibility to dampen oscillations

Approach out Outline of Talk:

- Realization algorithm to model (local) grid dynamics
- Control architecture to mitigate oscillations
- Control algorithm and Results

Analysis of Events - Realization Algorithm



detect beginning of event

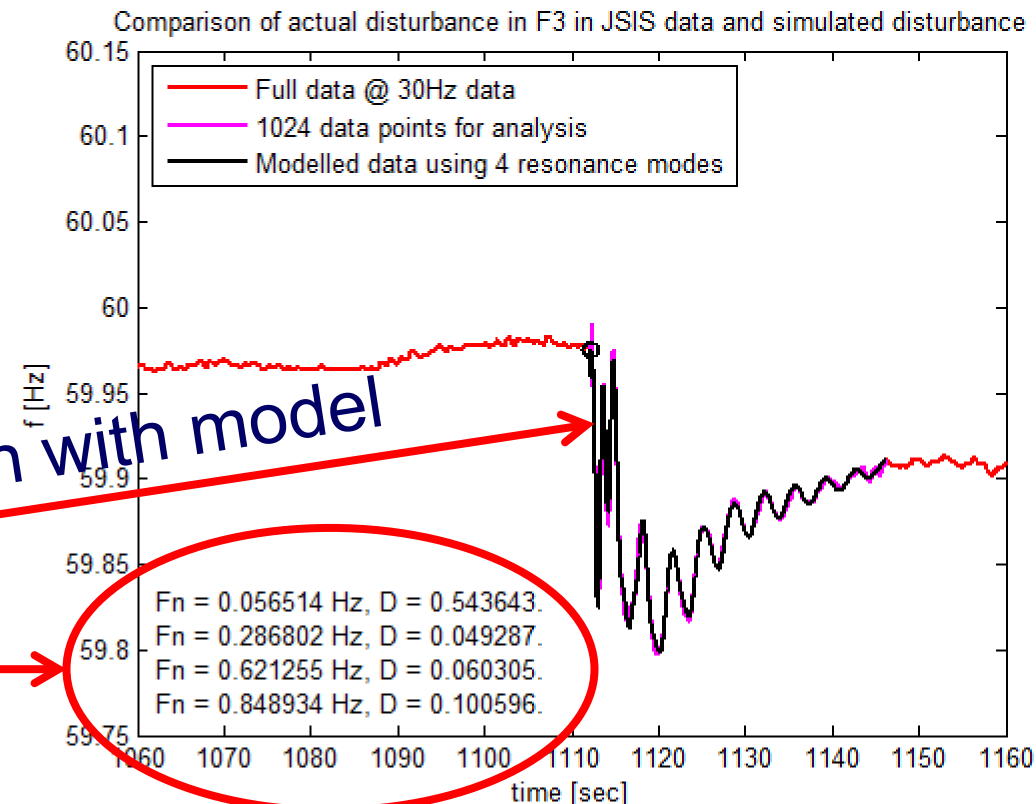
realization

$$x(t+1) = Ax(t) + Bd(t)$$

$$F(t) = Cx(t)$$

simulation with model

analysis



Analysis of Events - Realization Algorithm

Approach:

- Assume observed event in frequency F(t) is due to a deterministic system

$$x(k+1) = Ax(k) + Bd(k)$$
$$F(k) = Cx(k)$$

Discrete-time model

where (unknown) input d(t) can be \`impulse' or \`step' or \`known shape'

- Store a finite number of data points of F(t) in a special data matrix **H**
- Inspect rank of (null projection on) **H**: determines # modes
- Compute matrices A, B and C via Realization Algorithm.
- Extension of Ho-Kalman, Kung algorithm. Miller, de Callafon (2010)
- Applicable to multiple time-synchronized measurements! (multiple PMUs)

End Result:

