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PDCI Wide-Area Damping Control: PSLF Simulations of the 2016 Open and Closed Loop Test Plan

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Abstract

To demonstrate and validate the performance of the wide-area damping control system, the project plans to conduct closed-loop tests on the PDCI in summer/fall 2016. A test plan details the open and closed loop tests to be conducted on the PDCI using the wide-area damping control system. To ensure the appropriate level of preparedness, simulations were performed in order to predict and evaluate any possible unsafe operations before hardware experiments are attempted. This report contains the results from these simulations using the power system dynamics software PSLF (Power System Load Flow, trademark of GE). The simulations use the WECC (Western Electricity Coordinating Council) 2016 light summer and heavy summer base cases.

Keywords: Inter-Area Oscillations; Small Signal Stability; Phasor Measurement Units; Wide-Area Damping Control.

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TABLES

Table 1.	Operating conditions of WECC system cases studied	20
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NOMENCLATURE

AGC	Automatic Generation Control
BPA	Bonneville Power Administration
BL	Base load, refers to baseload conventional generation set to run at constant output power
COI	California-Oregon Intertie
CU	Conventional generating unit
DOE	Department of Energy
GW	Gigawatt, 10^9 watts
GR	Governor responsive, refers to generation equipped with a governor control system
Hz	Hertz, units are cycles per second
MVA	Megavolt amperes, 10^6 volt-amperes
MVar	Megavolt amperes reactive, 10^6 volt-amperes reactive
MW	Megawatt, 10^6 watts
NG	No governor, refers to generation that is not equipped with a governor control system
PDCI	Pacific DC Intertie
PSLF	GE's Positive Sequence Load Flow program employed for power system transient simulation
PSS	Power System Stabilizer
SNL	Sandia National Laboratories
WECC	Western Electricity Coordinating Council
WSIS	Western Wind and Solar Integration Study

1. INTRODUCTION

1.1. Background and Motivation

The Wide-Area Damping Control Project is a collaborative project between Sandia National Laboratories (SNL), Montana Tech University (MTU), and the Bonneville Power Administration (BPA), jointly funded by the BPA Technology Innovation (TI) Office, the Department of Energy (DOE)/Office of Electricity (OE) Transmission Reliability Program, and the DOE/OE Energy Storage Program. This project utilizes a control scheme that can mitigate inter-area oscillations by active power injection to increase the damping of inter-area oscillatory modes. The control system uses real-time phasor measurement unit (PMU) feedback to construct a commanded power signal to modulate the real power flow on the Pacific DC Intertie (PDCI). The control system is currently operating in open-loop mode, i.e., the commanded power signal is not being sent to the PDCI controller. Fig. 1 shows a block diagram of the closed loop set up where the controller is represented as $C(s)$ and the power system as $G(s)$. $H(s)$ is derivative-like transfer function used to obtain frequencies Δf from voltage angle differences $\Delta\theta$. Note that in the configuration in Fig. 1 there are two possible mechanisms to actuate with the power system: through the controller output signal (P_{cmd}) noted as *PDCI Command Signal* and using a probing signal (P_{probe}) called *PDCI Probe Signal*. This probing signal represents an input to the PDCI and is used to stimulate the system with different waveforms. Note that P_{probe} can come from the controller during open loop testing. The scenarios simulated in this testplan, however, include both open-loop experiments as well as closed-loop experiments wherein the commanded power signal will be sent to the PDCI controller.

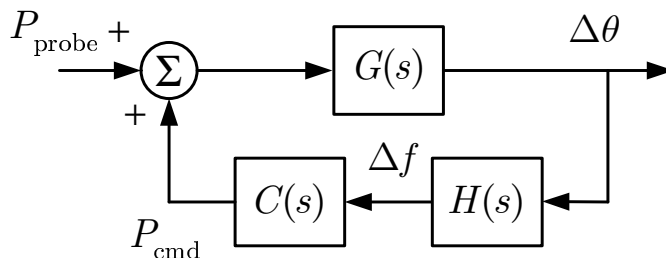


Figure 1. Block diagram of the controller setup.

To demonstrate and validate the performance of the wide-area damping control system, the project plans to conduct closed-loop tests on the PDCI in summer/fall 2016. A test plan (currently in draft form, subject to BPA approval) details the open and closed loop tests to be conducted on the PDCI using the wide-area damping control system. To ensure the appropriate level of preparedness, simulations were performed in order to predict and evaluate any possible unsafe operations before hardware experiments are attempted. This report contains the results from these simulations using the power system dynamics software PSLF (Power System Load Flow, trademark of GE). The simulations use the WECC (Western Electricity Coordinating Council) 2016 light summer and heavy summer base cases. Table 1 summarizes some main operating characteristics of the two base cases including the real power flow on the PDCI as well as the real and reactive flows on the California-Oregon Intertie (COI). A custom model of the controller was developed using PSLF to run the simulations. The results of all test plan simulations are shown in this report. The simulation scenarios are described briefly in the next section.

1.2. Overview of Simulation Scenarios

The simulation results presented herein are divided into four chapters. Chapter 2 presents results for the Light Summer 2016 case study for simulations with open-loop and closed-loop control of the damping controller. Likewise, Chapter 3 presents results for the Heavy Summer 2016 case with open-loop and closed-loop control. Open-loop scenarios include several probe tests wherein power commands are made

Table 1. Operating conditions of WECC system cases studied

Quantity	Light Summer 2016	Heavy Summer 2016
PDCI Active Power (MW)	1950	3100
COI Active Power (MW)	2650	3810
COI Reactive Power (MVar)	-437	-440

to the Pacific DC Intertie (PDCI) via the *PDCI Probe Signal* to excite the power system with a known stimulus. Closed-loop scenarios include several of these same probe-tests as well as a Chief Joseph Brake insertion. For Chapters 2 and 3, the following simulation scenarios were investigated.

Open Loop calibration tests:

- Base case, no event, no probe (150 seconds)
- ± 200 MW pulses of 0.5 seconds, 4 pulses total alternating up and down with 2.5 seconds between each pulse
- +20MW (10 seconds) and -20 MW (10 seconds)
- ± 20 MW multi-sine-function (MSF) for 100 seconds
- ± 125 MW sine function (SF) at 0.1 Hz for four cycles
- ± 125 MW sine function at 0.3 Hz for four cycles
- ± 125 MW sine function at 1.0 Hz for four cycles

Close loop tests with different gains and control limits:

- Chief Joe Brake insertion, 0.5 seconds (approximately 1400 MW)
- ± 200 MW pulses of 0.5 seconds, 4 pulses total alternating up and down with 2.5 seconds between each pulse, control limit of 125 MW
- ± 200 MW pulses of 0.5 seconds, 4 pulses total alternating up and down with 2.5 seconds between each pulse, control limit of 50 MW
- ± 200 MW pulses of 0.5 seconds, 4 pulses total alternating up and down with 2.5 seconds between each pulse, control limit of 35 MW
- ± 20 MW multi-sine-function for 100 seconds
- ± 125 MW sine function at 0.1 Hz for four cycles

The controller gains simulated included $K_d = 0, 3, 6, 9, 12$, and 18 MW/mHz. The commanded power signal sent to the PDCI, labeled *PDCI Command Signal*, is based on the frequency difference between the Pacific Northwest and California-Oregon areas which corresponds to the buses Big Eddy and Malin respectively.

In addition, this report includes simulations of large (rare but significant) events that could occur, however unlikely, during the closed-loop tests. Chapters 4 and 5 include these results for the Light and Heavy summer cases respectively. For these results, the Chief Joe Brake insertion, 200 MW pulses with control limit at 125 MW, and 20 MW multi-sine function tests listed above were applied with the following large events simulated:

- Forced oscillation at Grand Coulee of 90 MW peak-to-peak
- Double Palo Verde outage
- Columbia Generating Station (CGS)

The large events were simulated: 1 second into the Chief Joe Brake simulation, 1 second into the 200 MW pulses simulation, and 20 seconds into the multi-sine function simulation.

Longer multi-sine function (MSF) tests of 10 minutes and 20 minutes, where the 100 second MSF is repeated for 6 and 12 periods, will also be conducted in the open and closed loop tests. However, only one period is simulated.

1.3. Discussion of Results

The results for each scenario are presented consecutively with key quantities plotted versus time. Quantities include the PDCI Probe Signal used for defining power commands for probe tests, the PDCI Command Signal which defines the power command from the damping controller, PDCI power, real and reactive power flows on select lines, as well as voltage magnitudes, electrical angles, and frequencies at key buses. Some plot labels and captions include an abbreviated description of the event for brevity; for example:

- SF 0.1/4x refers to the sine function at 0.1 Hz for four cycles
- MSF 1/30/1/100 refers to the multi-sine function whose: highest frequency at which the signal amplitude is 1 is 1Hz, smallest frequency at which the signal amplitude is 0 is 30 Hz, with a roll-off rate of first order after 1Hz and with a duration of 100 seconds.

For these simulation studies, the results are evaluated primarily based on the amplitude and relative affect on system damping as seen in the frequency differences, bus voltages and flows. Specifically, operating the damping controller in closed-loop should not cause the amplitude of any dynamic response to increase and should not cause oscillations to damp slower following a system stimulus. In fact, closed-loop operation should improve damping and mitigate system response in select scenarios.

After analysis of all simulations, the controller behaved as expected and was observed to yield improved system damping. In no case did the controller degrade the system response. In particular, the beneficial action of the controller can be noticed in the events corresponding to the Chief Joseph Brake insertion presented in Sections 2.2.1 and 3.2.1 for the Light and Heavy Summer Cases respectively.

It is noted that a base case simulation (no event) was run for 150 seconds; these scenarios are presented first in chapters 2 and 3 for each of the base cases. The base case shows a small scale (± 10 MW) oscillation in real power flow on Path 75. This small oscillation is in the base case, and therefore also in all other simulation cases.

2. CASE STUDY: LIGHT SUMMER 2016

2.1. Open Loop Testing

2.1.1. *Test System: Light Summer 2016. Controller Open Loop. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe*

