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Evaluation of Energy Storage Technologies for Damping Control

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Wednesday, October 24, 2012

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U.S. DEPARTMENT OF ENERGY

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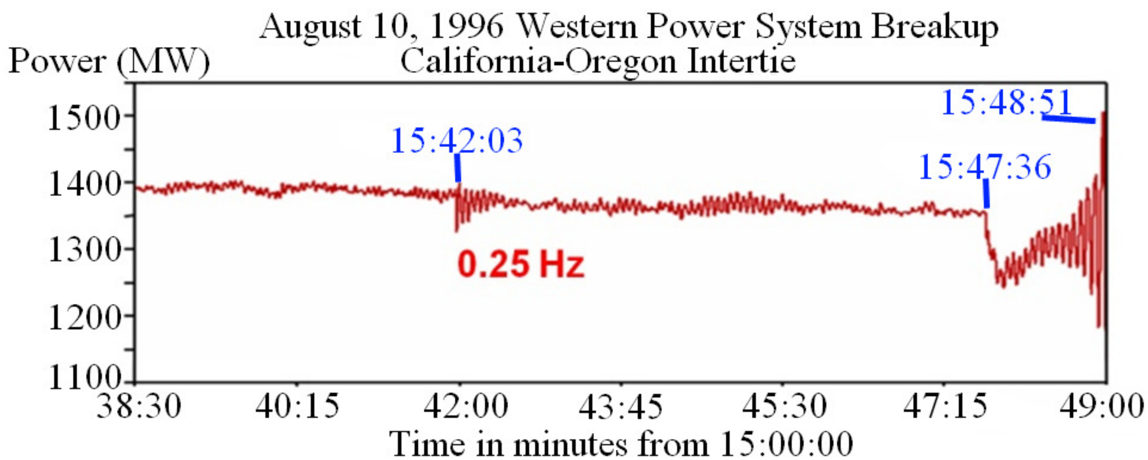
Energy Storage Controls for Grid Stability

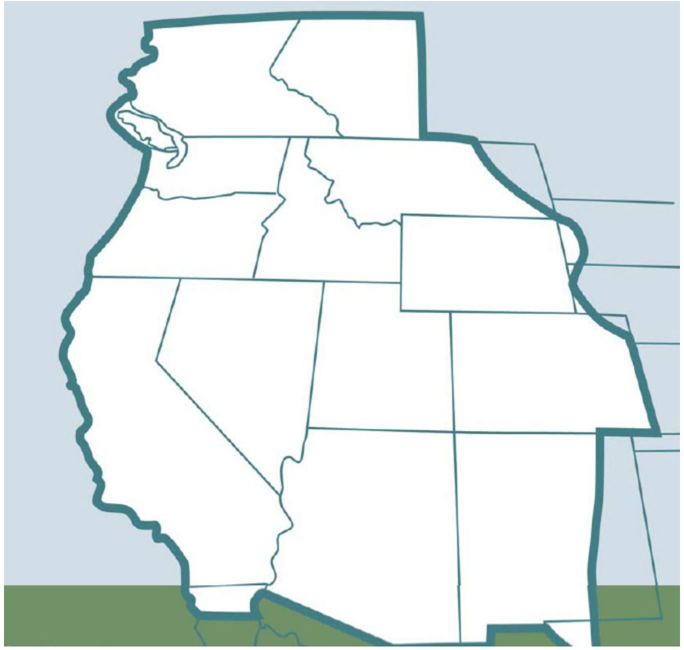
- Power systems are susceptible to low frequency oscillations caused by generators separated by long transmission lines that oscillate against each other
- These oscillations are not as well damped as higher frequency "local" oscillations
- Energy storage-based damping controllers can mitigate these oscillations

1996 breakup caused by low-frequency oscillations



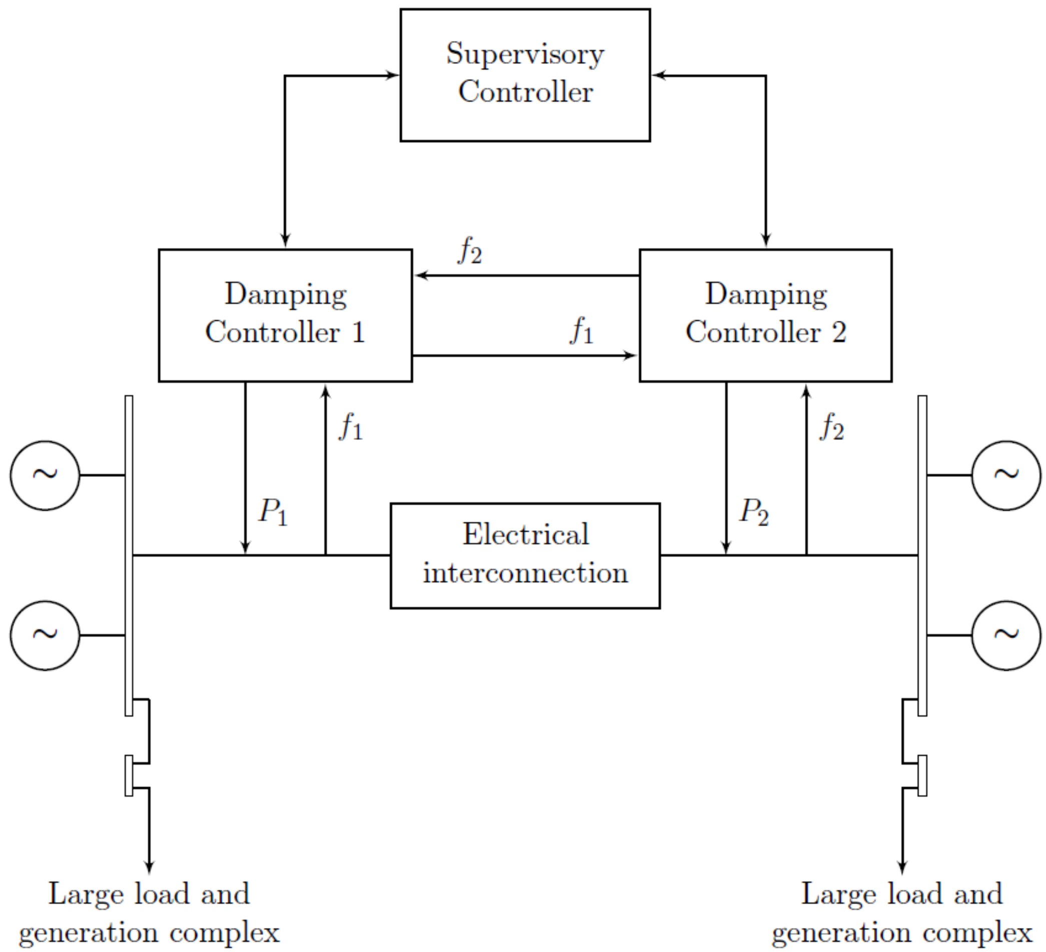
Energy Storage Controls for Grid Stability

- There are several low frequency oscillation modes in the Western Electricity Coordinating Council (WECC) region[1]
  - "North-South" mode nominally near 0.25 Hz;
  - "Alberta-BC" mode nominally near 0.4 Hz;
  - "BC" mode nominally near 0.6 Hz; and,
  - "Montana" mode nominally near 0.8 Hz.
- Researchers at Montana Tech and Bonneville Power Administration (BPA) have investigated damping controls for the WECC
- This project builds on their results



[1]D. Trudnowski, "Baseline Damping Estimates," Report to Bonneville Power Administration, September 2008.

Damping control basics



$$\Delta P_1(t) = -K_d(f_1(t) - f_2(t - \delta))$$

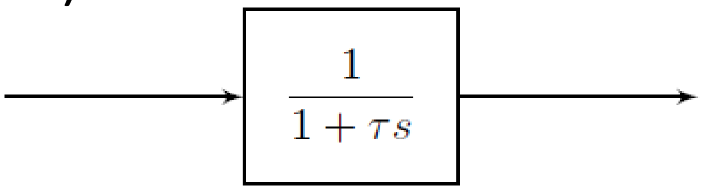
$$\Delta P_2(t) = -K_d(f_2(t) - f_1(t - \delta))$$

Project Goals

- Assess storage technologies for the damping control application
  - Develop high fidelity models
  - Perform PSLF simulations to validate performance
- Develop safeguards for the supervisory control system to insure that it can never destabilize the grid
- Develop a pilot project to be deployed in 2013

Damping Control Performance Requirements

- A typical damping control node must meet the following performance requirements:
  - Output power +/- 10MW per device, ~10 total devices
  - Bandwidth to track a $P_{command}$ signal in the 0.25-1Hz range (real power modulation)
  - Minimal latency
- Previous simulation results from BPA and Montana Tech have shown acceptable performance with a first order system model[1] (bandwidth ~ 3.2 Hz)