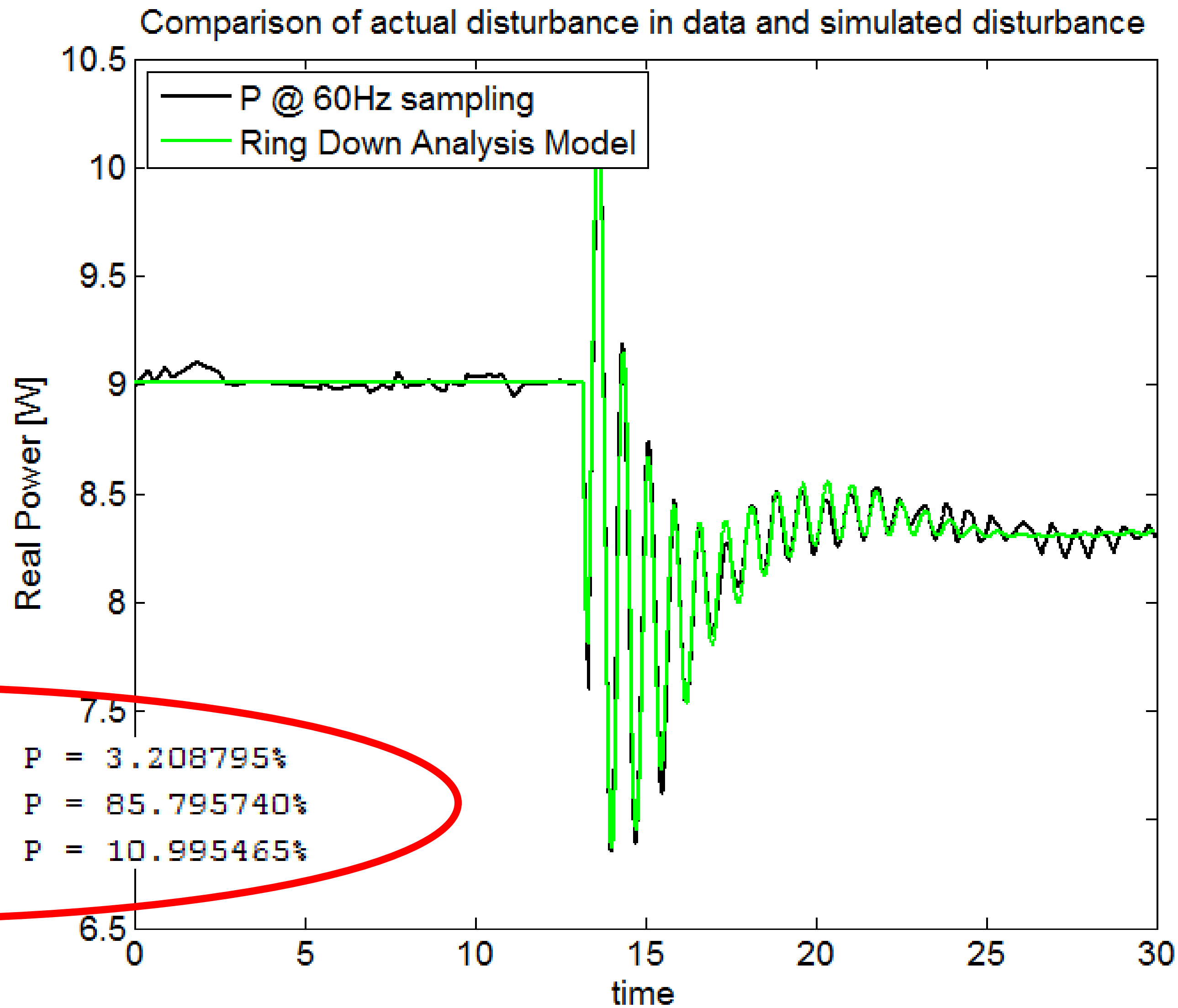
- Dynamic model (state space model) can be used for
  - Simulation: simulate the disturbance data
  - Analysis: Compute resonance modes and damping (from eigenvalues of A)

Analysis of UCSD microgrid dynamics

Realization Algorithm:

excellent fit of oscillation/damping

Modeled frequencies Fn, damping D and model participation P:




```
Fn = 0.094653 Hz, D = 0.450955, P = 3.208795%
Fn = 1.353568 Hz, D = 0.044507, P = 85.795740%
Fn = 1.461354 Hz, D = 0.026519, P = 10.995465%
```

Mode around 1.4Hz
less than 5% damping, 85% participation

Analysis of UCSD microgrid dynamics

Dynamic model found by realization in Bode plot (frequency domain)

$$G(z) = C(zI - A)^{-1}B$$

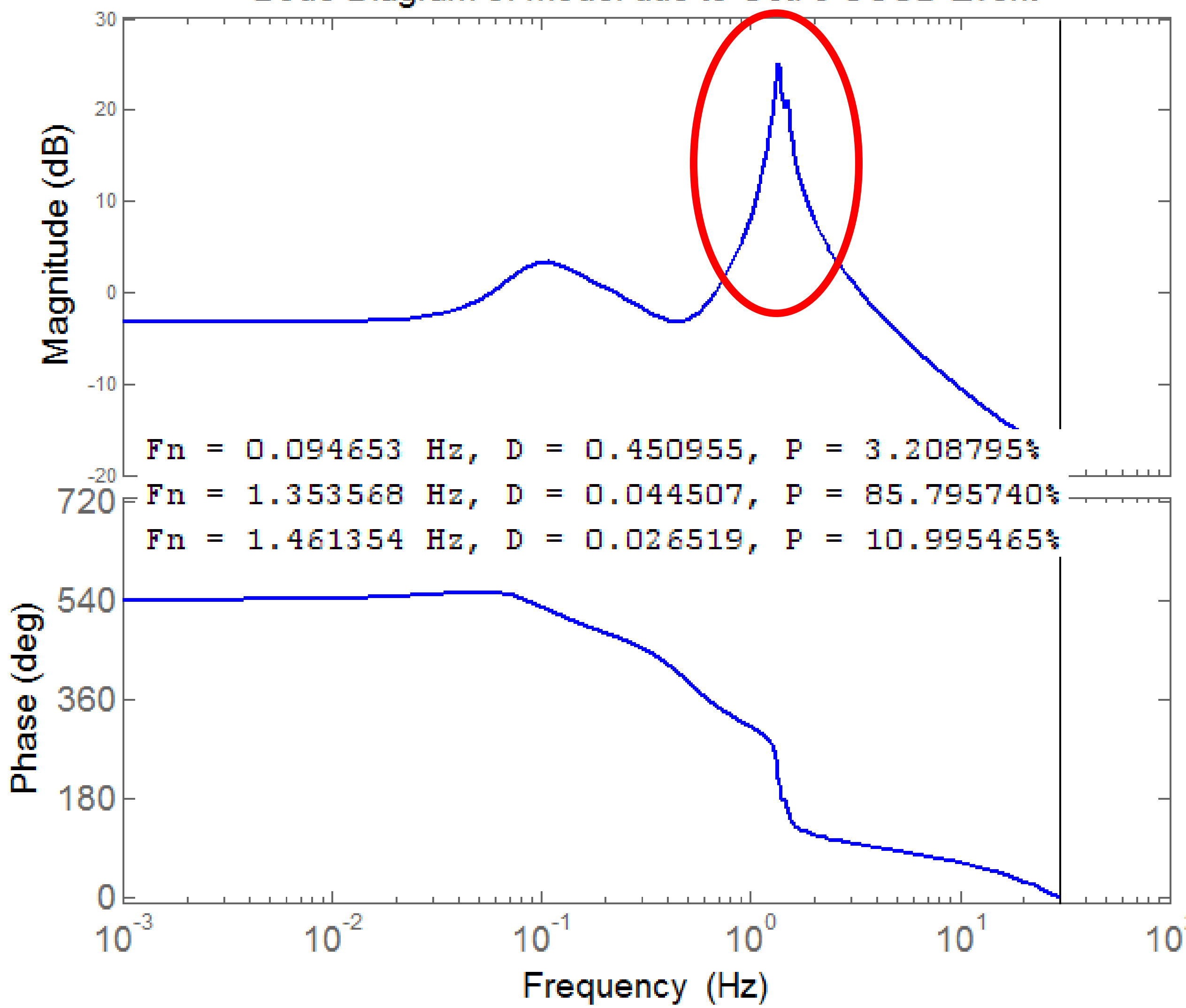
$$|G(e^{j\omega\Delta t})|, \quad \prec G(e^{j\omega\Delta t})$$