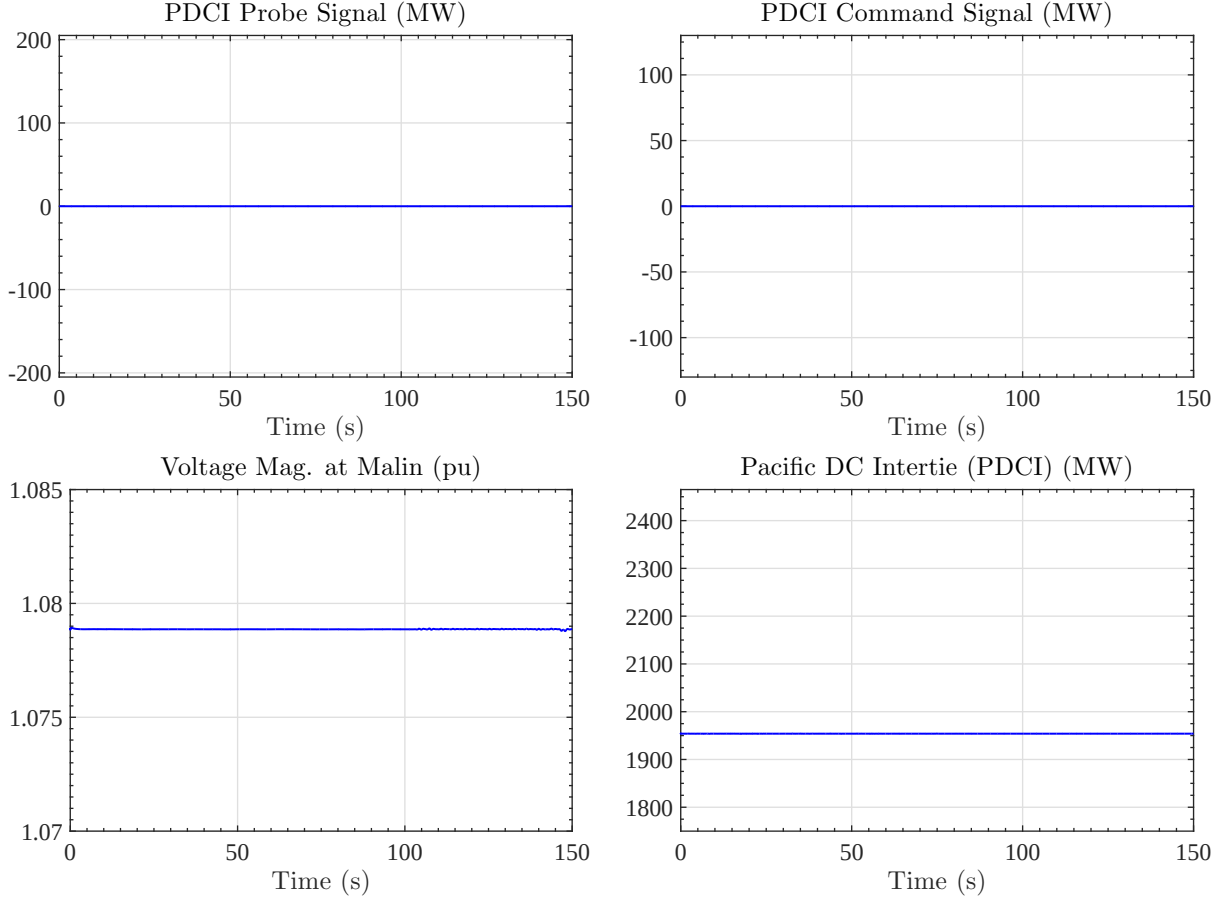


Figure 2. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

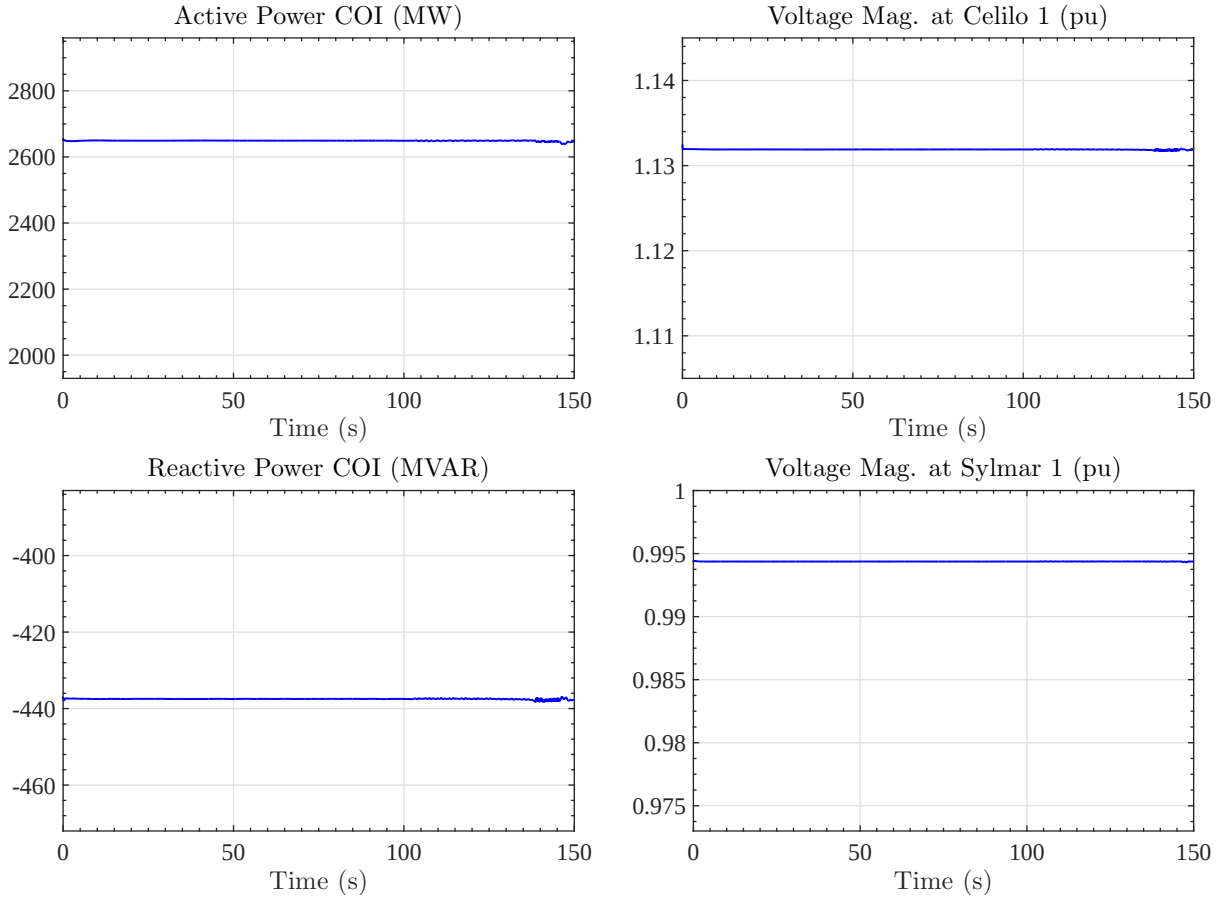


Figure 3. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

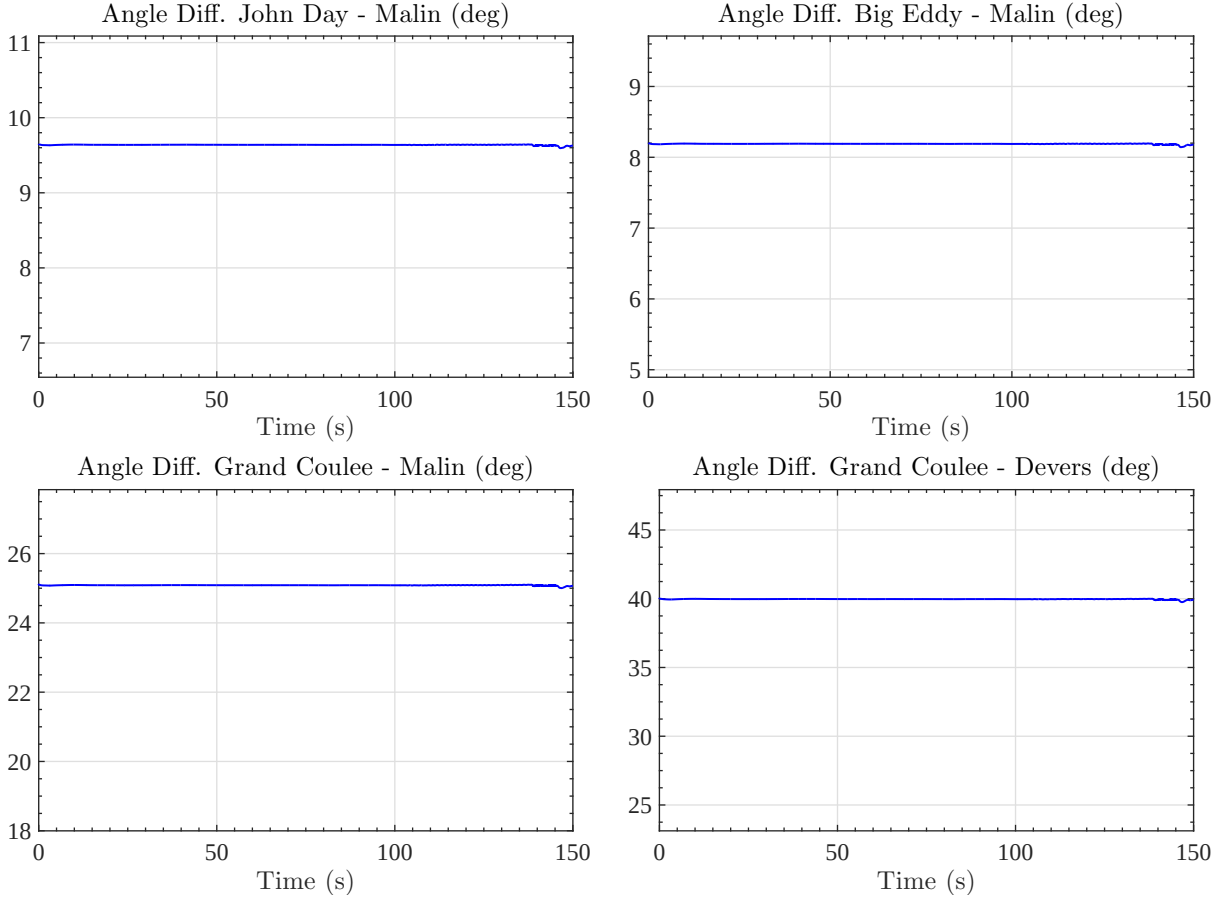


Figure 4. Angle differences. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

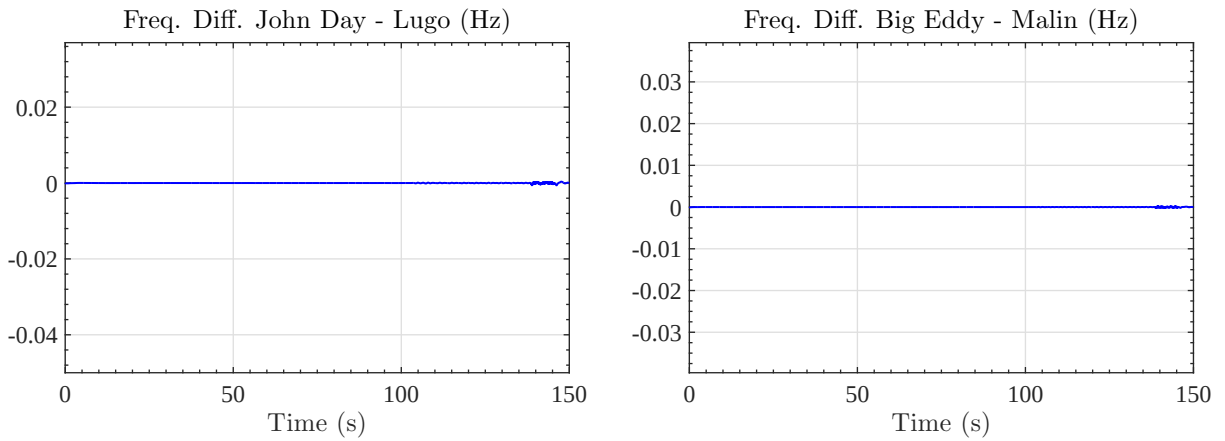


Figure 5. Frequency differences. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

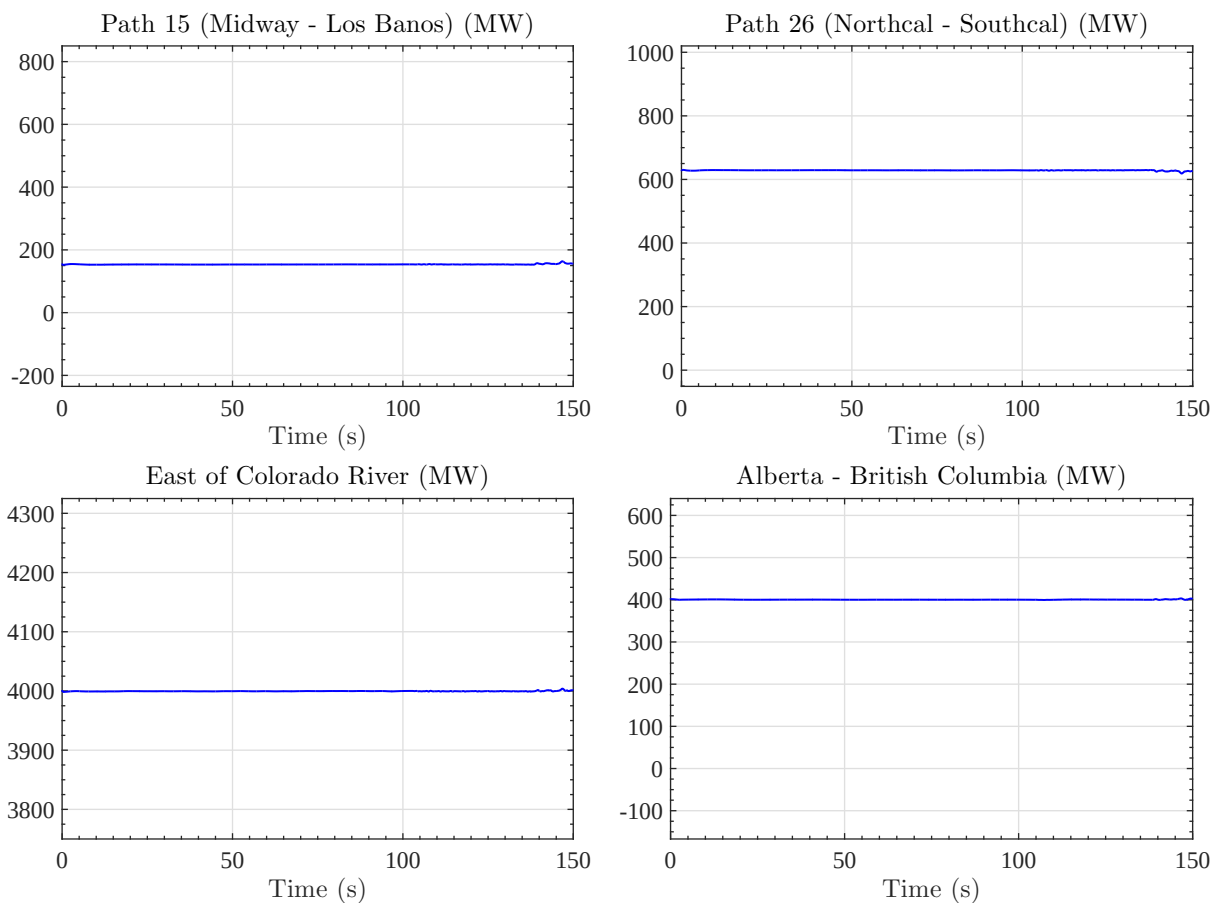


Figure 6. Active power flows. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

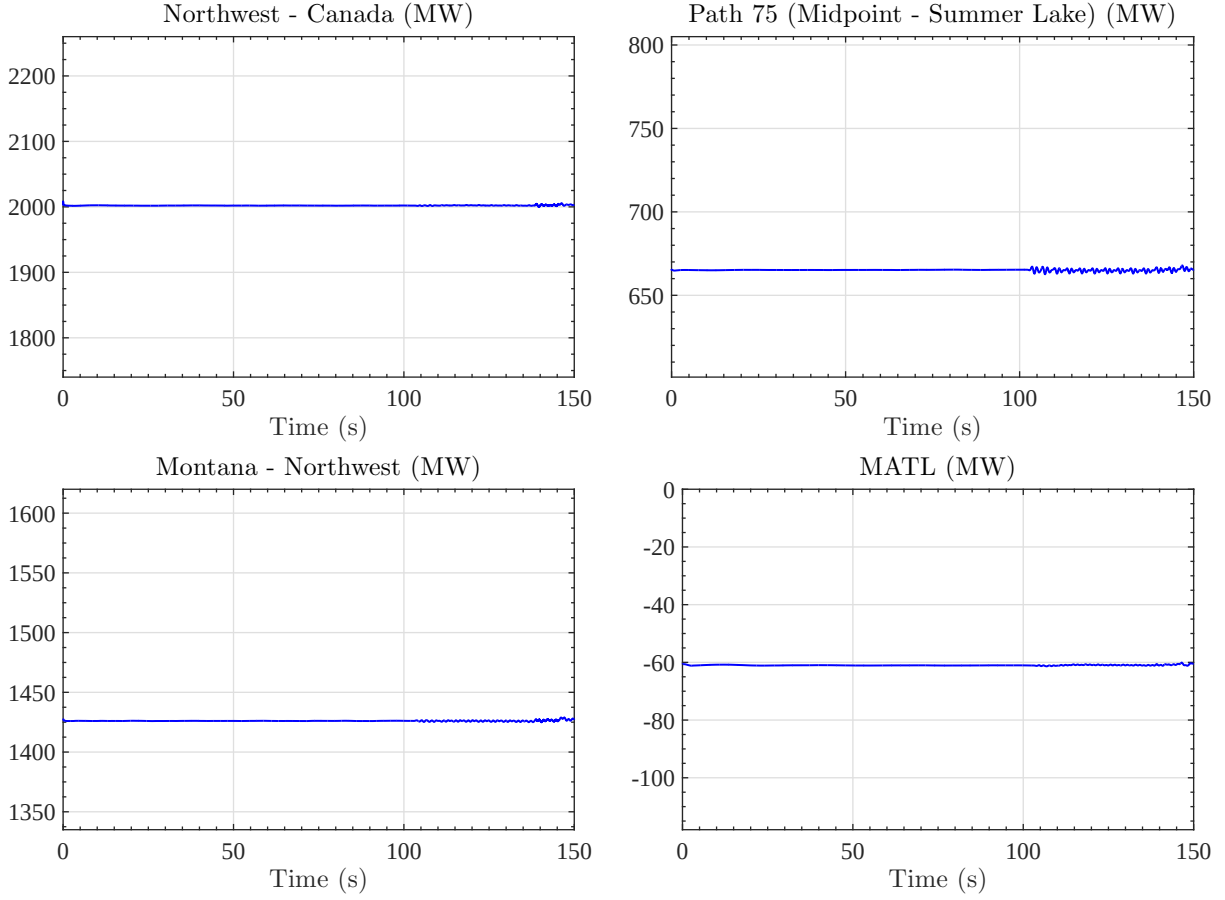


Figure 7. Active power flows. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