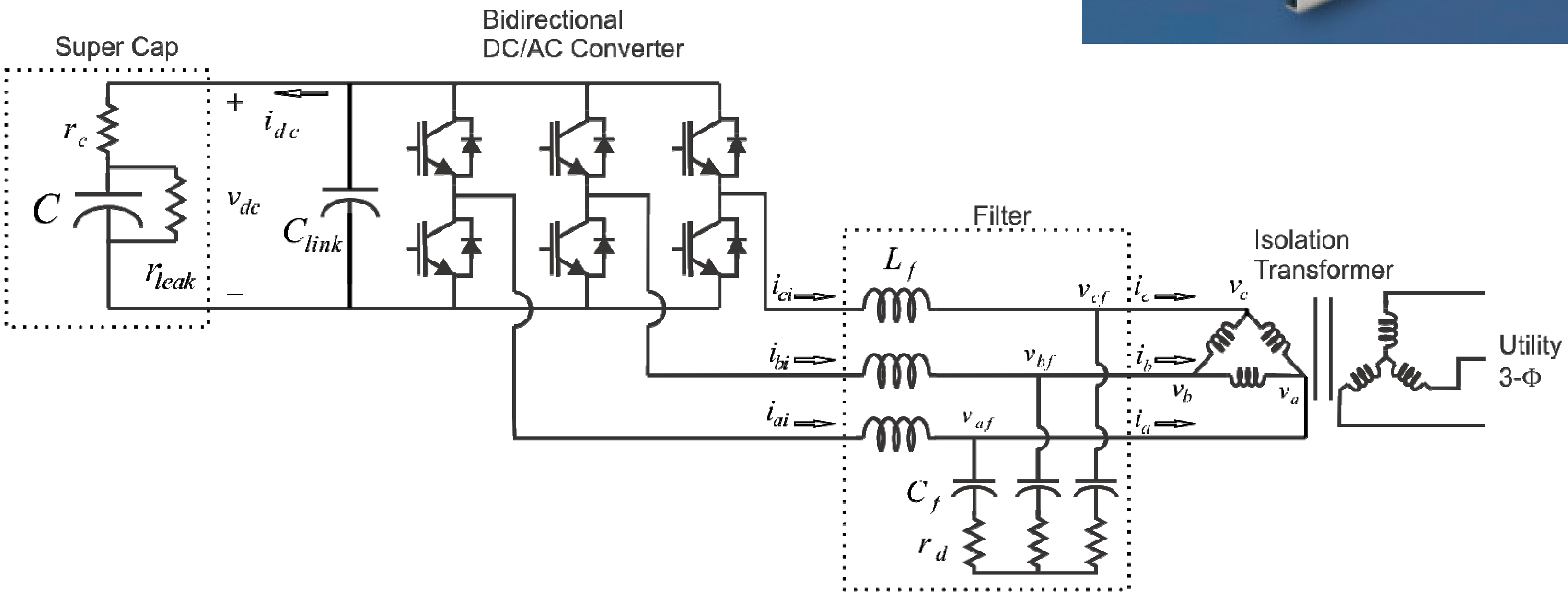


$\tau = 0.05$

[1] Dan Trudnowski, "Analytical Assessment of Proposed Controls," Report to Bonneville Power Administration under contract number 37508, September 2008.

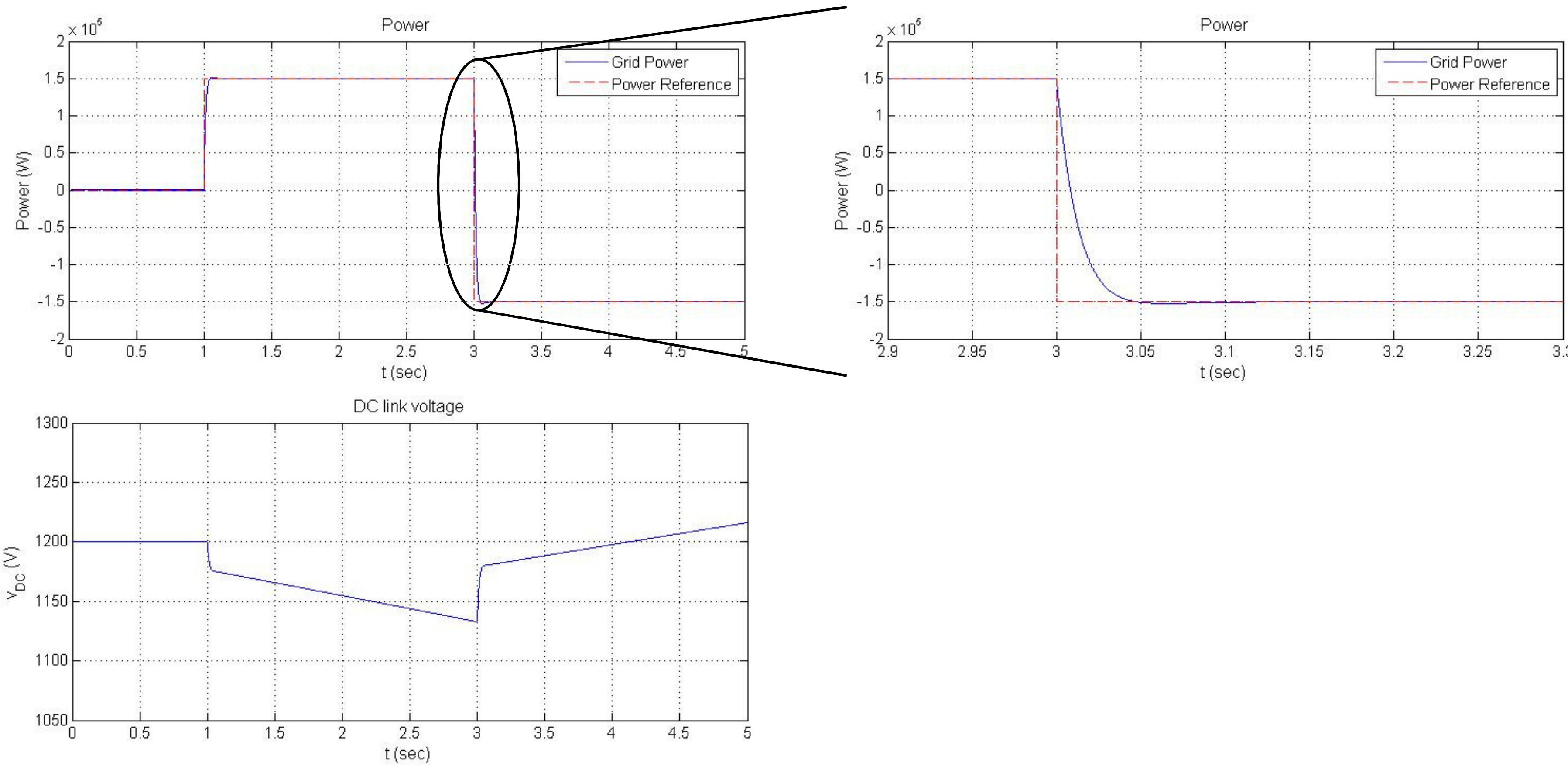
Ultra Capacitor System

- High fidelity (13th order) model based on a Maxwell Technologies ultra-capacitor
  - 125V Heavy Transportation Module
  - 1,000,000 charge/discharge cycles
  - 63F, 125V
  - Model accurate to ~10% power dissipated across the ESR



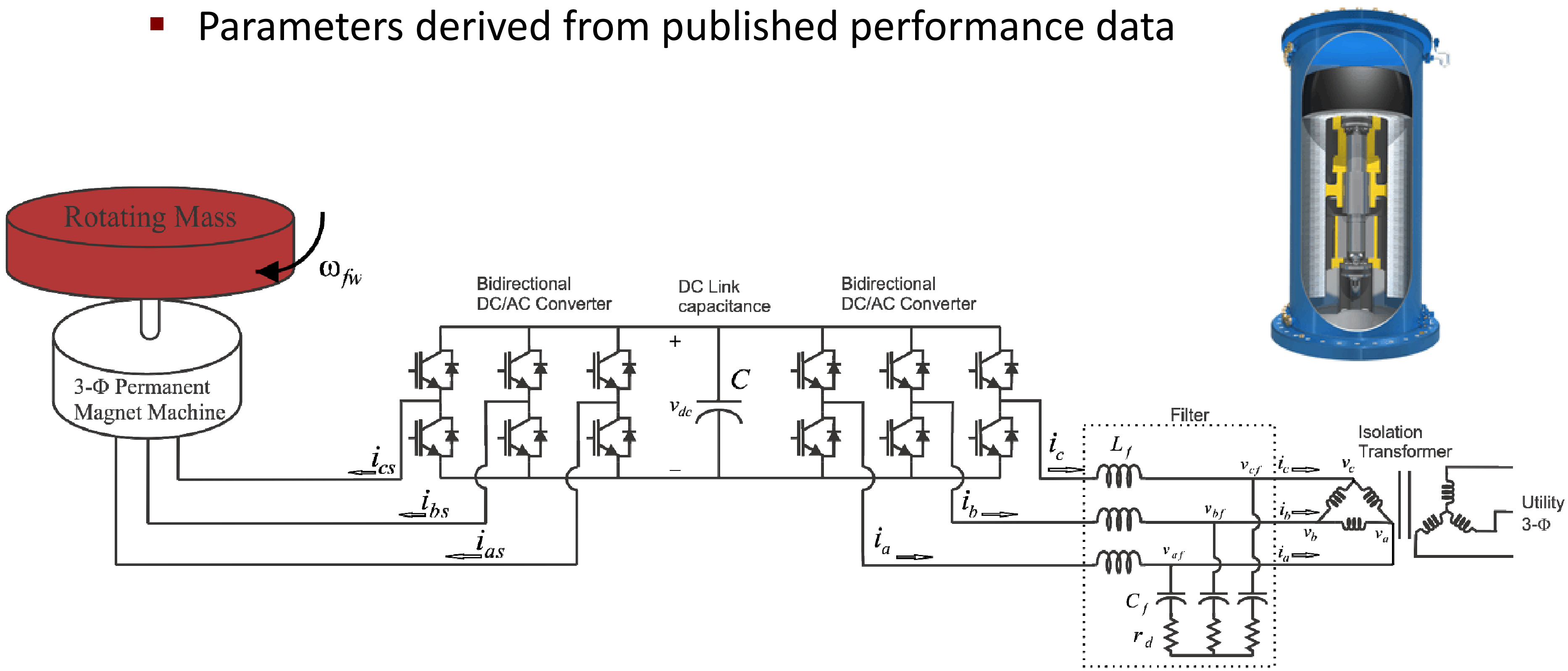
Ultra Capacitor System

- Detailed state-space models are used to simulated system with steps in power reference: 10 series-connected 63F caps