Observe large resonance frequency around 1.4Hz

MITIGATION

Control/damping of 1.4Hz oscillation

Bode Diagram of model due to Oct. 9 UCSD Event



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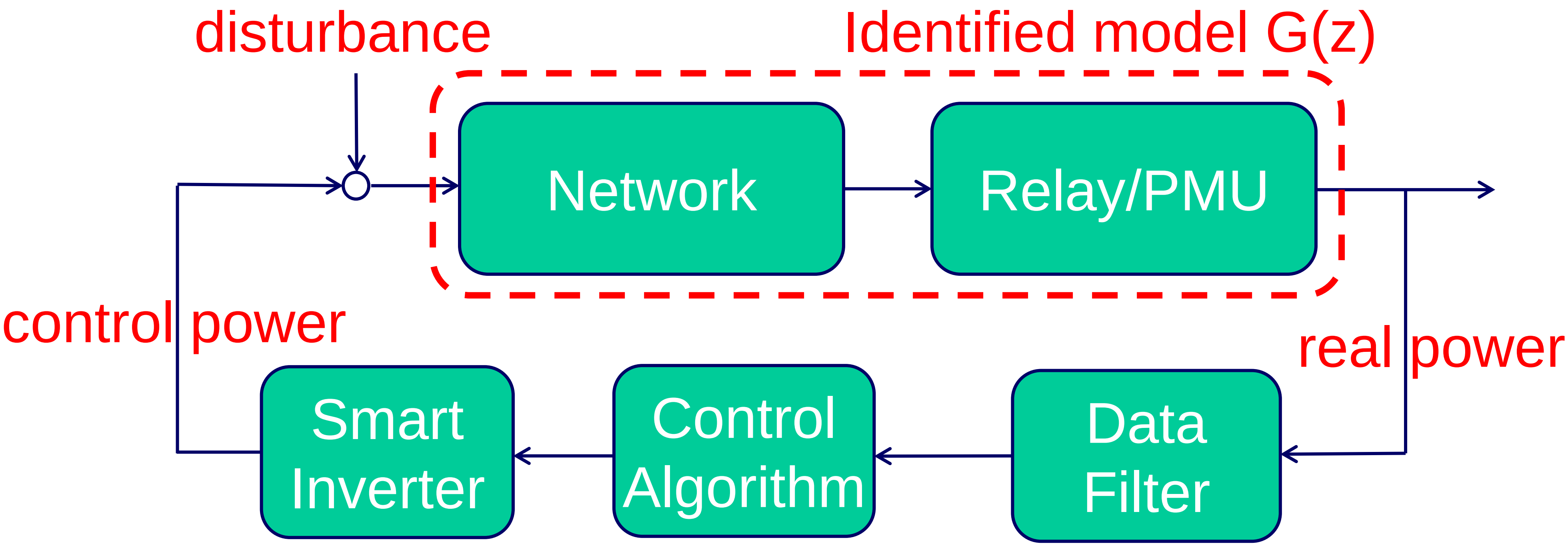
MITIGATION

Control/damping of 1.4Hz oscillation via Real Power control:



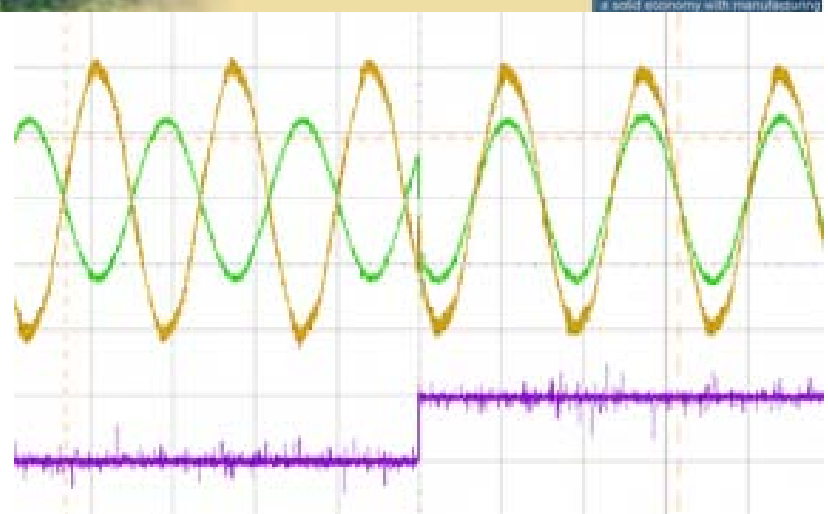
- What is the smart inverter, data filter and control algorithm?
- **How much control power is needed** to dampen oscillation?

Mitigation of power oscillations

Smart Inverter from One-cycle Control

One-Cycle Control, Inc.
The Art of Power Processing

- Grid Tied Inverter (OCC-GTI)
- four quadrant operation
- Fast dynamics

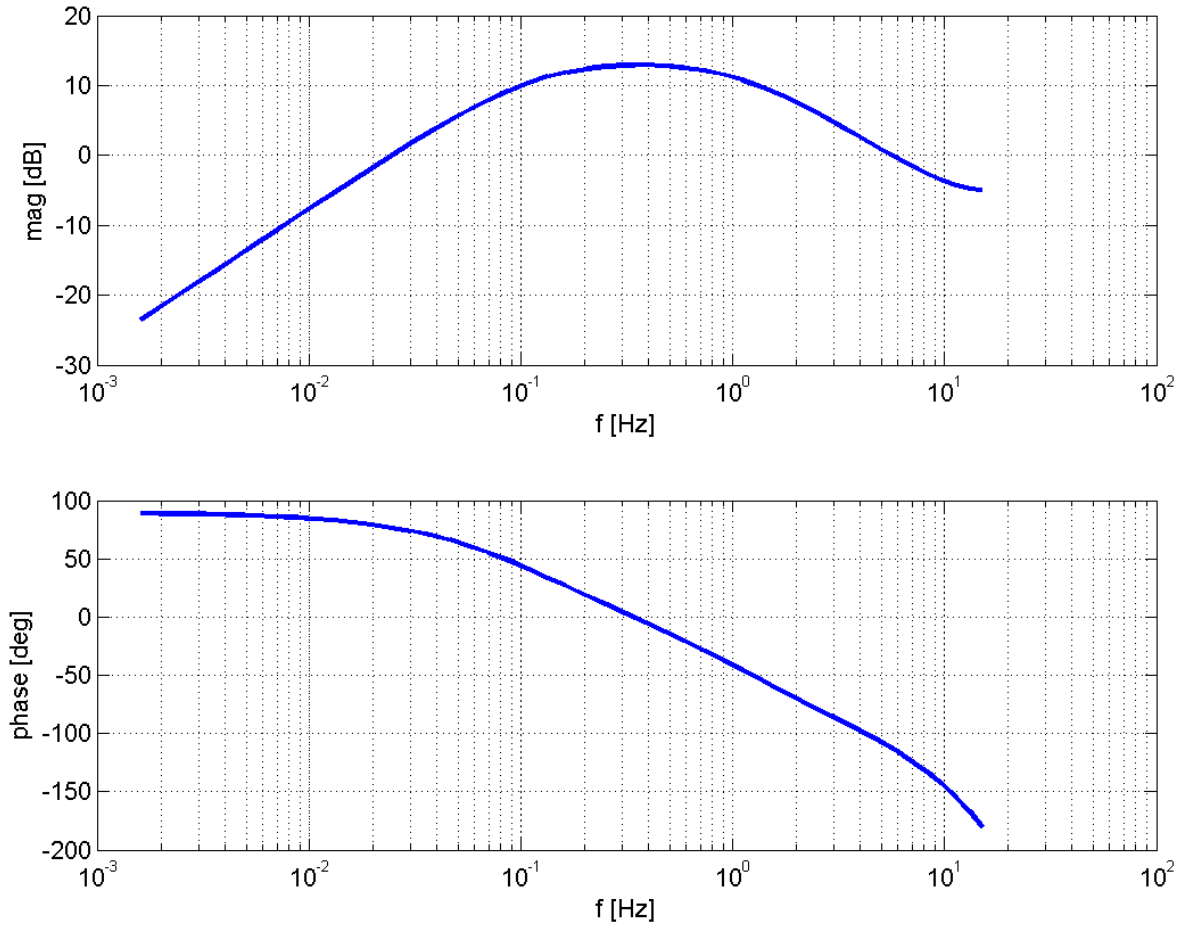


Mitigation of power oscillations

Define a data filter $F(z)$ on the real-power data:

$$F(z) = \frac{z-1}{(z-a)(z-b)}$$

- Discrete-time differentiator
- Two poles (a,b) to limit bandwidth of control to frequency range of interest.