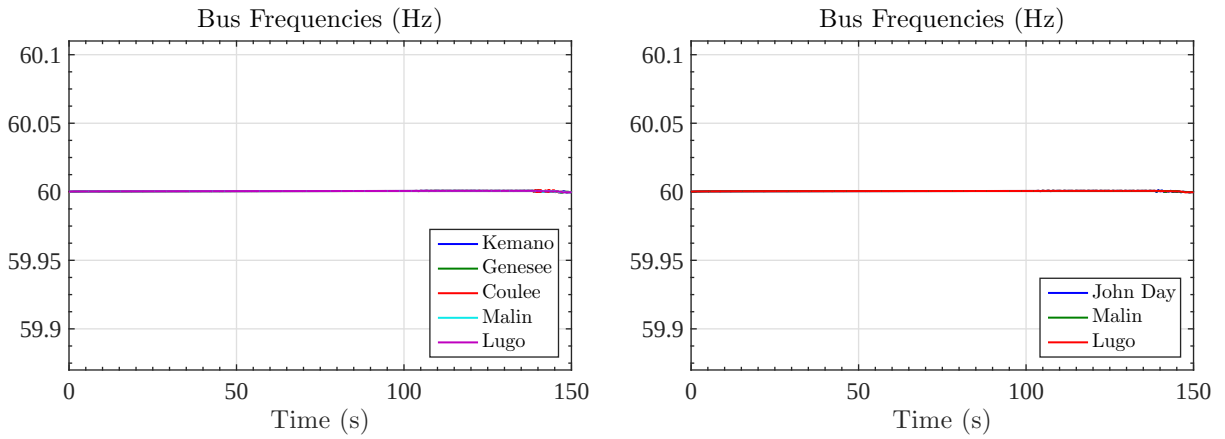


Figure 8. Bus frequencies. Event: WECC Light Summer ran for 150 seconds: Base case, no event, no probe.

2.1.2. *Test System: Light Summer 2016. Controller Open Loop. Event: 200 MW positive and negative pulses*

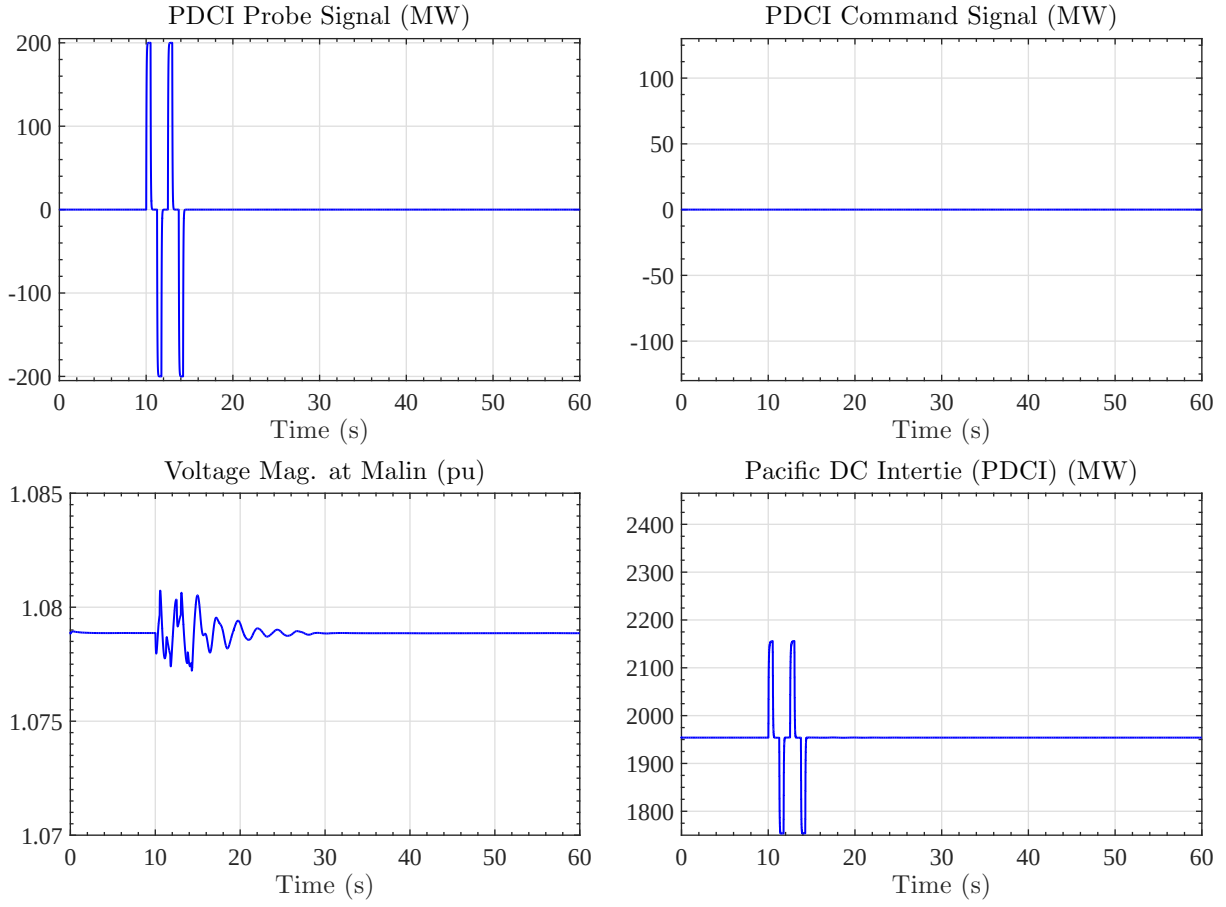


Figure 9. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW positive and negative pulses.

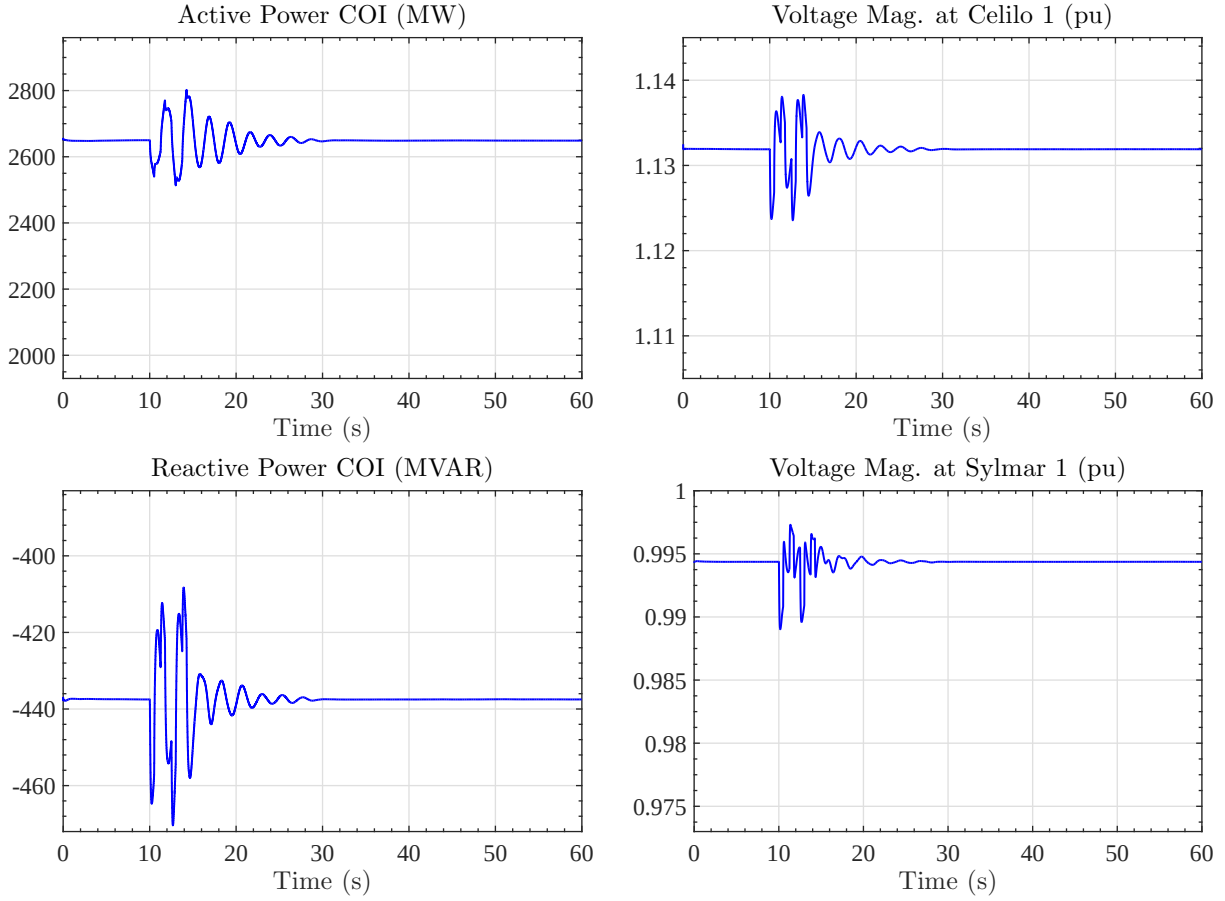


Figure 10. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW positive and negative pulses.

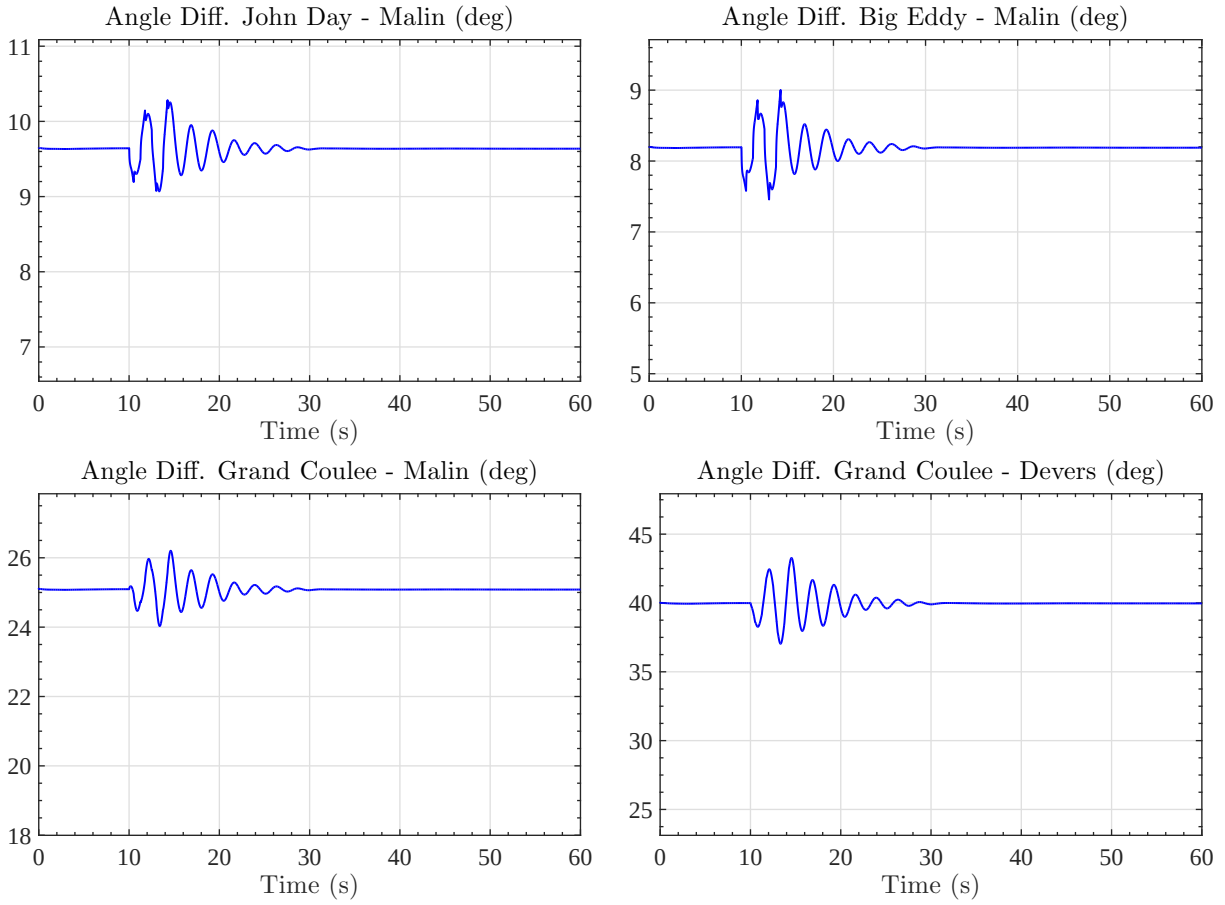


Figure 11. Angle differences. Event: 200 MW positive and negative pulses.