Flywheel System

- High fidelity (21st order) model based on a Beacon flywheel (Smart Energy 25 Flywheel) and Sandia custom control
  - Parameters derived from published performance data



Flywheel System

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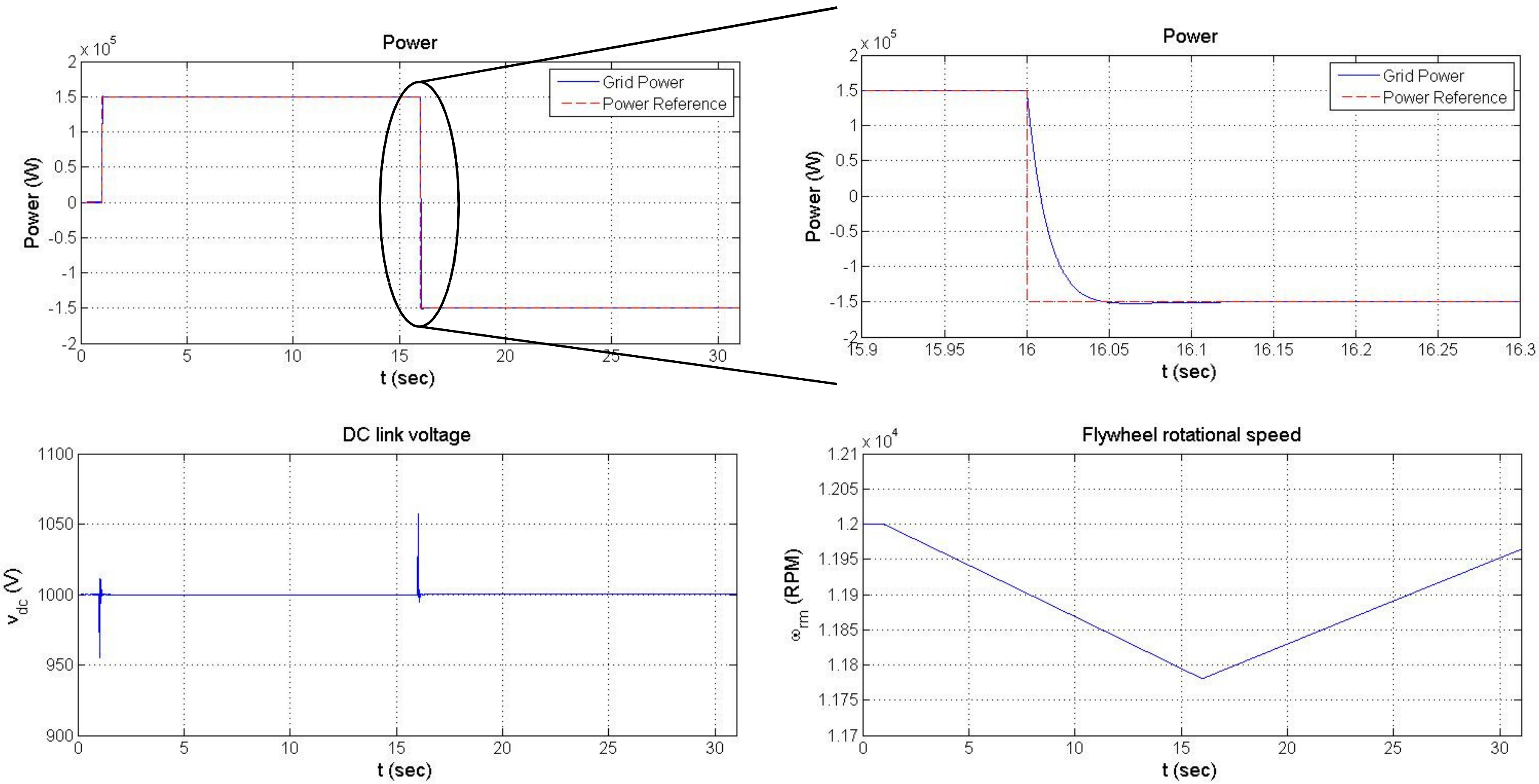
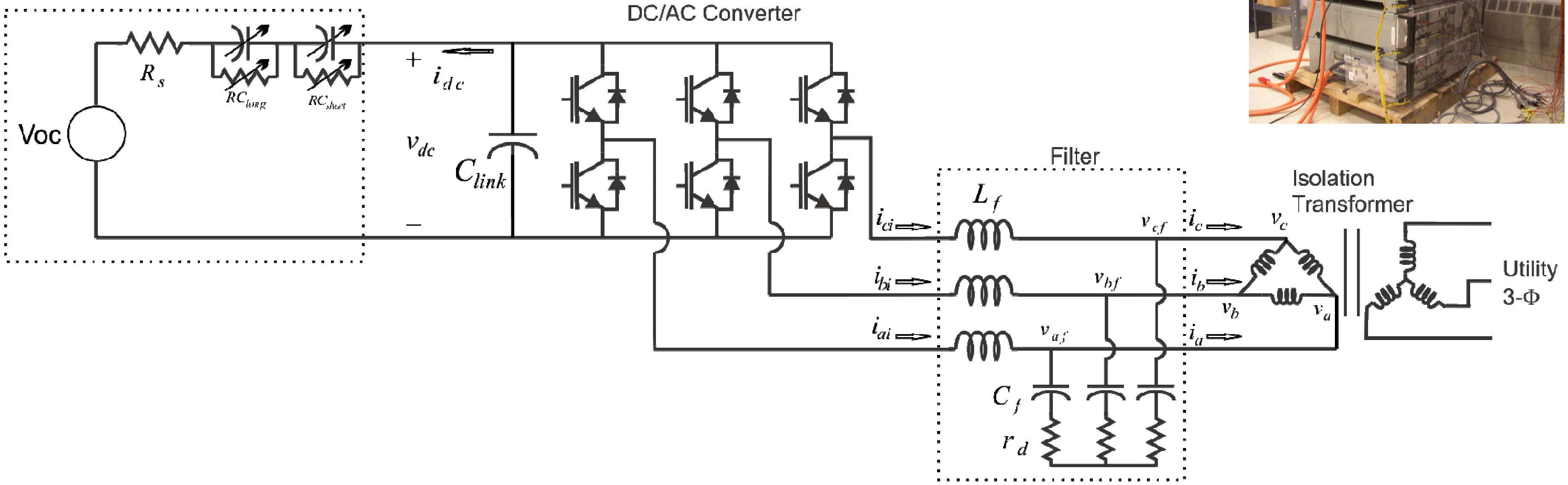


Battery System

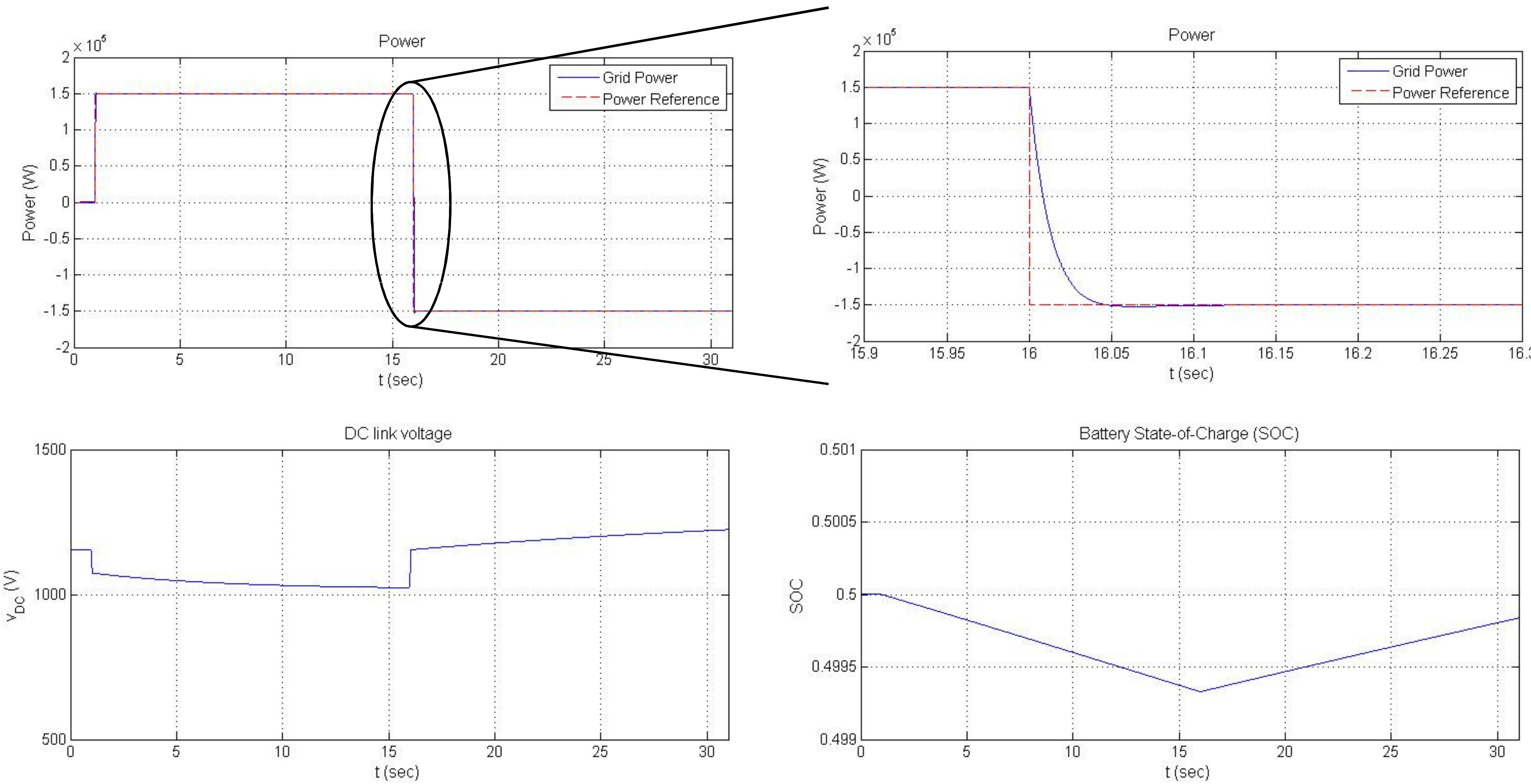
- High fidelity (15th order) model with polarization and over 60 parameters based on a carbon enhanced valve regulated lead acid battery from East Penn Manufacturing[1]



[1]D. Fregosi, S. Bhattacharya, and S. Atcitty, "Empirical Battery Model Characterizing a Utility-scale Carbon-enhanced VRLA Battery", 2011 IEEE Energy Conversion Congress and Exposition (ECCE), September 17-22, 2011, pages 3541-3548.