Mitigation of power oscillations

Tuning of control algorithm C(z) based on:

- Identified Discrete-Time Model G(z):

$$\frac{-0.2791\,z\hat{}6 + 1.677\,z\hat{}5 - 4.204\,z\hat{}4 + 5.63\,z\hat{}3 - 4.249\,z\hat{}2 + 1.713\,z - 0.2882}{z\hat{}7 - 6.89\,z\hat{}6 + 20.39\,z\hat{}5 - 33.58\,z\hat{}4 + 33.26\,z\hat{}3 - 19.8\,z\hat{}2 + 6.564\,z - 0.9344}$$

- Chosen data filter $F(z)$ on the real-power data:

$$F(z) = \frac{z-1}{(z-a)(z-b)}$$

- Known dynamics of smart inverter

Damping control (similar to a snubbing circuit):

- C(z) = K = simple gain **would do the job**!
- Improvement of damping via direct linear feedback control!

Mitigation of power oscillations

Fixed gain control does an O.K. job:

Gain K chosen such that control power is +/- 125KW

```
Fn = 0.092977 Hz, D = 0.448233.
Fn = 1.349573 Hz, D = 0.132450.
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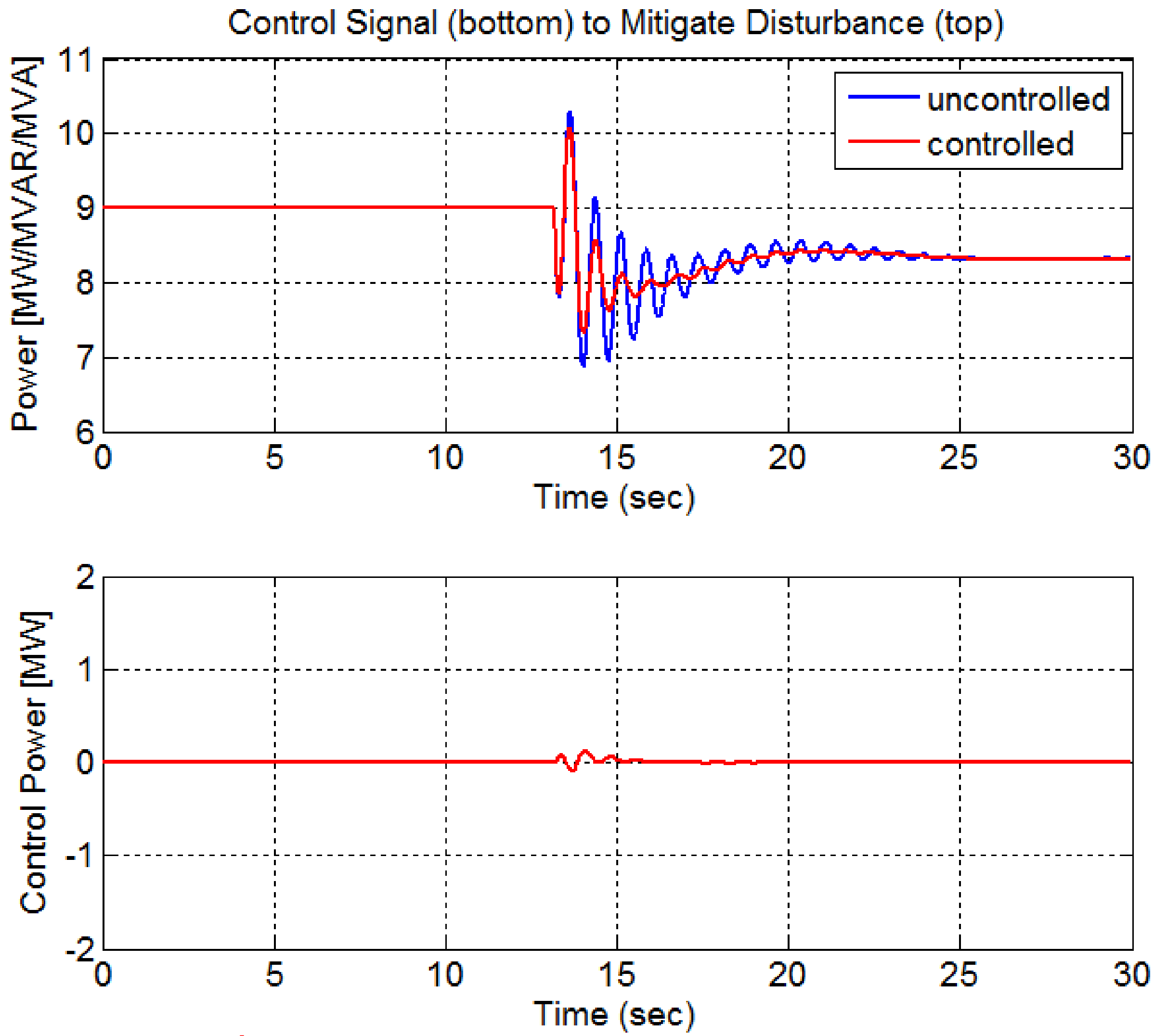
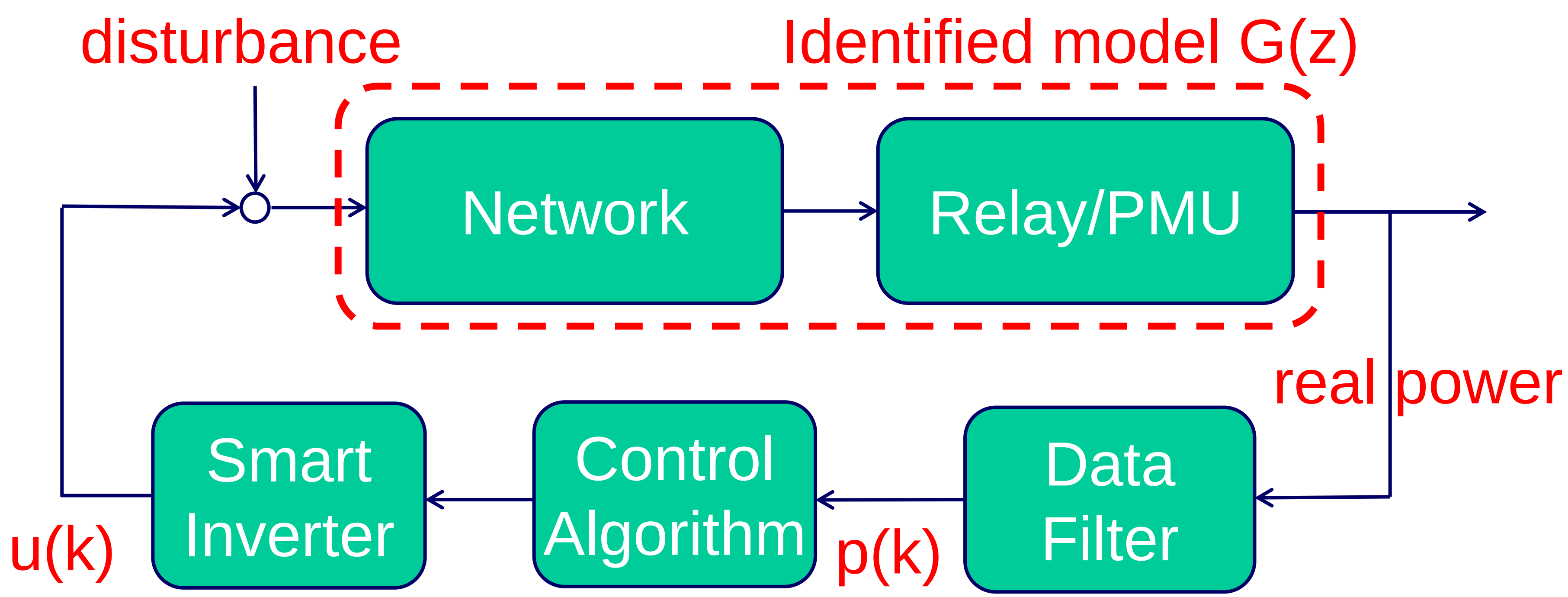


- Damping increased from 2.6% to 13.2%
- Oscillations mitigated faster!
- However: requires (temp) power storage

Mitigation of power oscillations

Next step in advancement of control algorithm:

- Leave data filter F(z) in place – defines "performance" signal p(k)
- Compute control algorithm that minimizes variance of p(k) while maintaining bounds on u(k) (power control)



Mitigation of power oscillations

Advanced control algorithm uses:

- Identified Discrete-Time Model G(z):

$$\frac{-0.2791\, z\hat{}6 \;+\; 1.677\, z\hat{}5 \;-\; 4.204\, z\hat{}4 \;+\; 5.63\, z\hat{}3 \;-\; 4.249\, z\hat{}2 \;+\; 1.713\, z \;-\; 0.2882}{z\hat{}7 \;-\; 