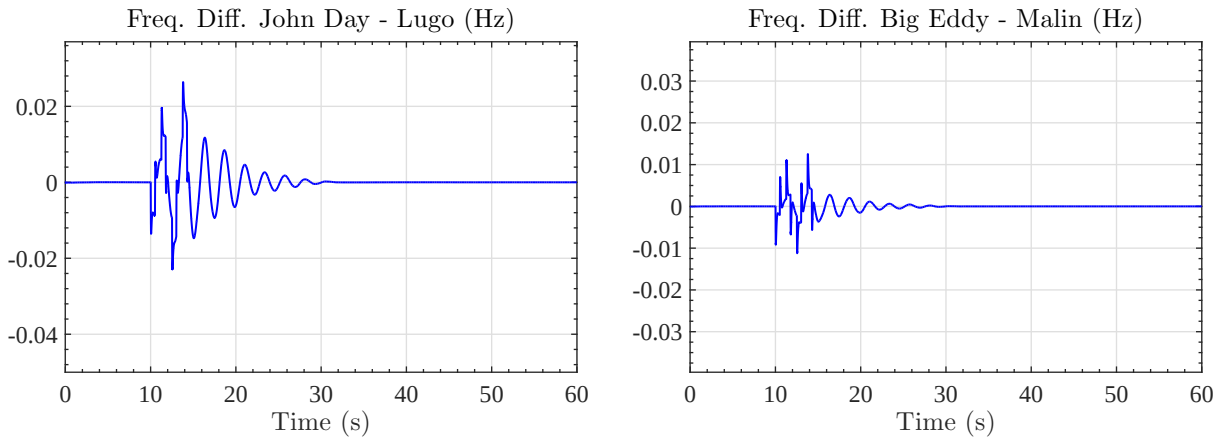


Figure 12. Frequency differences. Event: 200 MW positive and negative pulses.

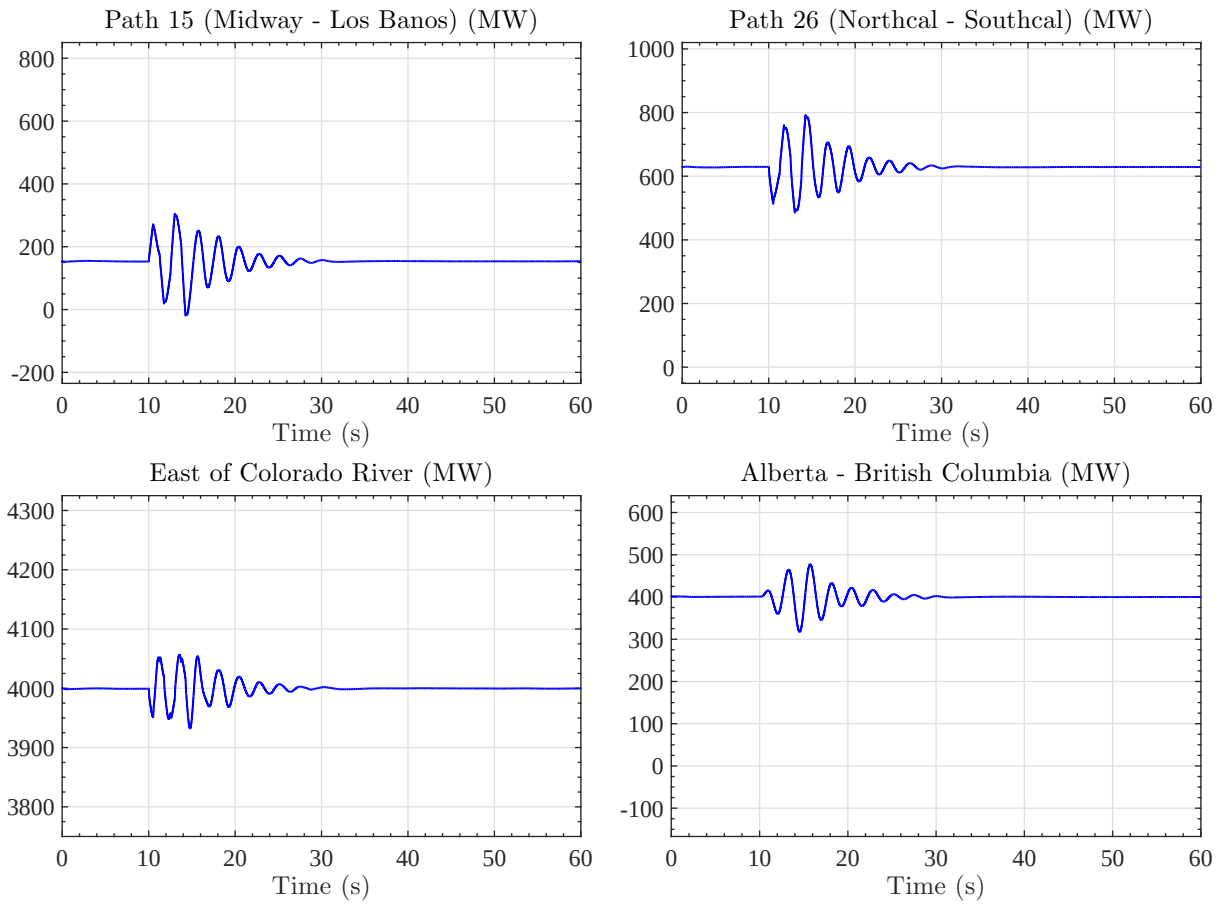


Figure 13. Active power flows. Event: 200 MW positive and negative pulses.

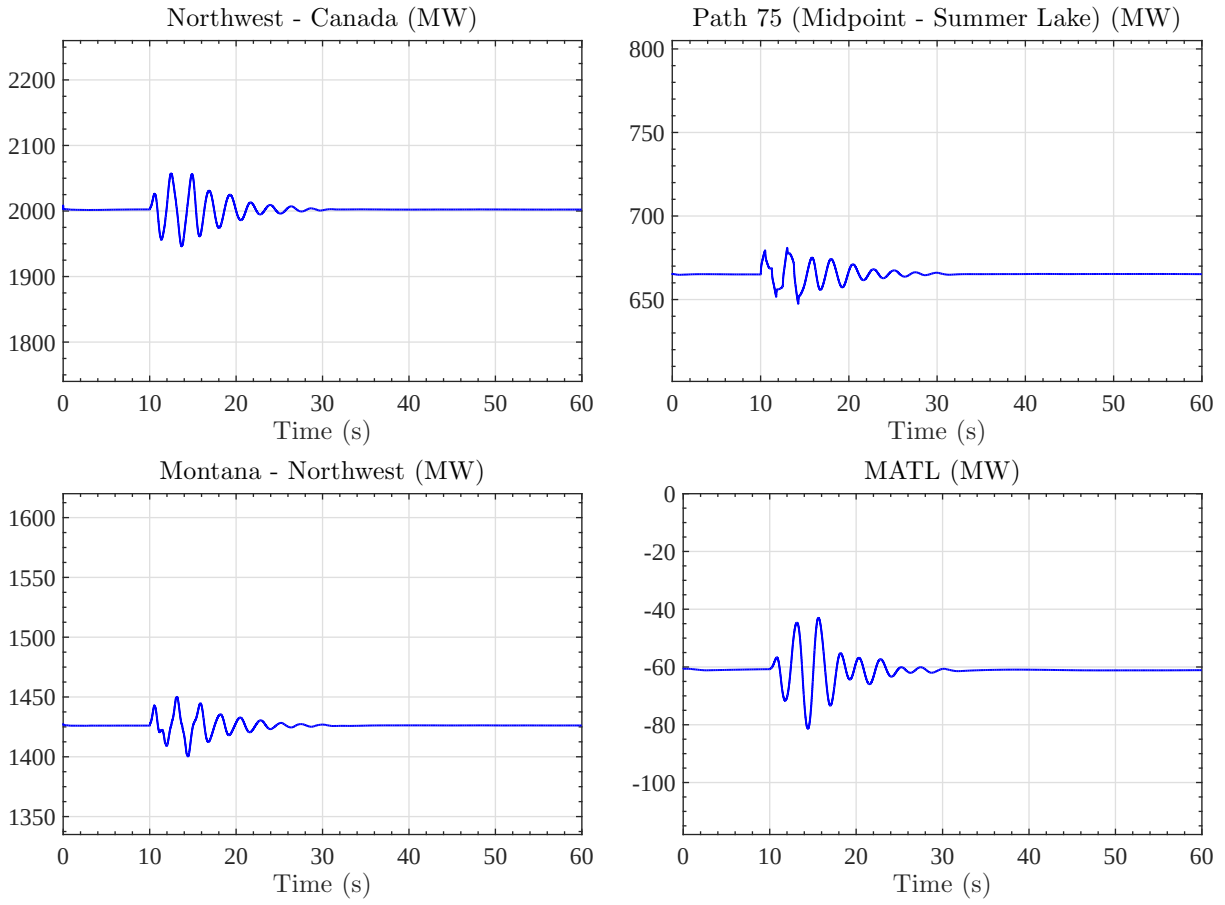


Figure 14. Active power flows. Event: 200 MW positive and negative pulses.

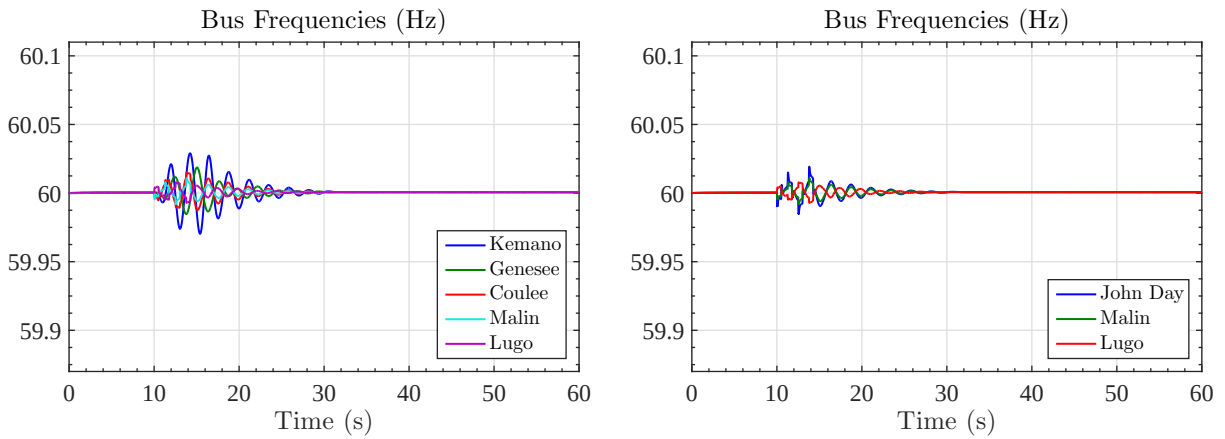


Figure 15. Bus frequencies. Event: 200 MW positive and negative pulses.

2.1.3. *Test System: Light Summer 2016. Controller Open Loop. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds*