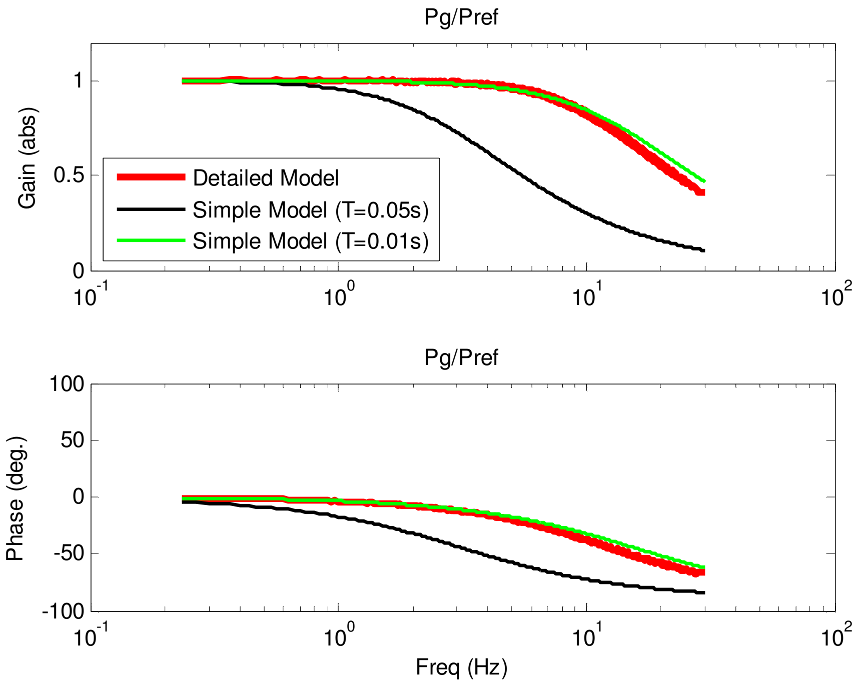
Battery System

- Detailed state-space models are used to simulated system with steps in power reference



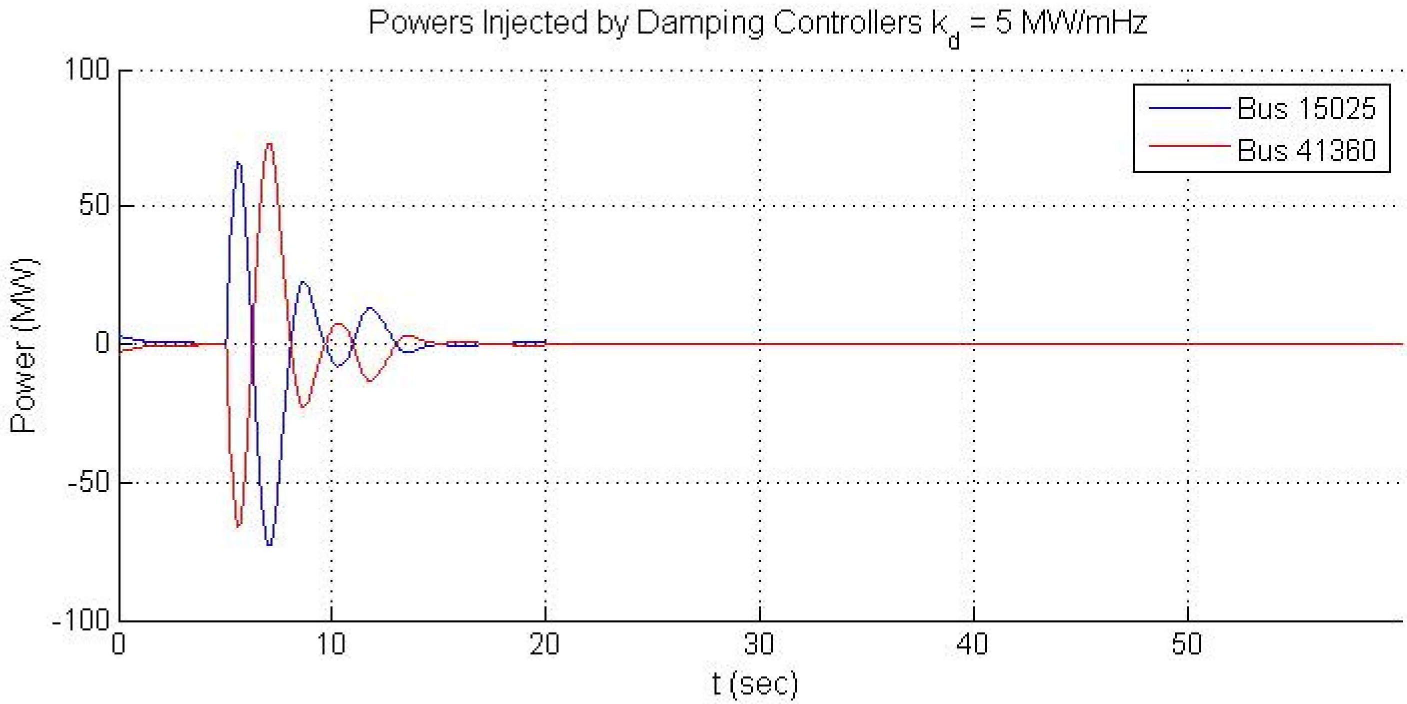
Performance Validation

- Dynamics are dominated by the control system design (PI of currents in the qd reference frame)
- First order model accurately approximates the higher order system model
- All designs exceed the bandwidth requirements of 3.2 Hz



WECC PSLF Simulation Results

- 2017 Heavy Summer Base Case
  - PSLF simulation of line fault between CBK500 and CHAPRI
  - Ultra-Capacitor based damping control nodes at **Palo Verde⇔ Coulee**
  - Power Rating +/- 100 MW with $K_d = 5$ MW/mHz