6.89\, z\hat{}6 \;+\; 20.39\, z\hat{}5 \;-\; 33.58\, z\hat{}4 \;+\; 33.26\, z\hat{}3 \;-\; 19.8\, z\hat{}2 \;+\; 6.564\, z \;-\; 0.9344}$$

- Chosen data filter $F(z)$ on the real-power data:

$$F(z) = \frac{z-1}{(z-a)(z-b)}$$

- Known dynamics of smart inverter
- Computation of control power via Model Predictive Control (MPC) by direct computation of $u(l), l = k, .., n+k$ via

$$min \sum_{l=k}^{k+n} p(k)^2 + \mu u(k)^2$$

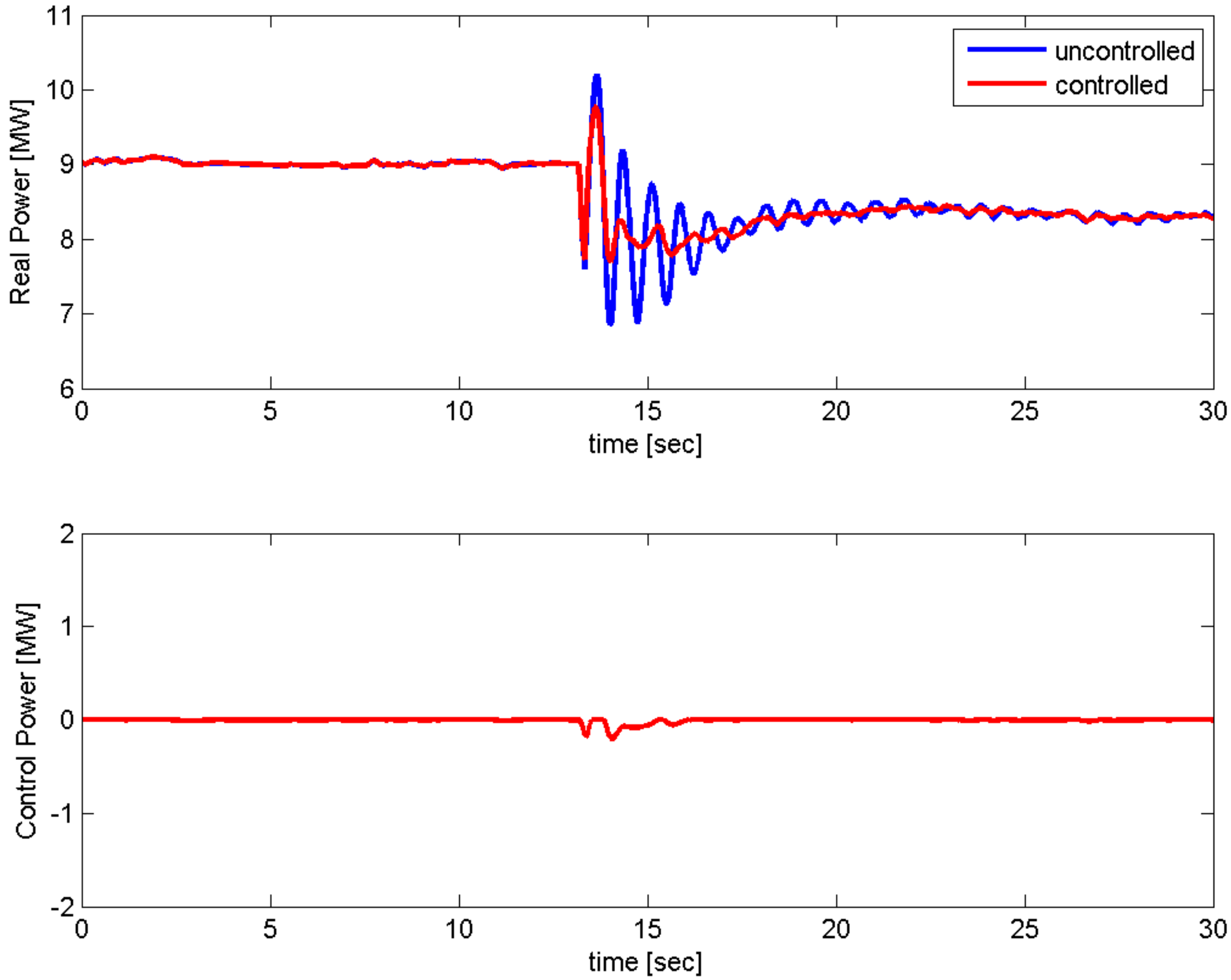
$$sub.to.p(k) = G(z)F(z)u(k) + F(z)d(k)$$

$$and\ \alpha_l < u(k) < \alpha_u$$

Mitigation of power oscillations

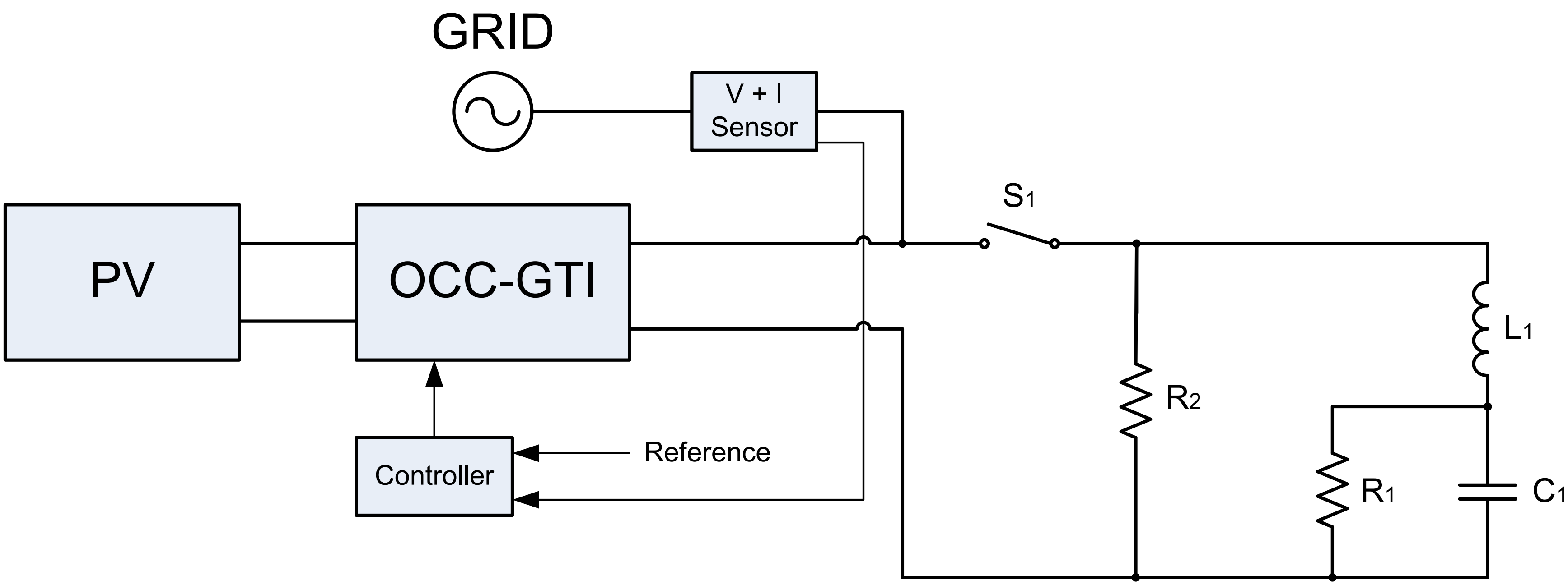
Results

- $\alpha_u = 0, \alpha_l = -0.25$
- Notice how control input is only "negative"
- Only needs (temp) power delivery reduction
- No (temp) power storage – so can be implemented via a controlled PV system!