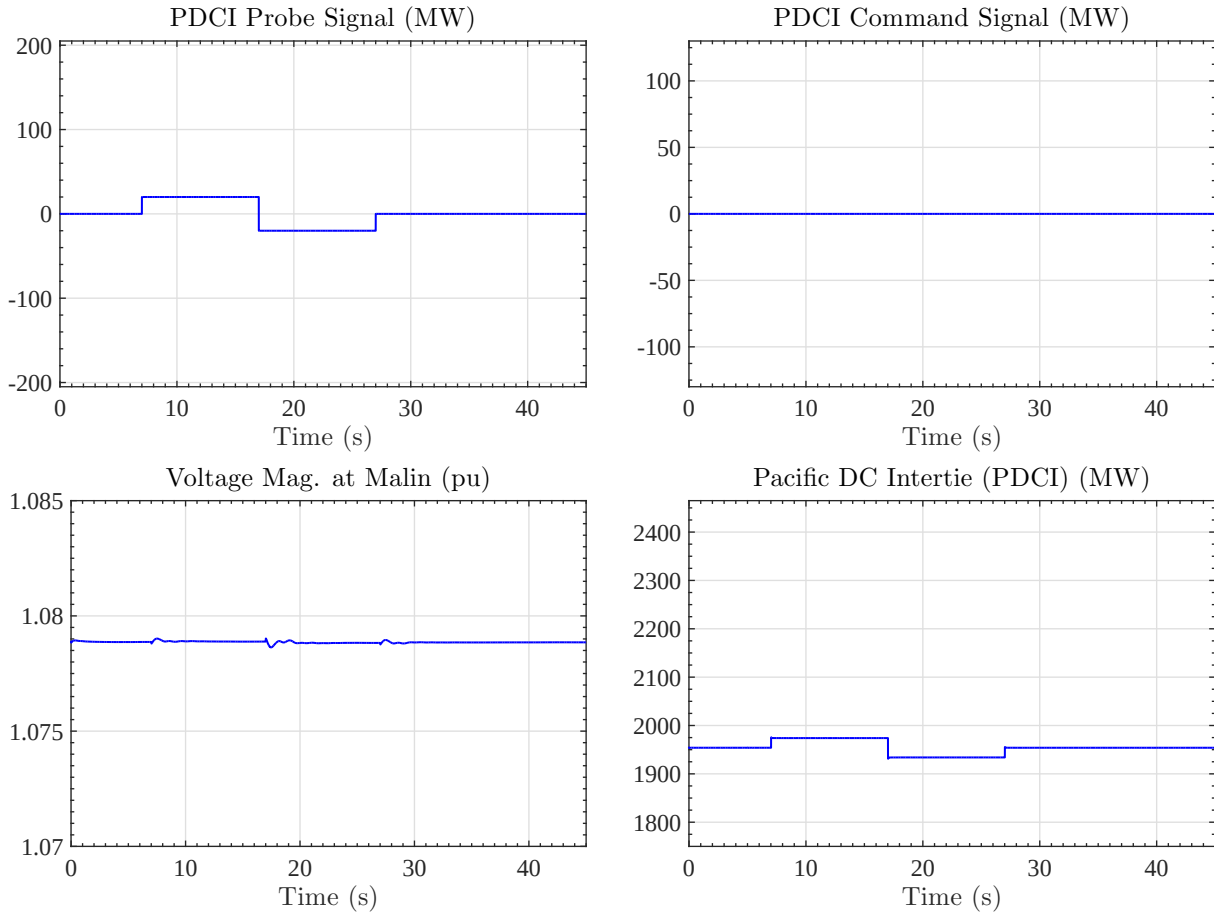


Figure 16. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

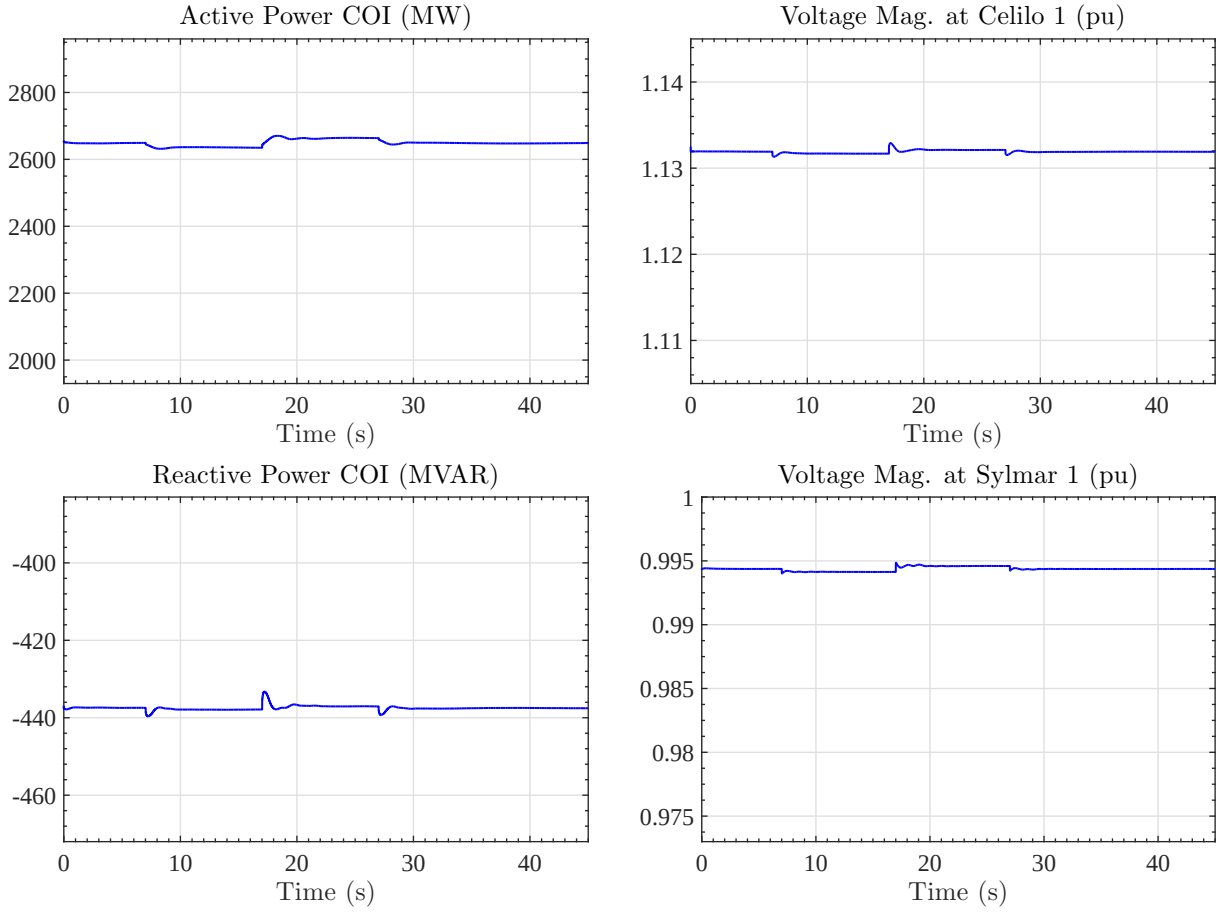


Figure 17. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

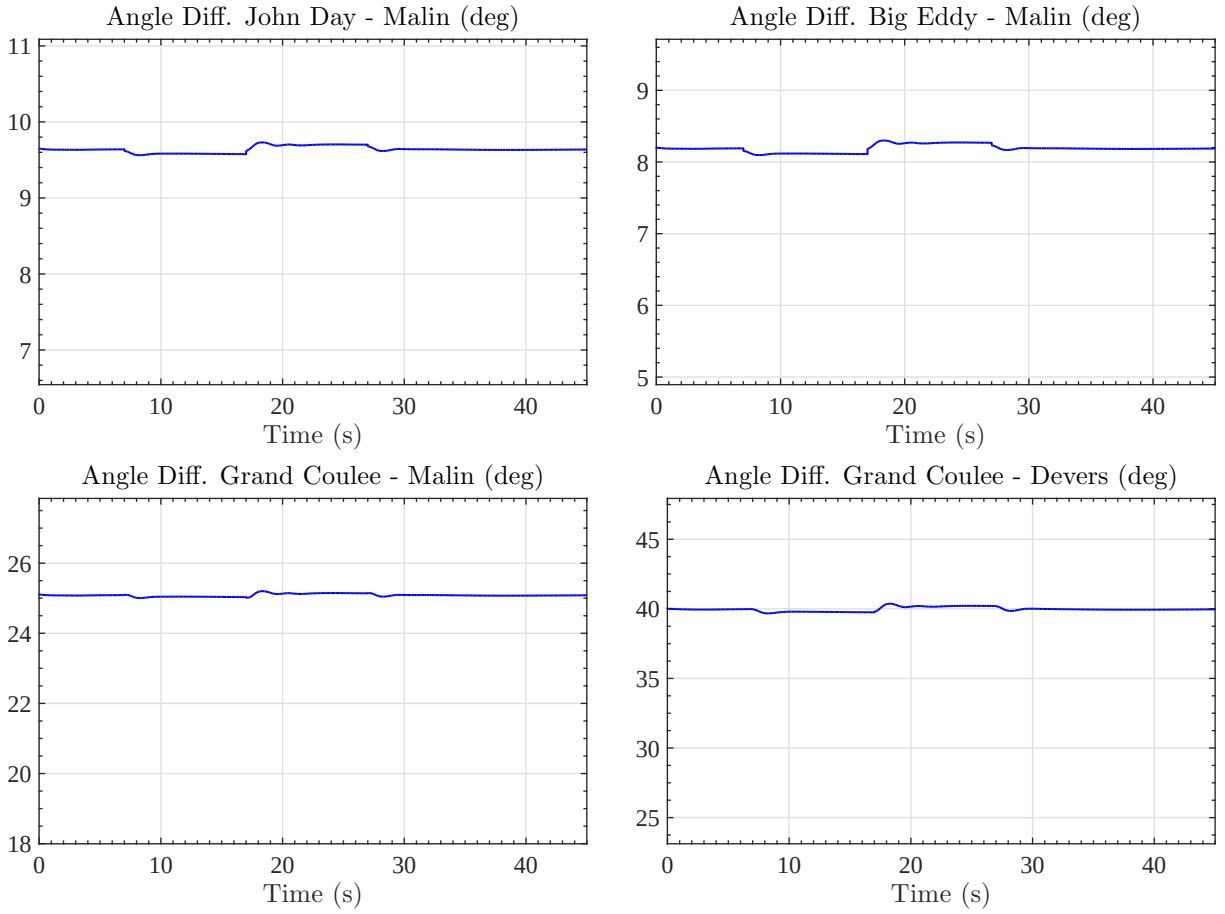


Figure 18. Angle differences. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

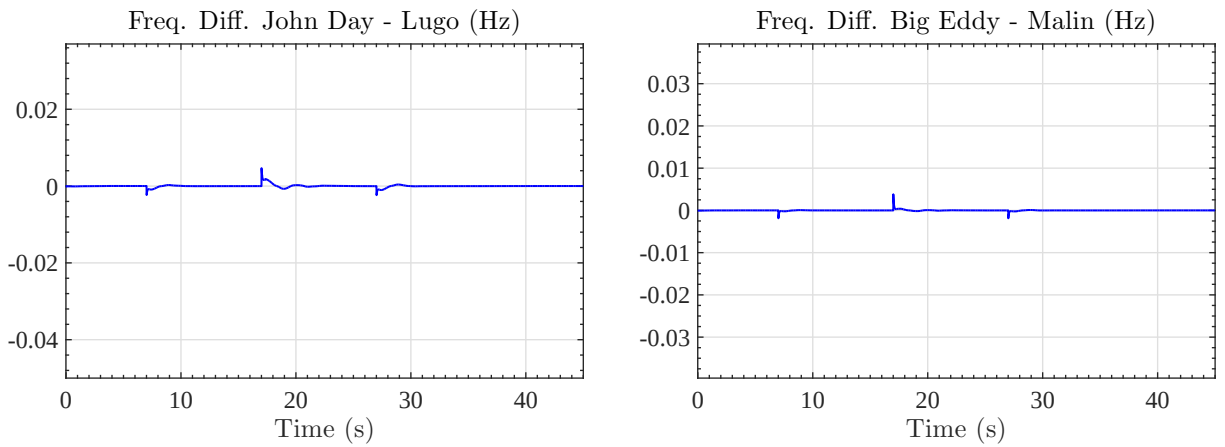


Figure 19. Frequency differences. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

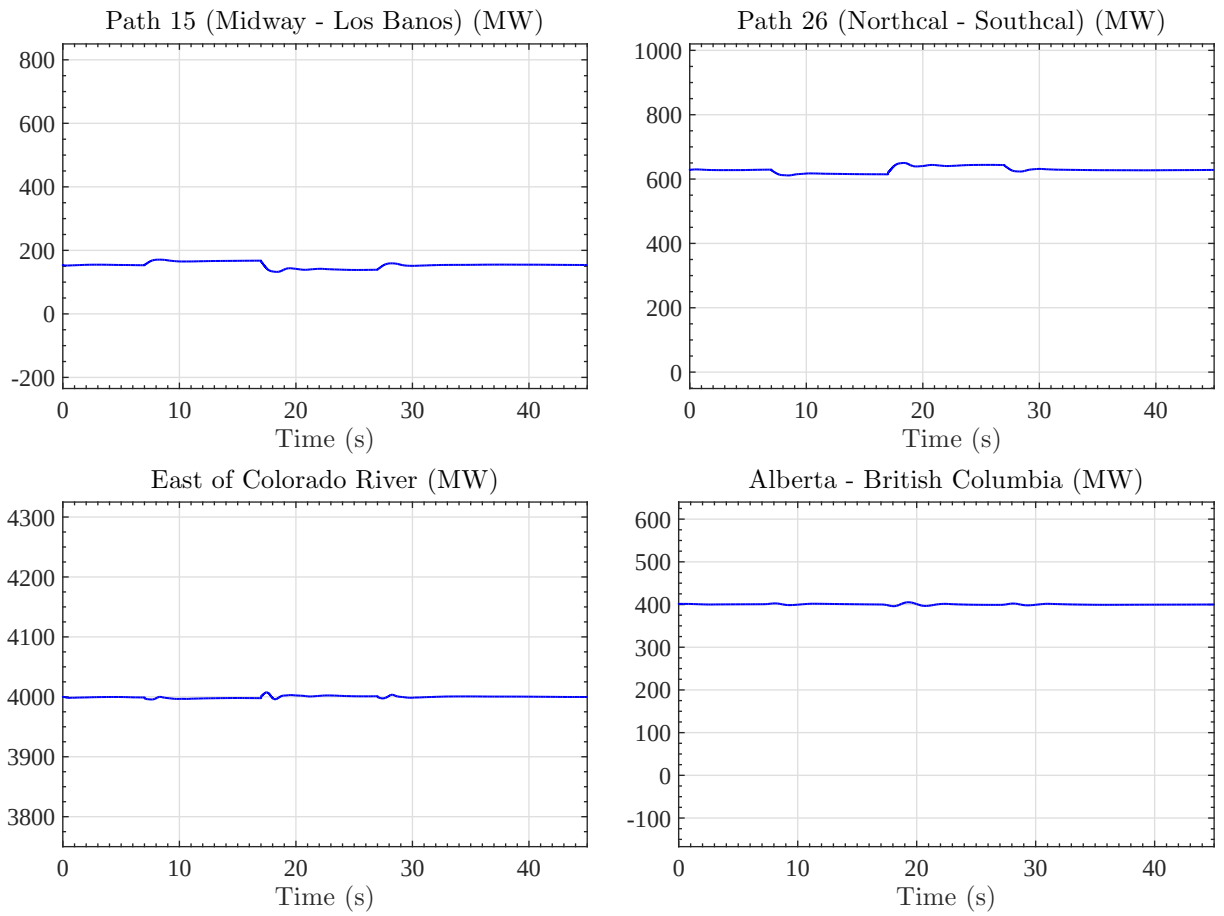


Figure 20. Active power flows. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