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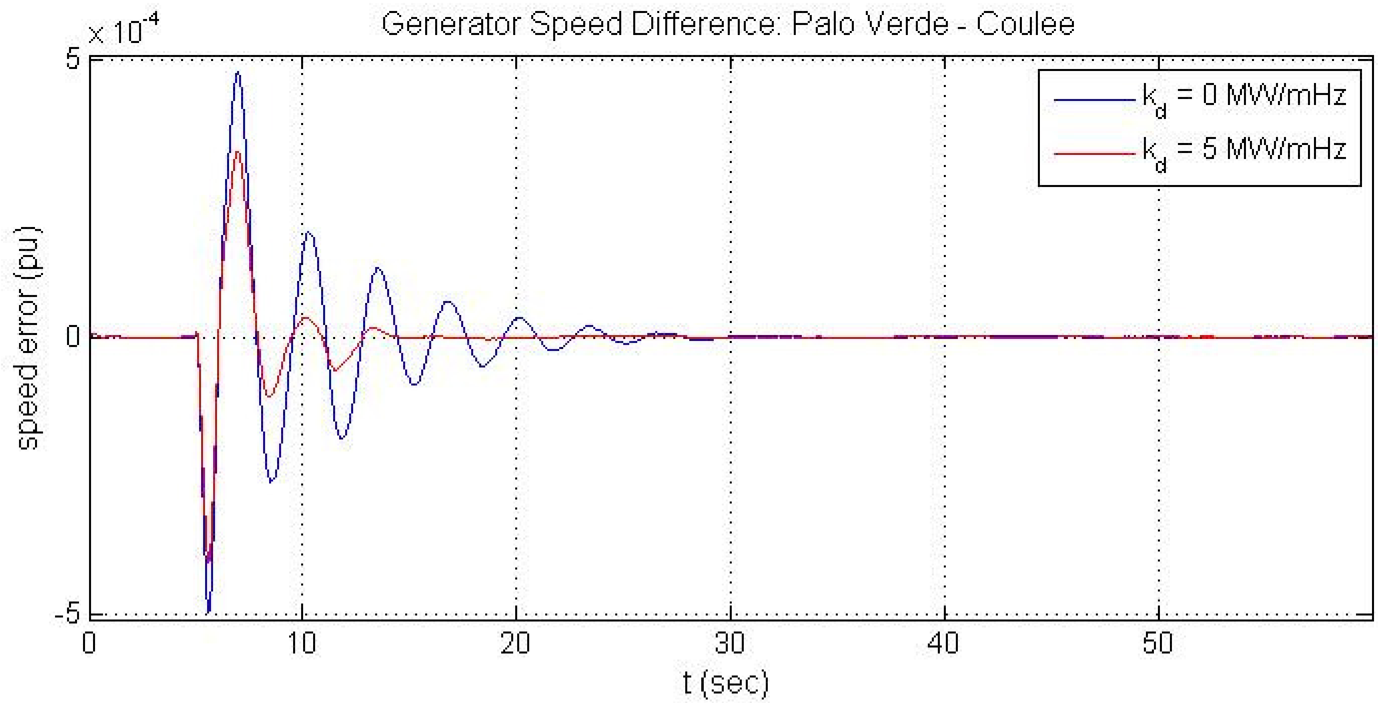
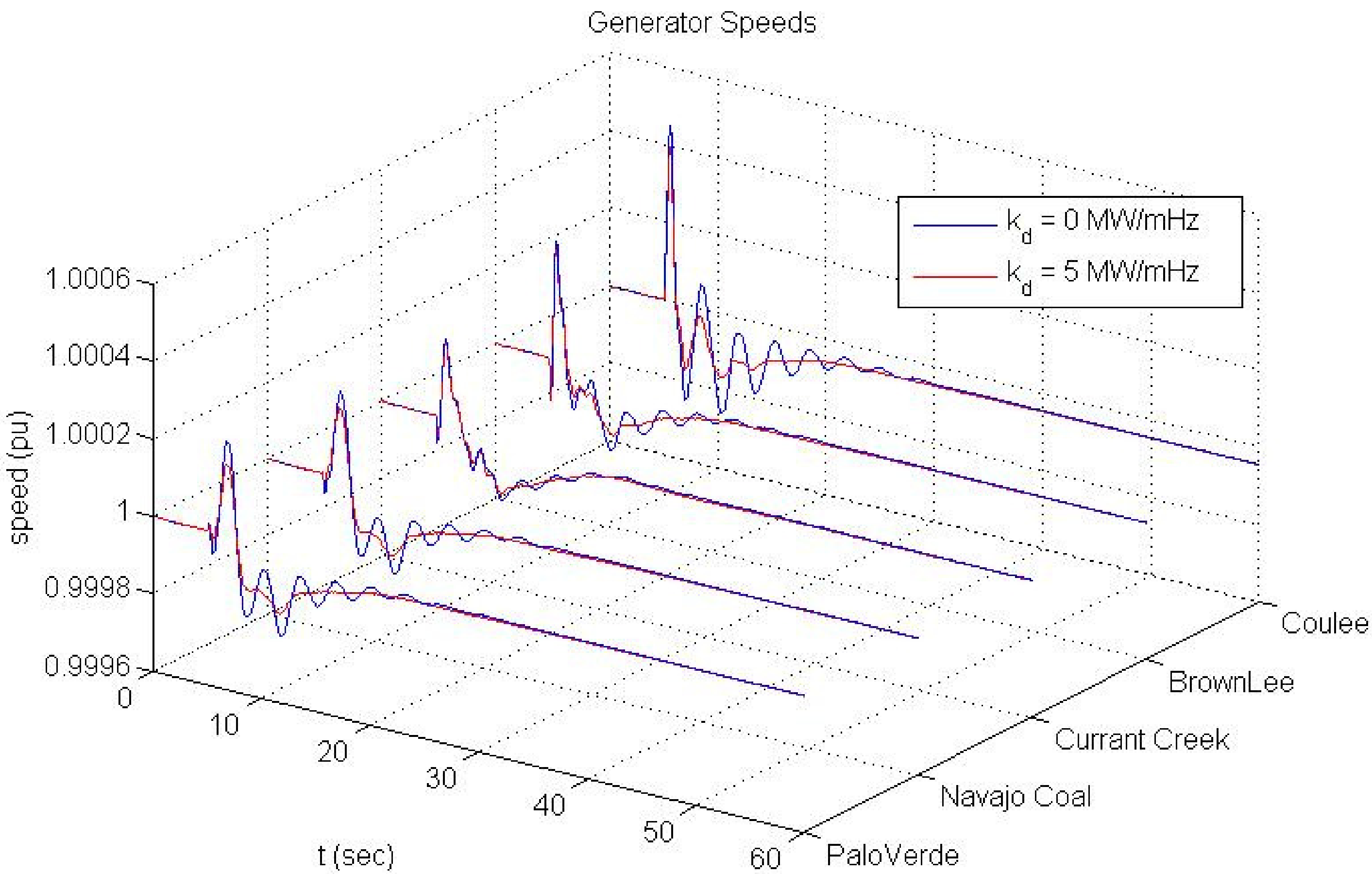


WECC PSLF Simulation Results

- Benefit is seen by several generators in the system



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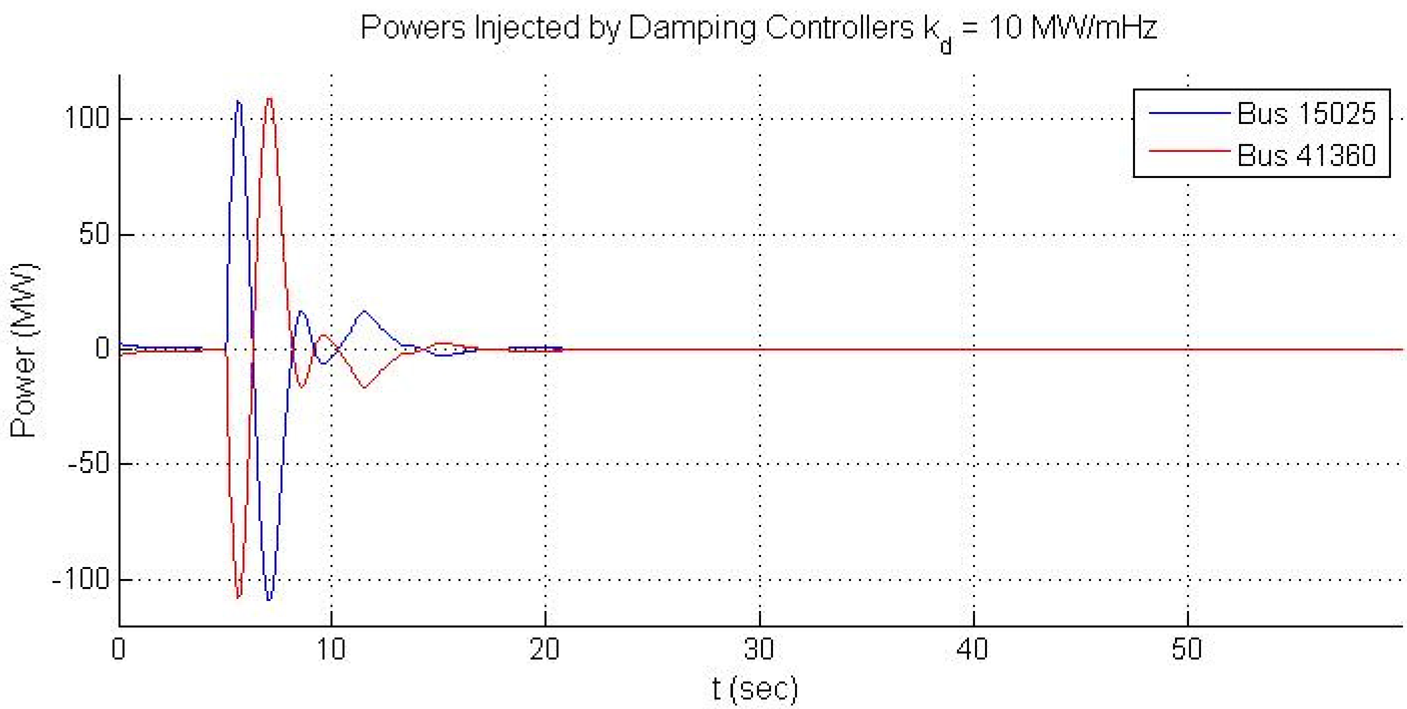

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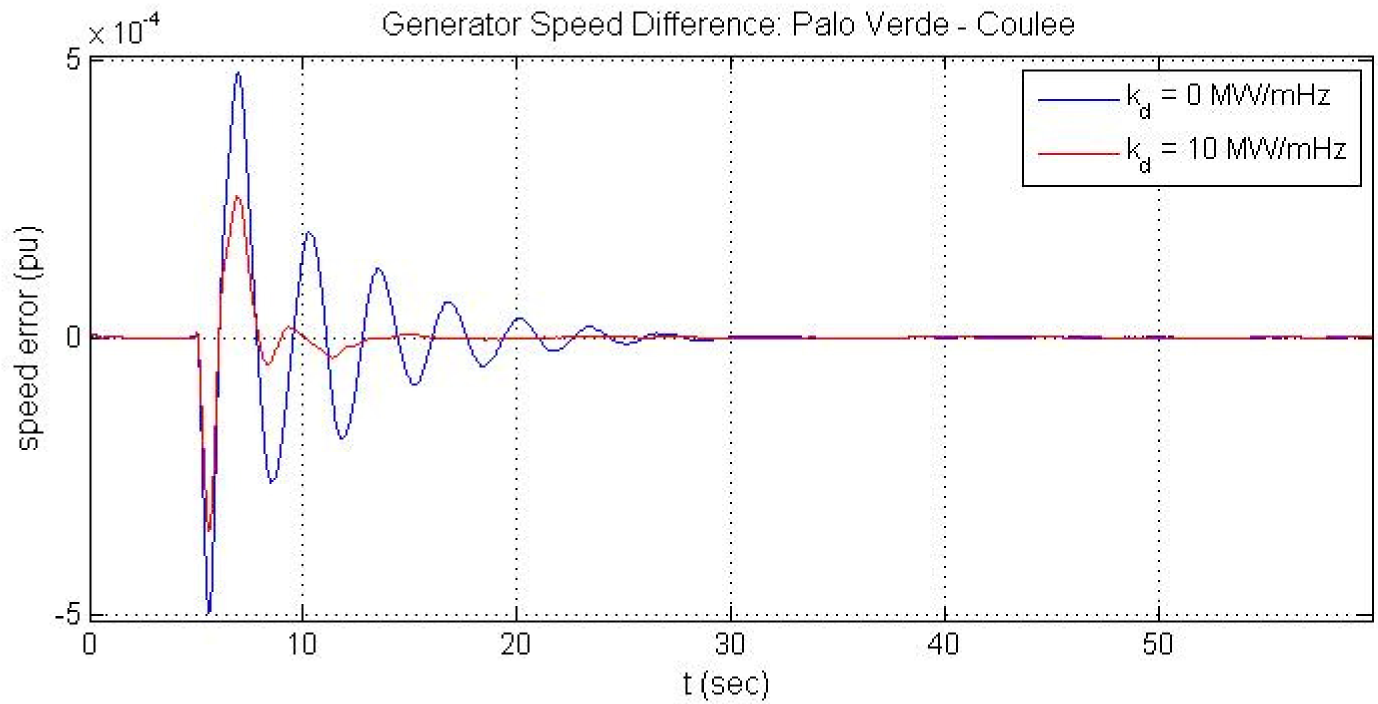