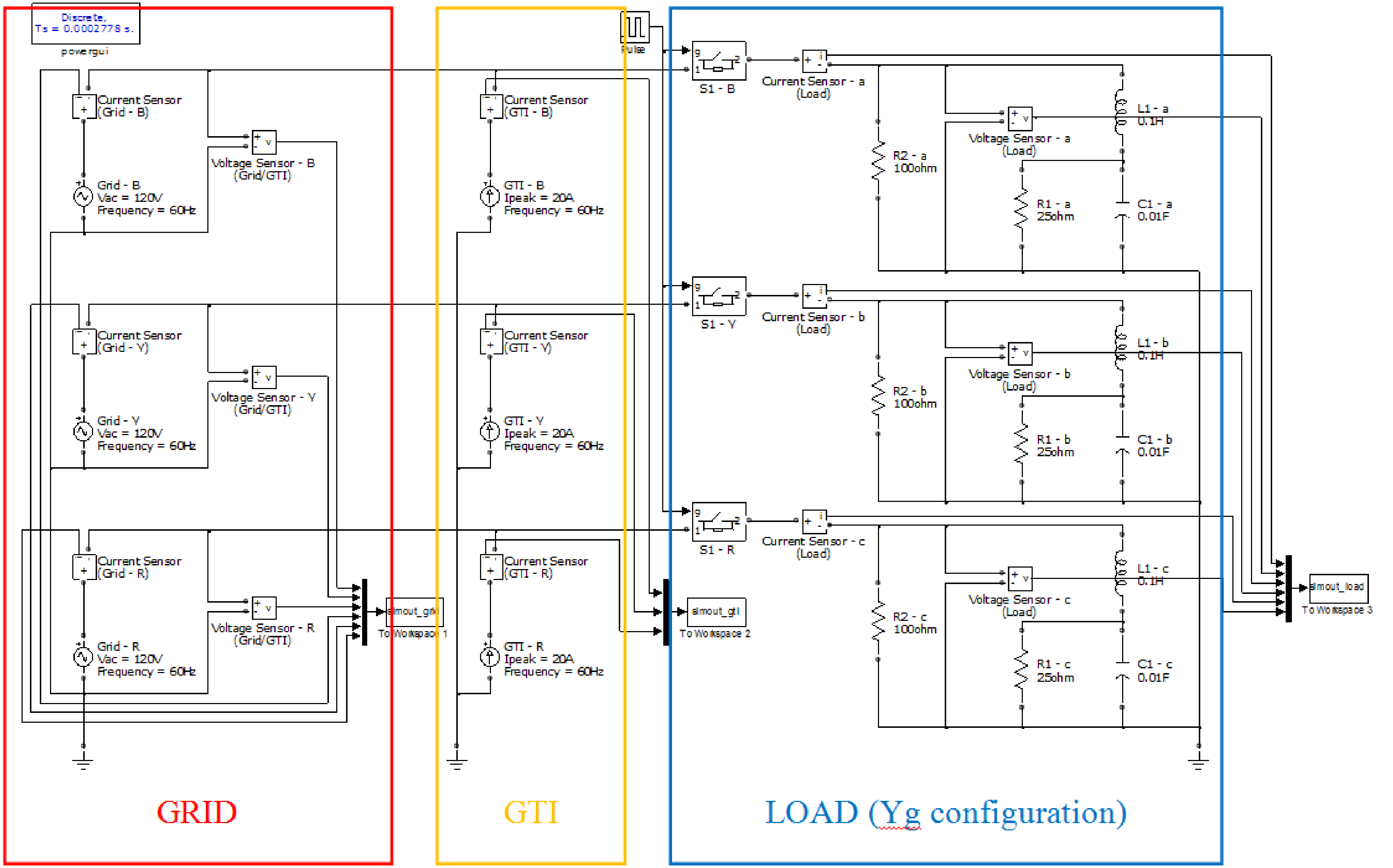
Experimental Facility for Testing

Actual testing on simulated 3-phase inductive load



- Rooftop PV system at UCSD Powel Lab
- OCC-GTI for power modulator (smart inverter)
- NI myRIO as PMU and controller
- Inductive load to simulate power oscillations

3-phase dynamic simulation



Wrap up/Conclusions

- Automatically estimate:
  - # of modes of oscillations in measured disturbance
  - Estimate frequency and damping of the modes
  - Put results in dynamic model that can be used for control design!
- All done in real-time
- Resulting dynamic model can be used for feedback control design to mitigate oscillations
- MPC can be used to take into constraints
- Very promising results on disturbances measured at UCSD microgrid.