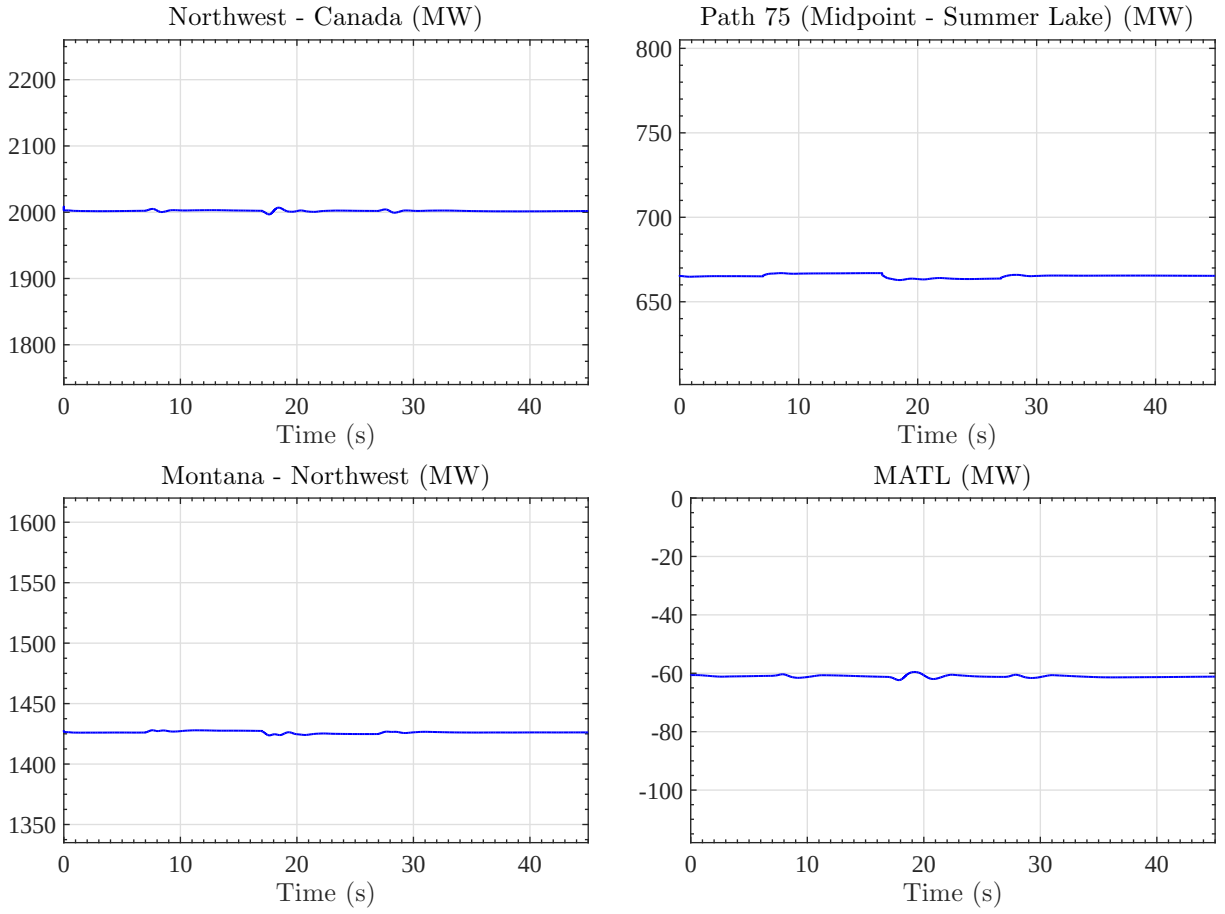


Figure 21. Active power flows. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

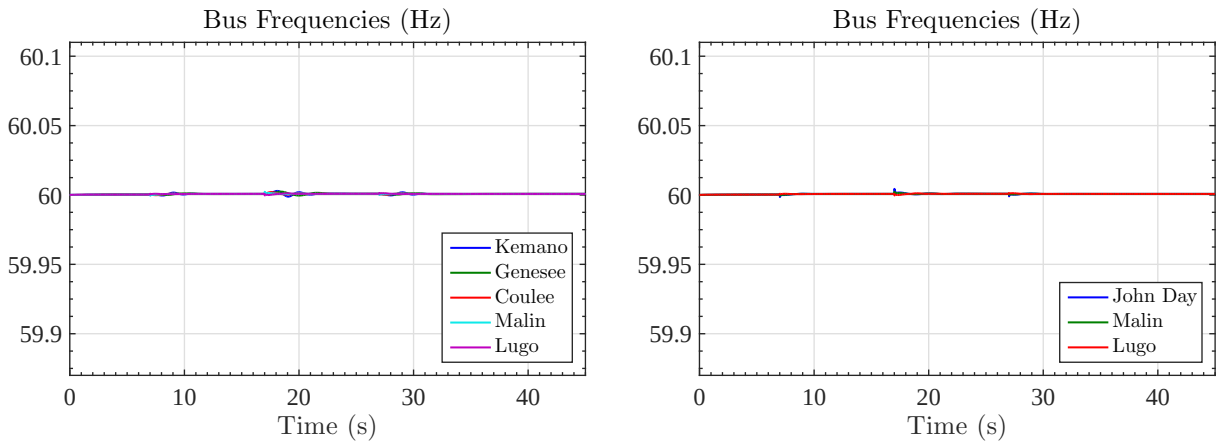


Figure 22. Bus frequencies. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

2.1.4. *Test System: Light Summer 2016. Controller Open Loop. Event: MSF 1/30/1/100 with amplitude of 20MW*

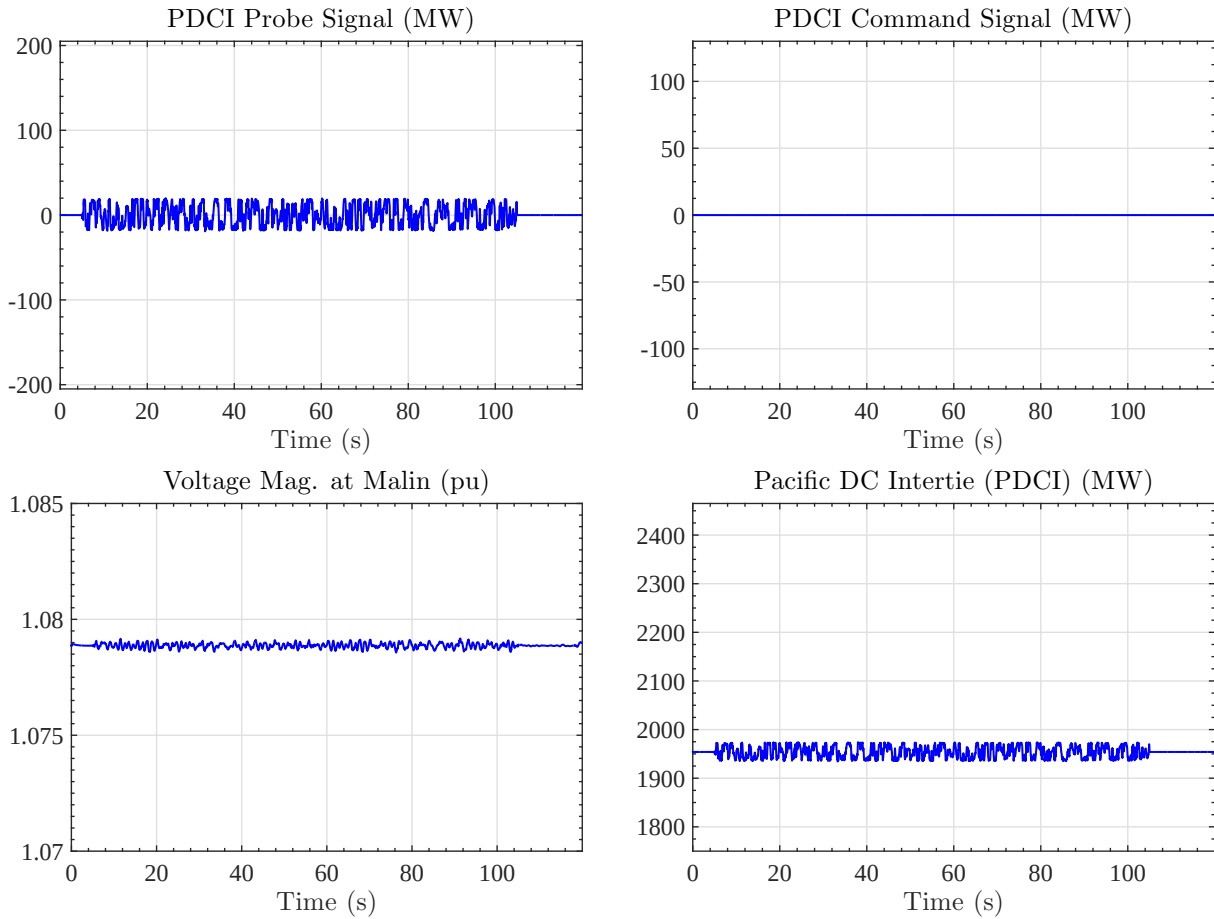


Figure 23. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 1/30/1/100 with amplitude of 20MW.

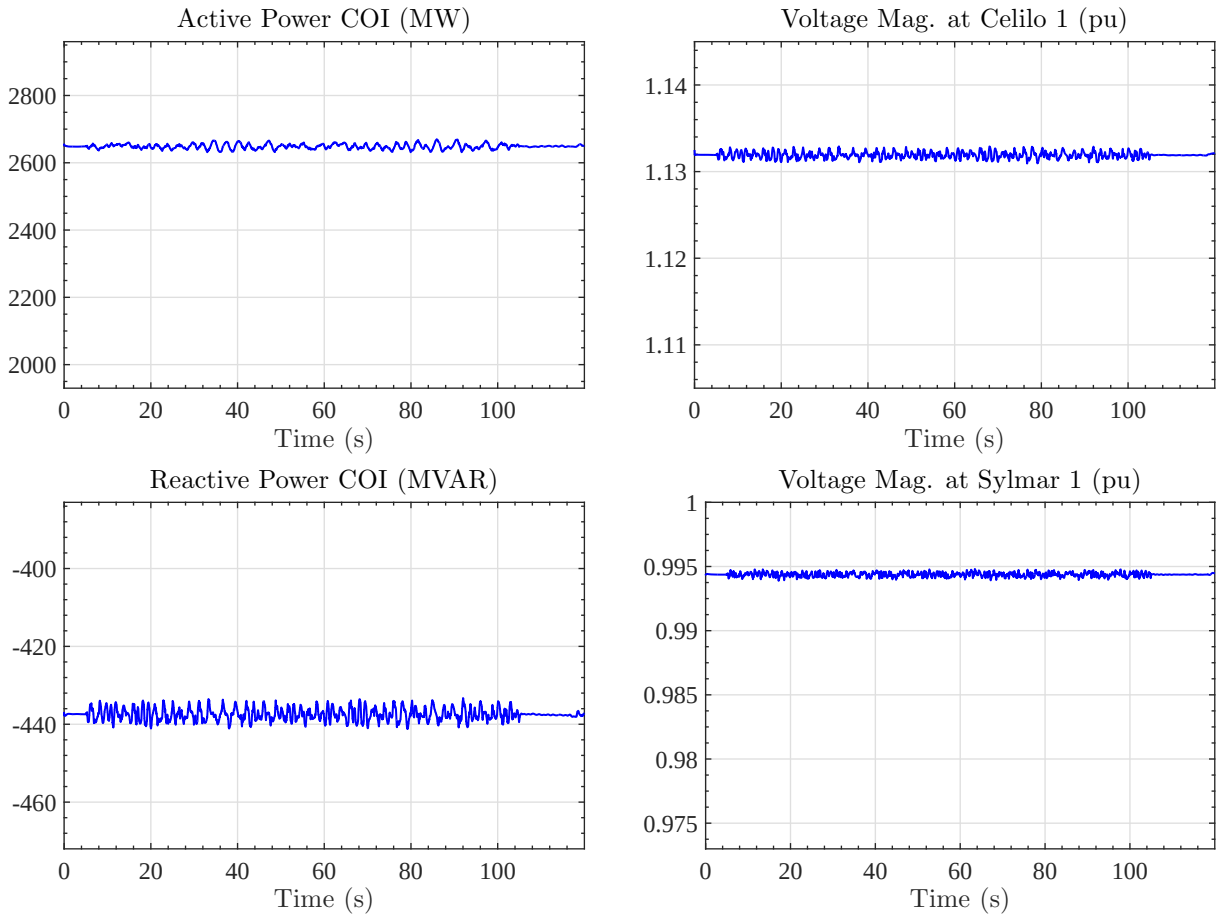


Figure 24. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 1/30/1/100 with amplitude of 20MW.