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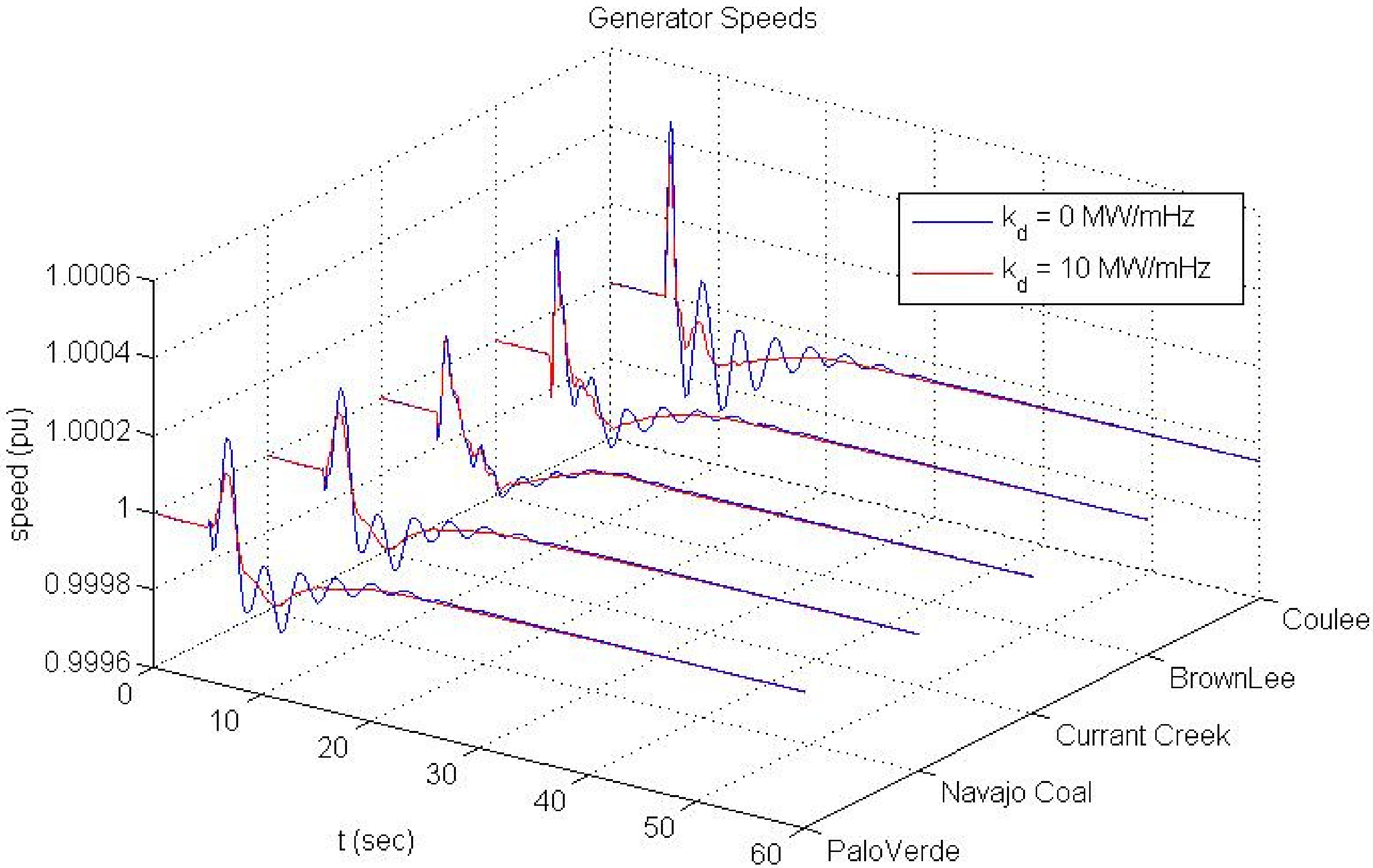
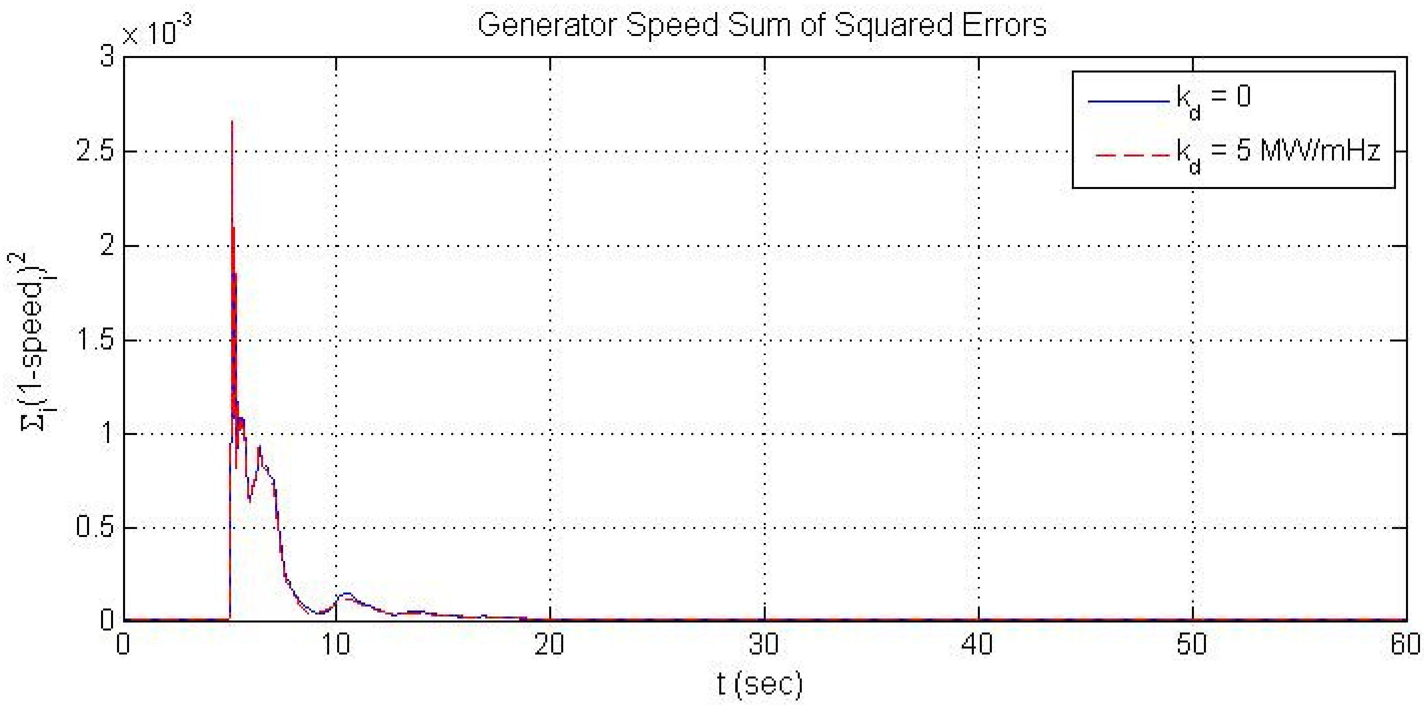


WECC PSLF Simulation Results

- Inter-area damping does not appear to effect system frequency



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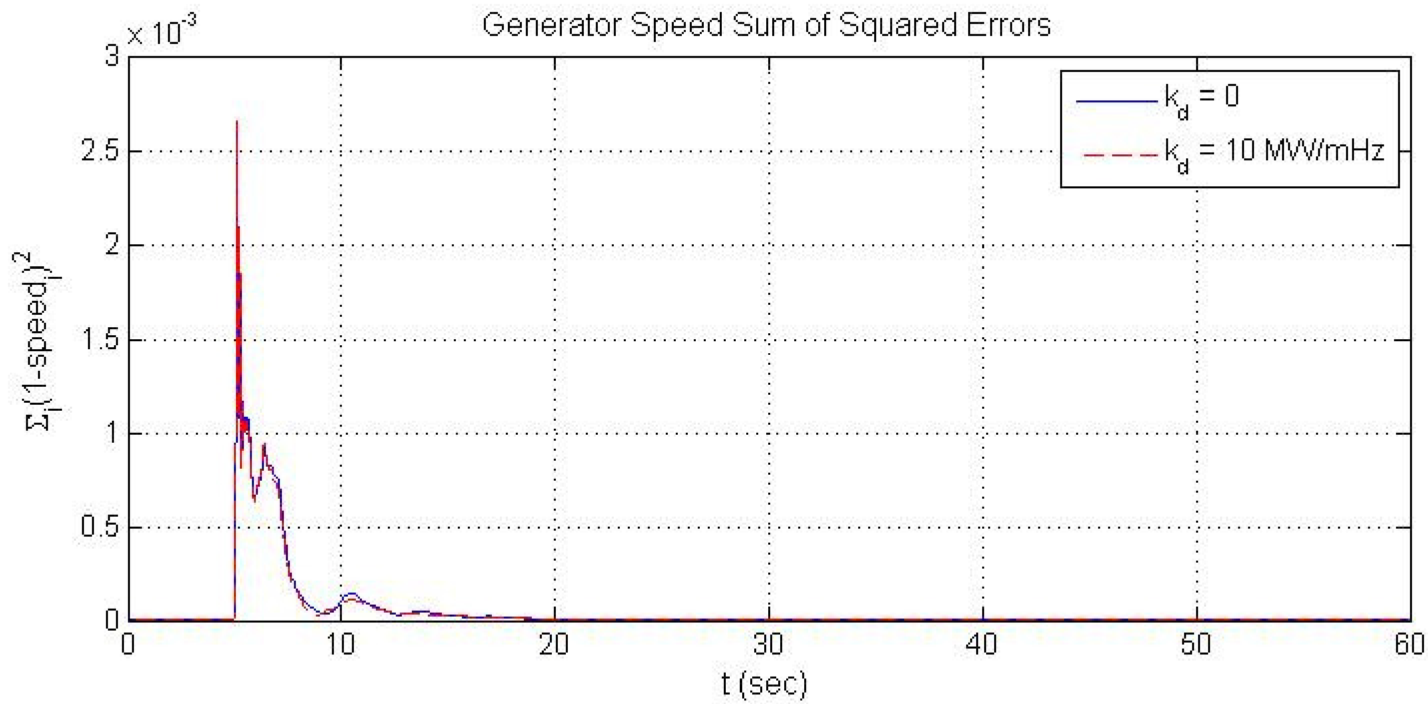