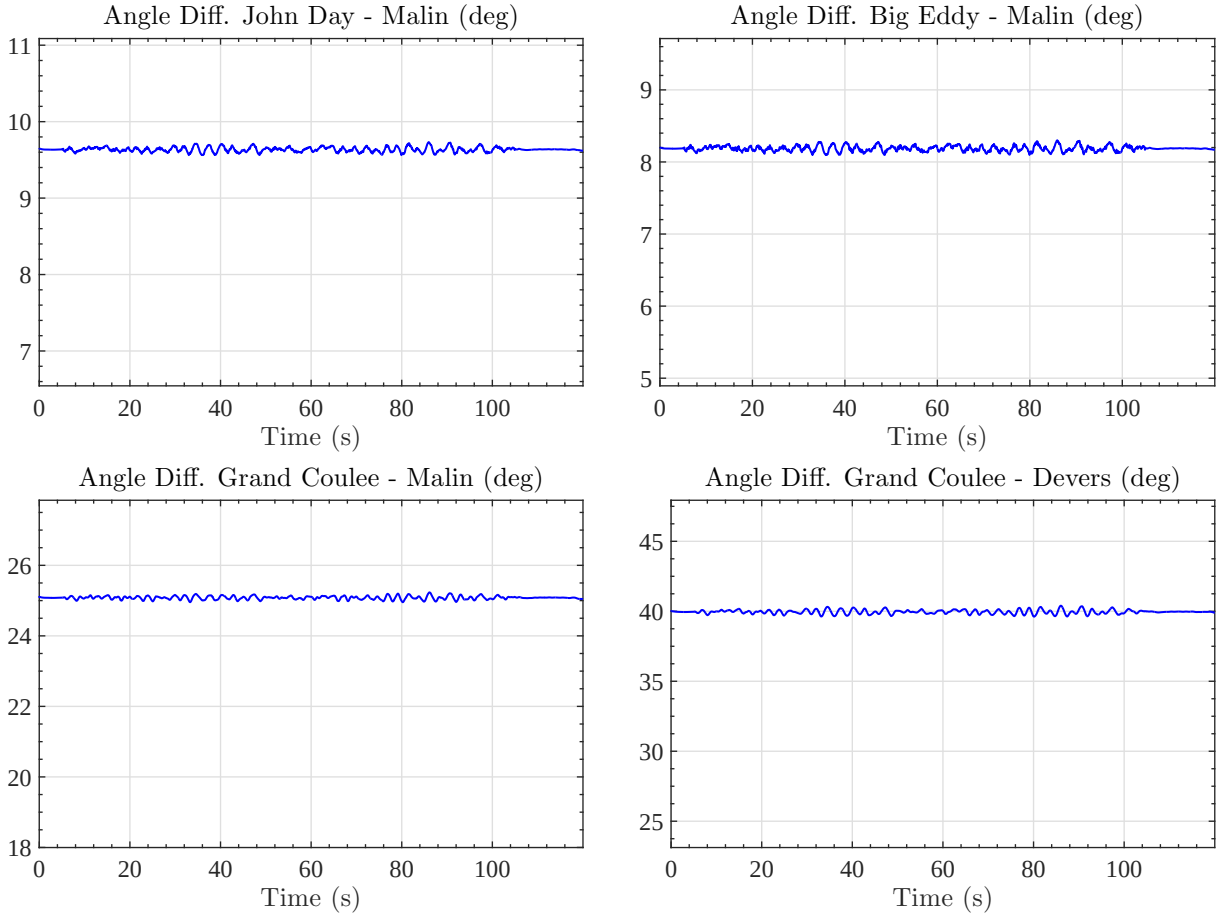


Figure 25. Angle differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

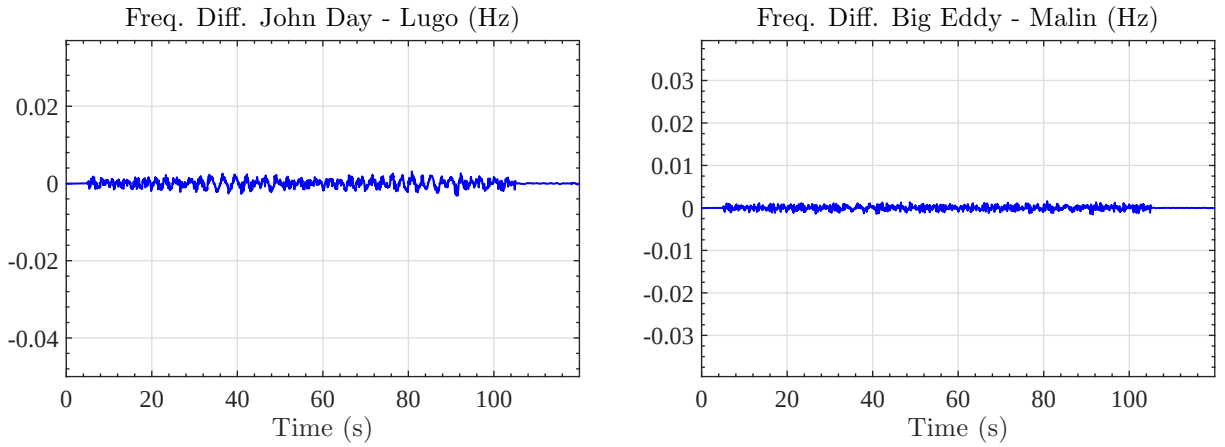


Figure 26. Frequency differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

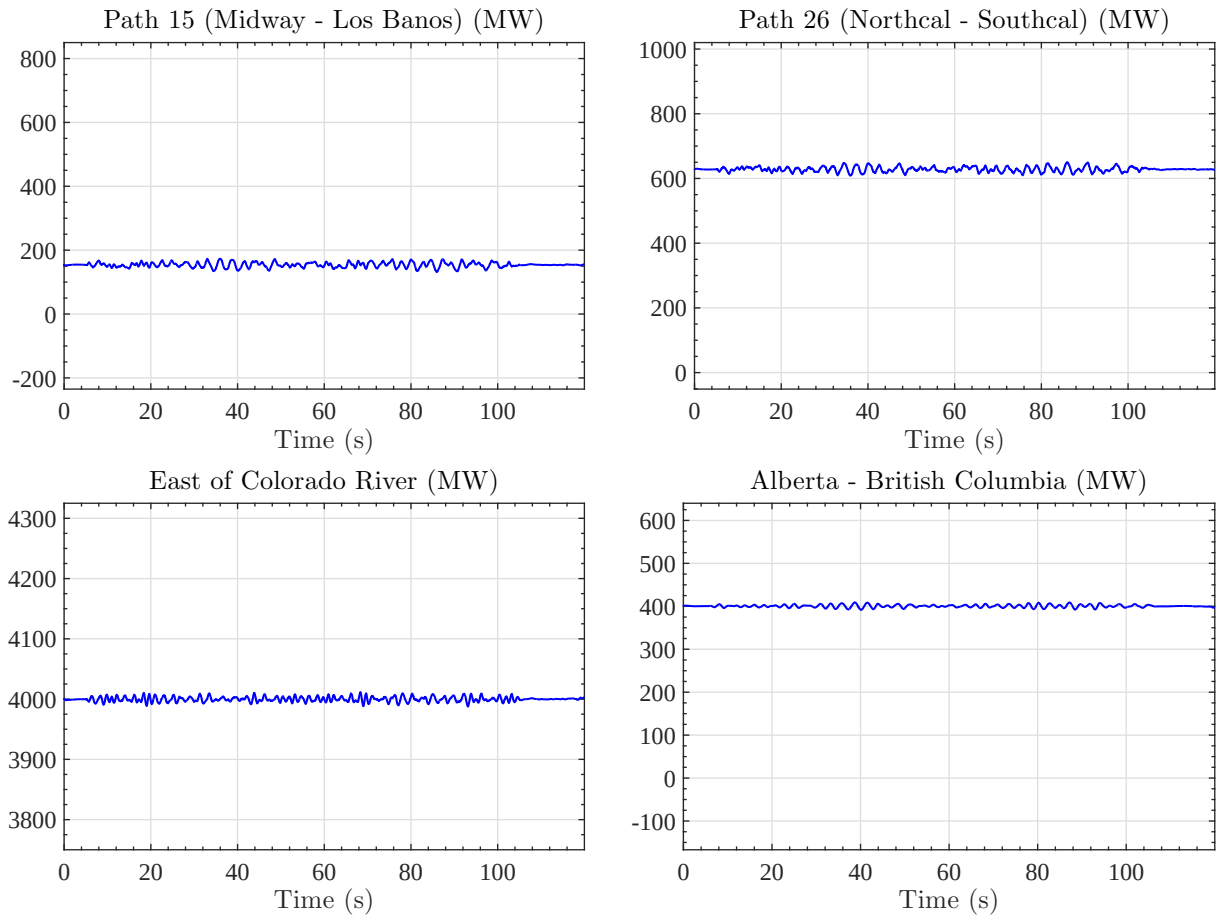


Figure 27. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

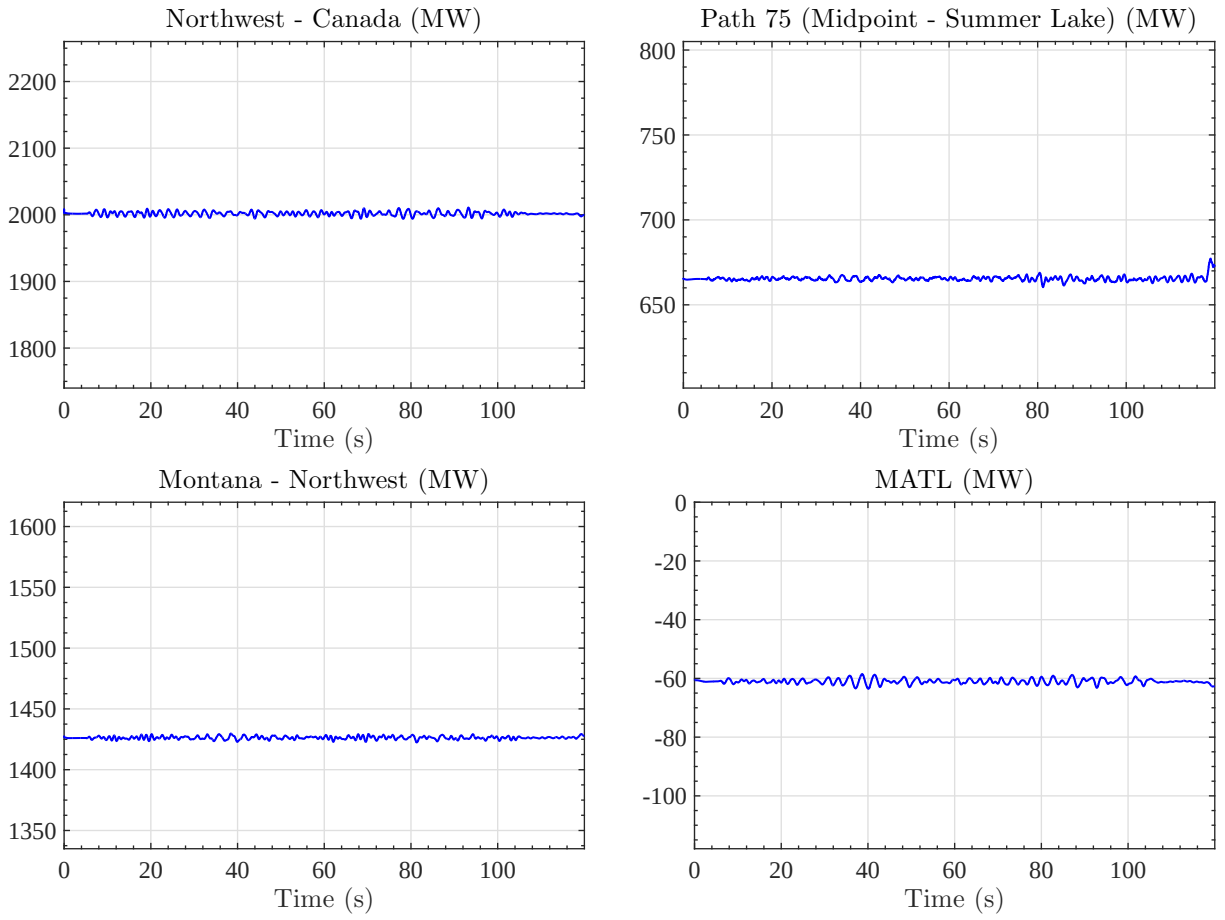


Figure 28. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

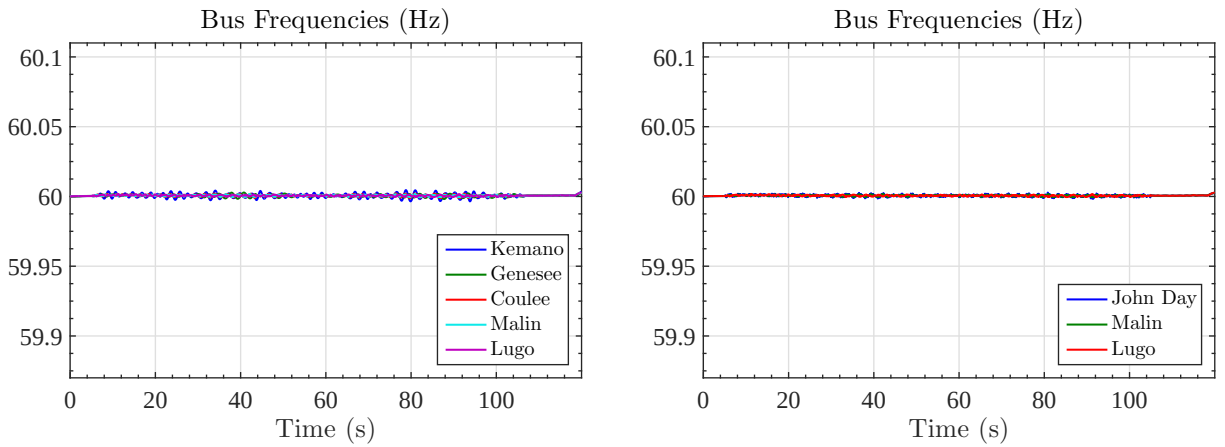


Figure 29. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

2.1.5. *Test System: Light Summer 2016. Controller Open Loop. Event: SF 0.1/4x with amplitude of 125MW*

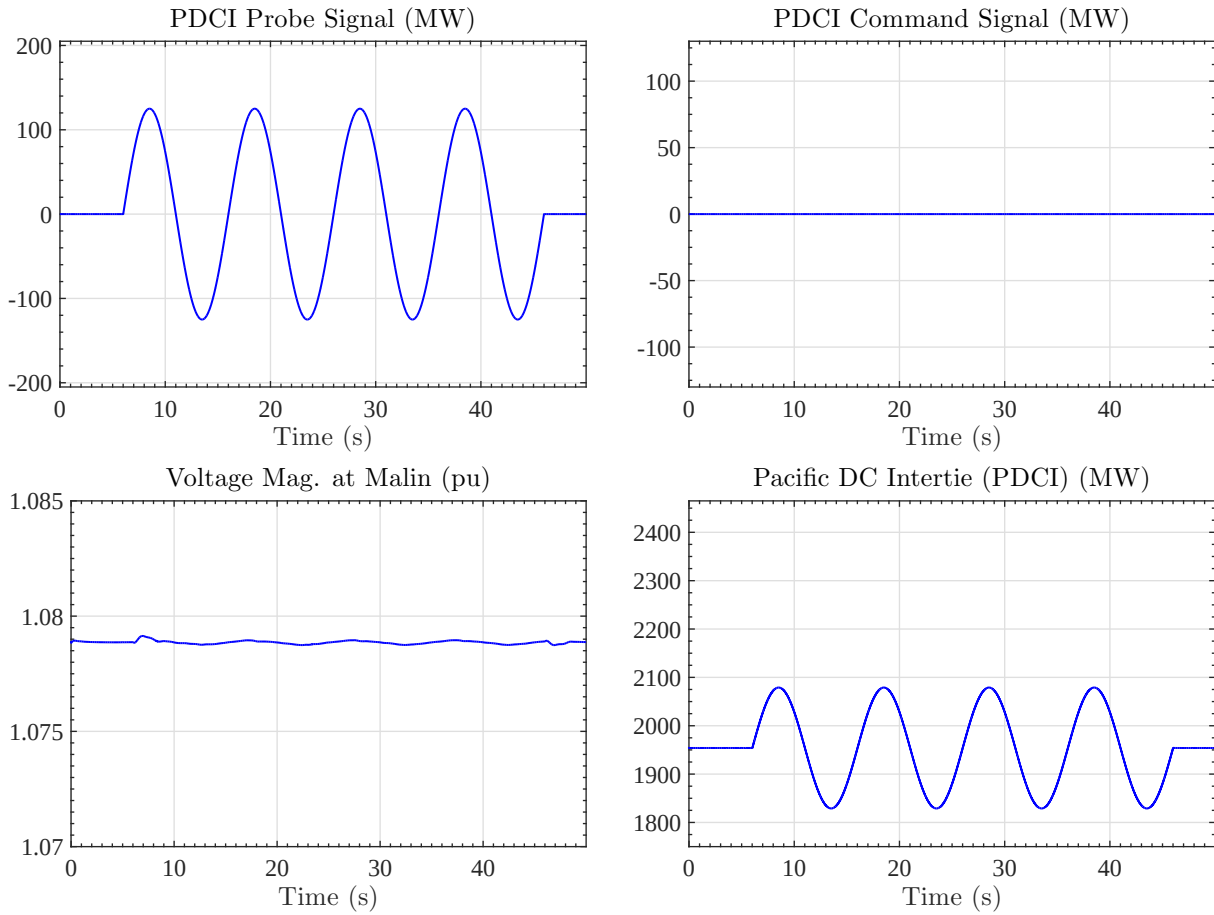


Figure 30. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 0.1/4x with amplitude of 125MW.