WECC PSLF Simulation Results

- The benefit of the gain K_d may be better quantified by applying Prony Analysis across a large data set to measure the damping benefit
  - Specifically, for some mode, we would like to know how much damping K_d adds to the system at that frequency:

$$d_{\mathrm{i}} = \bar{d}_{\mathrm{i}} + f_i\left(K_d\right)$$

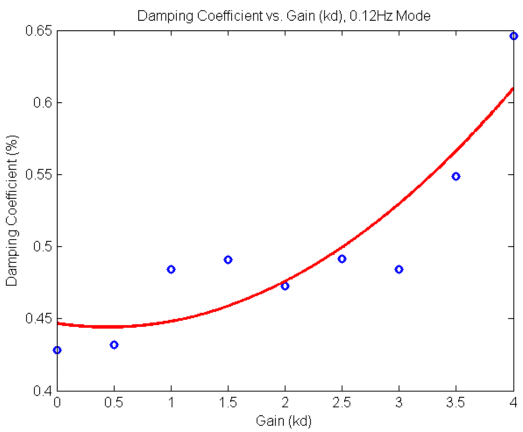
where i is the index of the mode

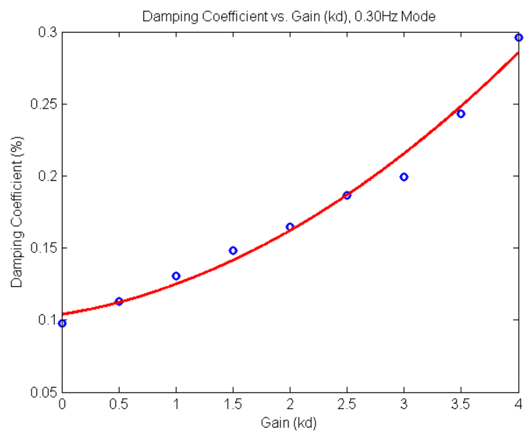
- The function f_i may be selected to give good agreement
  - Linear, quadratic, cubic … etc

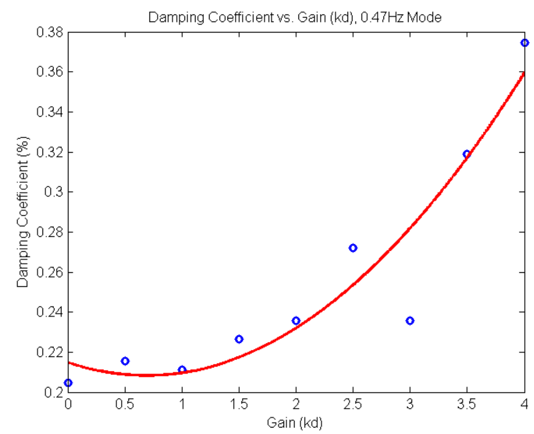
WECC PSLF Simulation Results

0.12 Hz mode | 0.30 Hz mode | 0.47 Hz mode

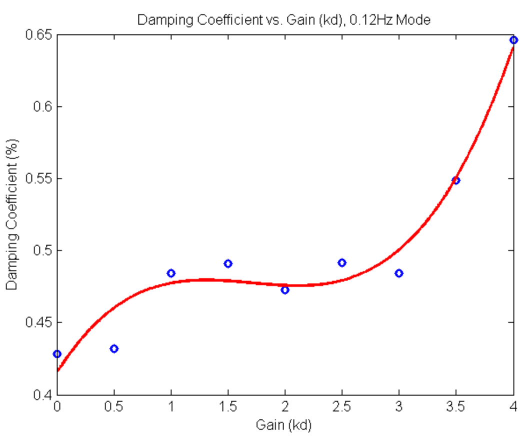
2nd order

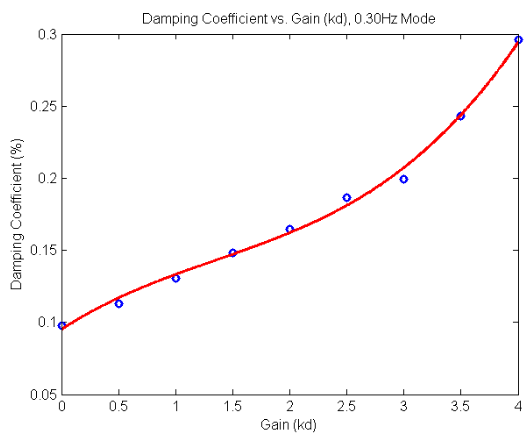


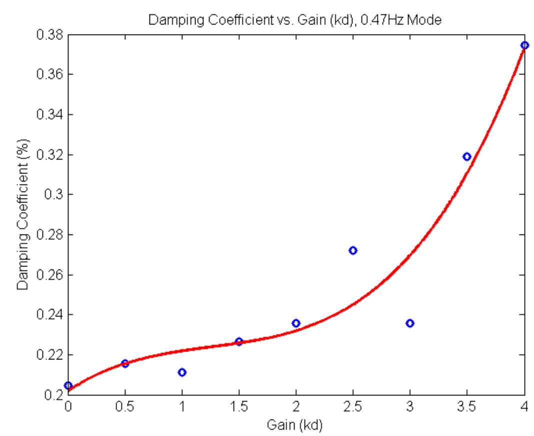




3rd order







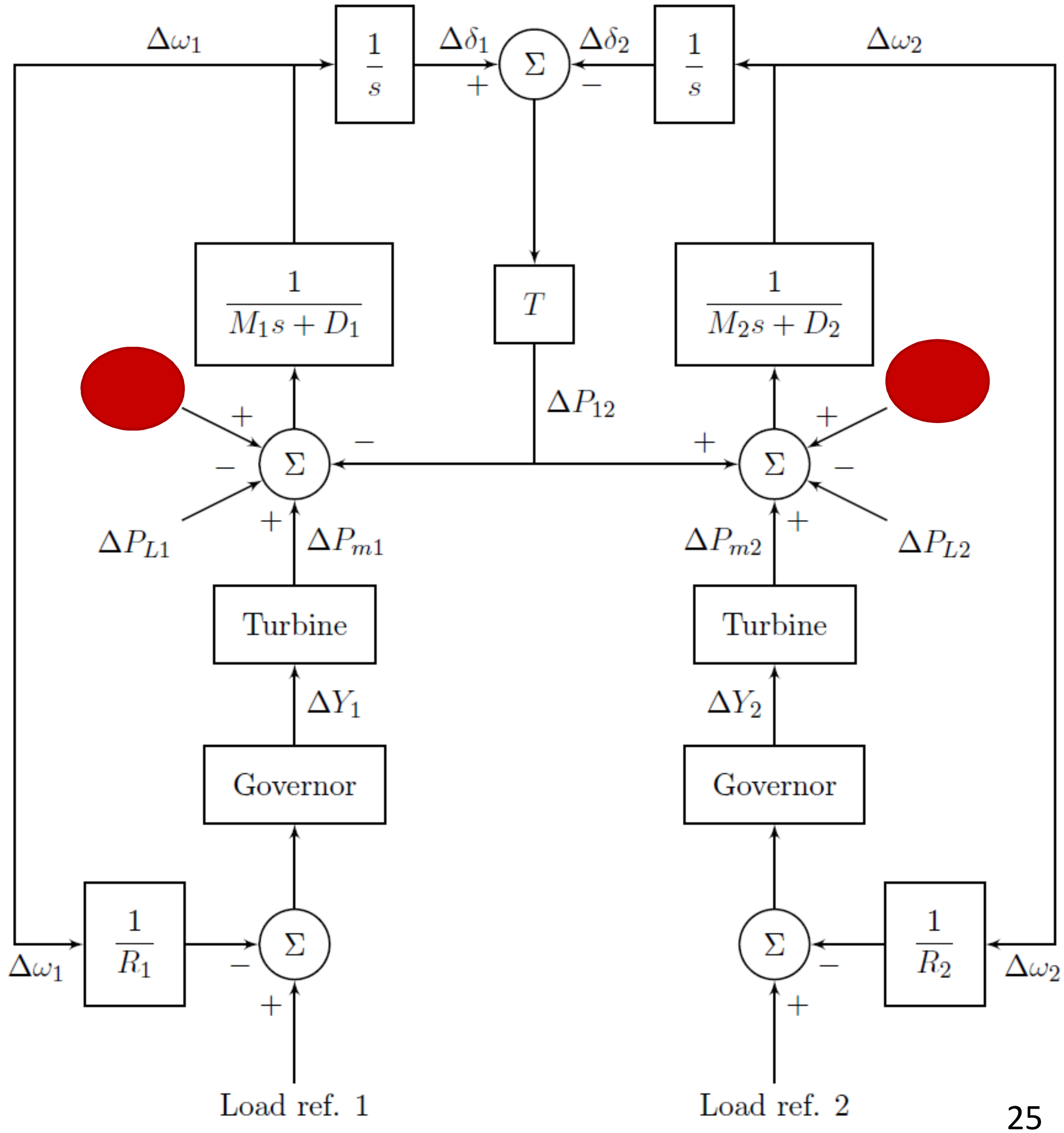
Stability Analysis

- Two-area model
- Damping controllers

have the form:

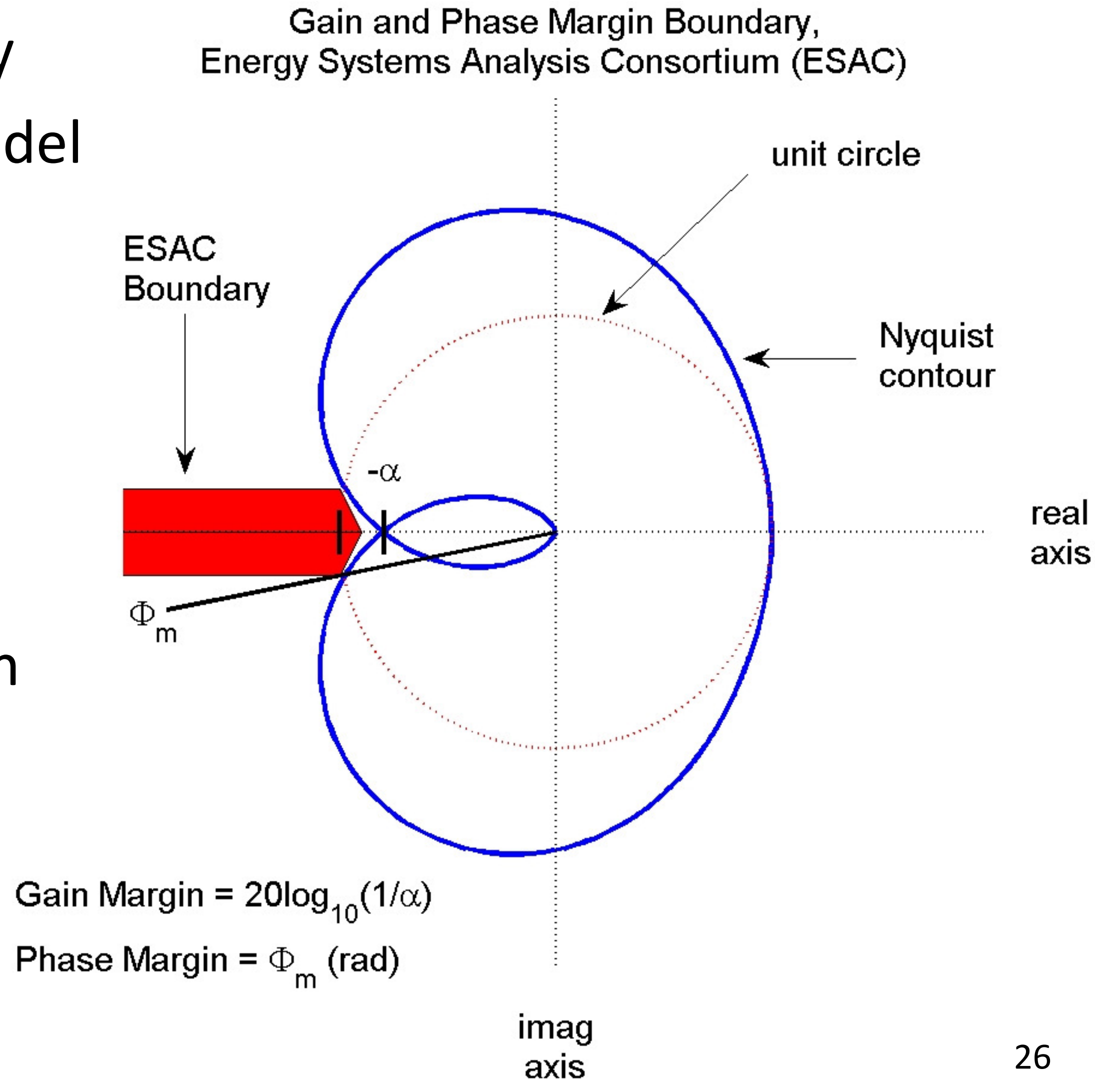
$$P_{D1}(t) = -K_d(\omega_1 - \omega_2(t - T_d))$$
$$P_{D2}(t) = -K_d(\omega_2 - \omega_1(t - T_d))$$

$$P_{D1}(s) = -K_d(\omega_1(s) - \omega_2(s)e^{-sT_d})$$
$$P_{D2}(s) = -K_d(\omega_2(s) - \omega_1(s)e^{-sT_d})$$



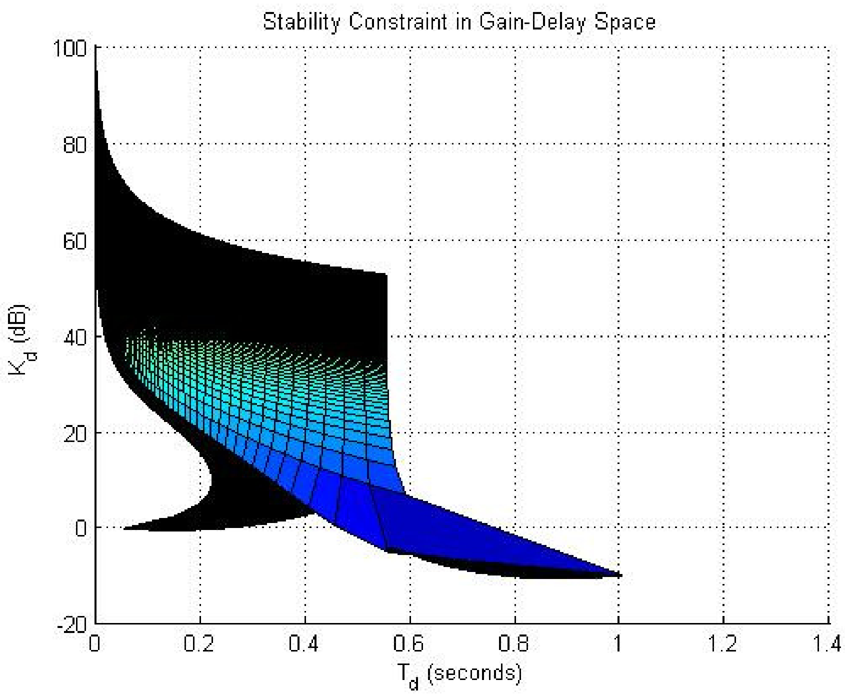
Stability Analysis

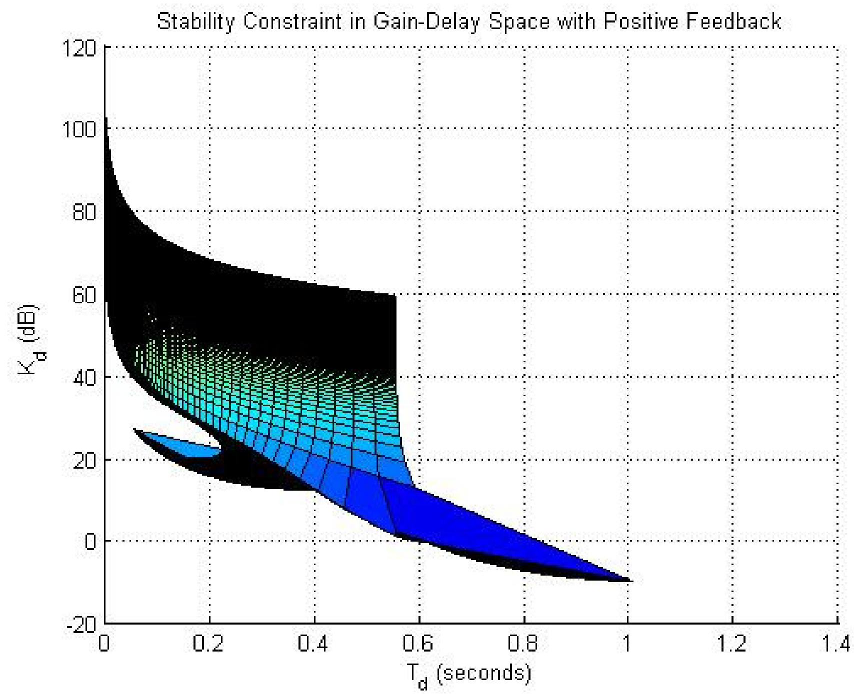
- Apply the Nyquist stability criterion to the two-area model
- Specify a relative stability margin
  - Gain margin
  - Phase margin
- ESAC Boundary
- Identify stability regions in (gain, delay) space



Stability Analysis - Results

- ESAC Boundary
  - 3 db gain margin
  - 9 degrees phase margin
- Unstable system (e.g. damping control required)





Accomplishments

- Developed high fidelity models for:
  - Ultra capacitor system
  - Flywheel system
  - Battery system
- Validated damping controller performance in PSLF using a WECC model
- Developed an analytical approach for supervisory control gain scheduling
- A Technology Innovation Proposal to Bonneville Power Administration was accepted for a follow-on demonstration project (co-funded by DOE)

Contact Information

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