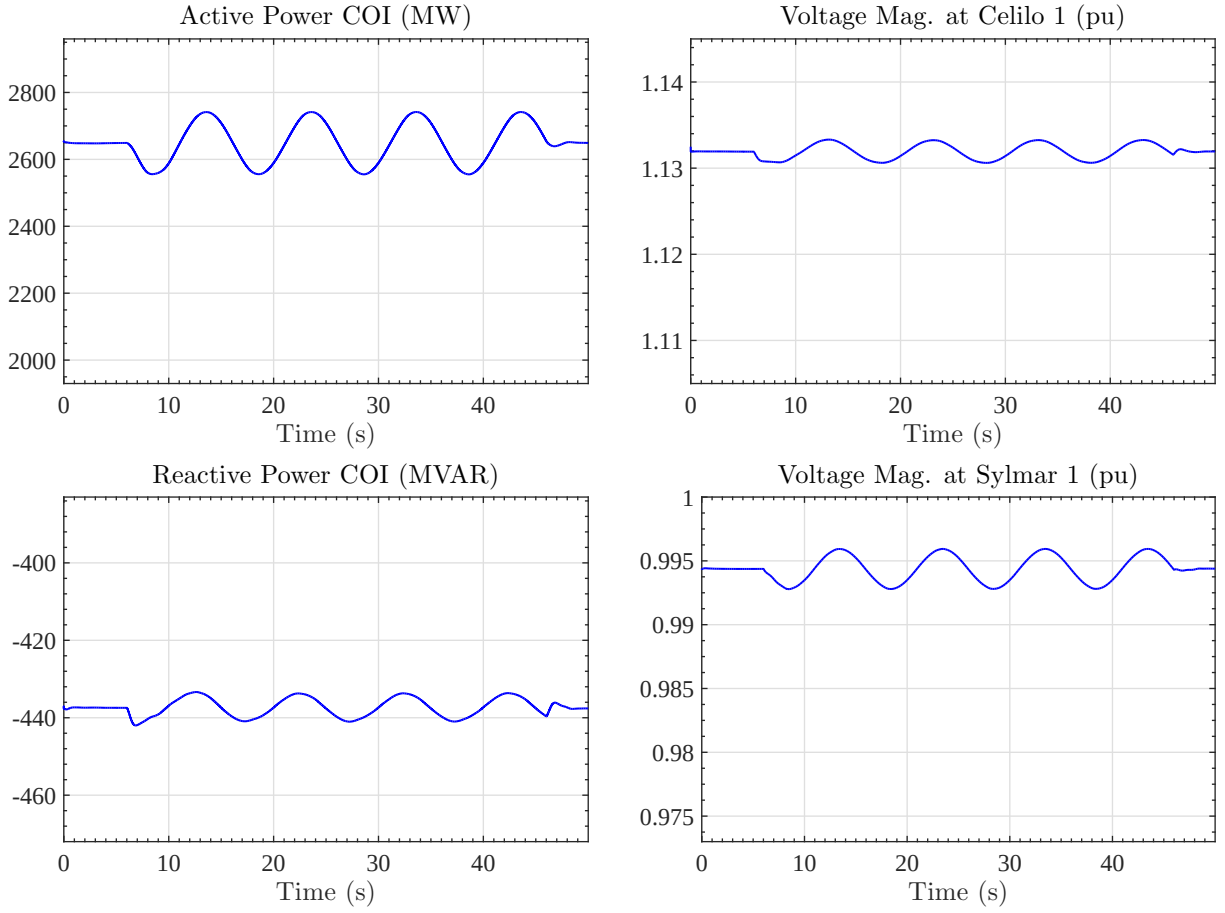


Figure 31. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 0.1/4x with amplitude of 125MW.

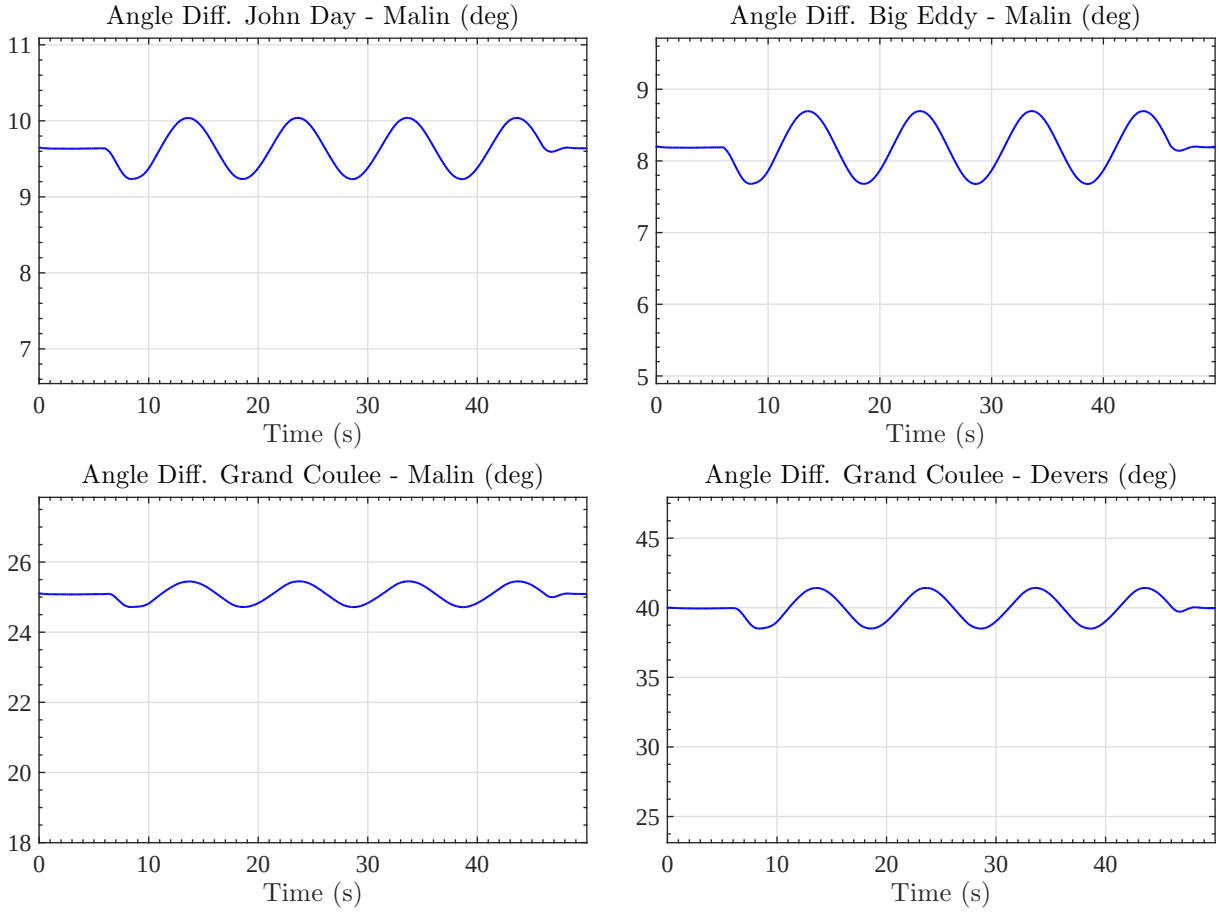


Figure 32. Angle differences. Event: SF 0.1/4x with amplitude of 125MW.

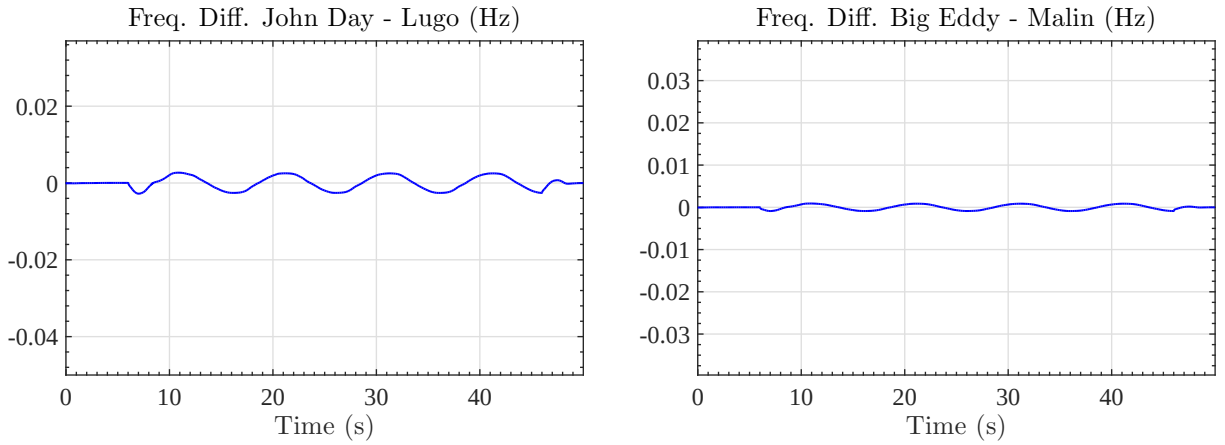


Figure 33. Frequency differences. Event: SF 0.1/4x with amplitude of 125MW.

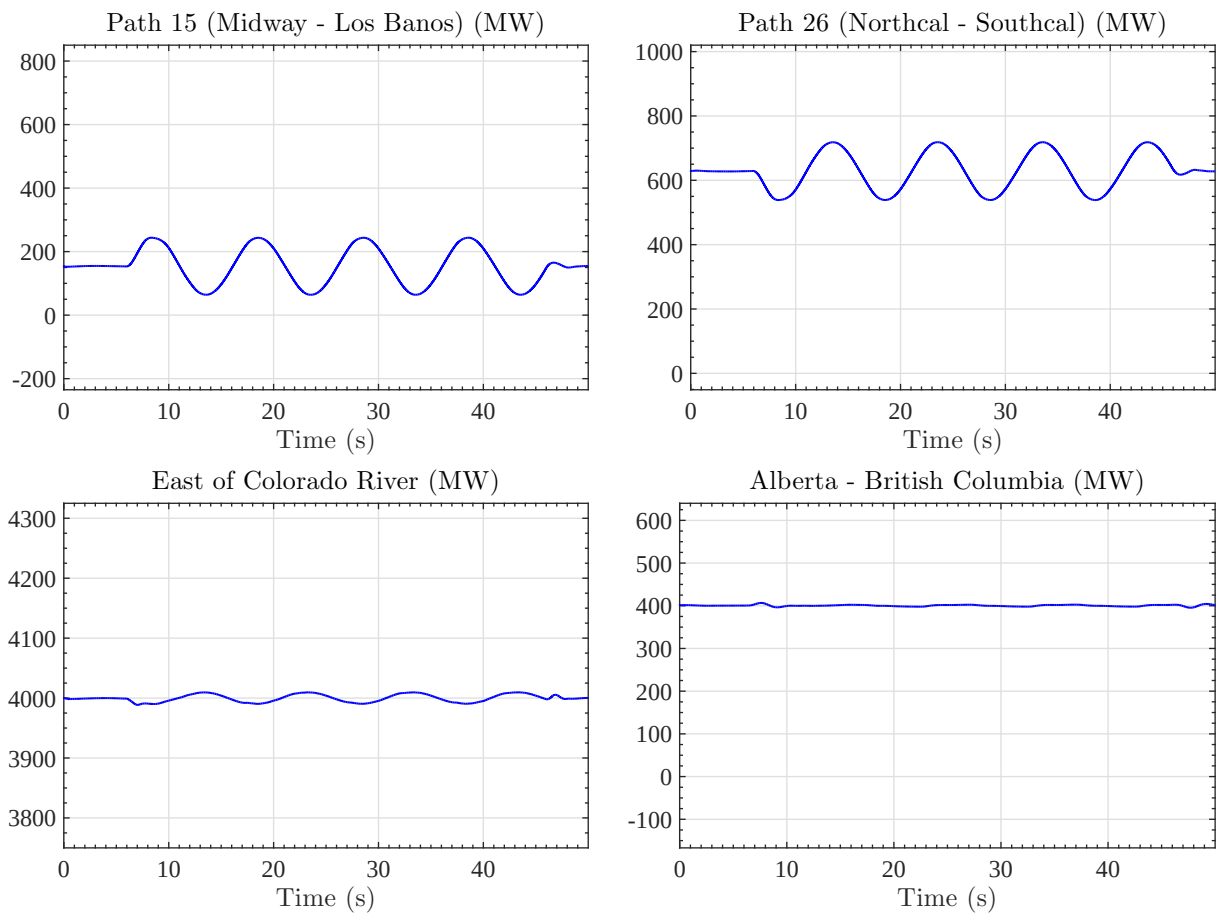


Figure 34. Active power flows. Event: SF 0.1/4x with amplitude of 125MW.

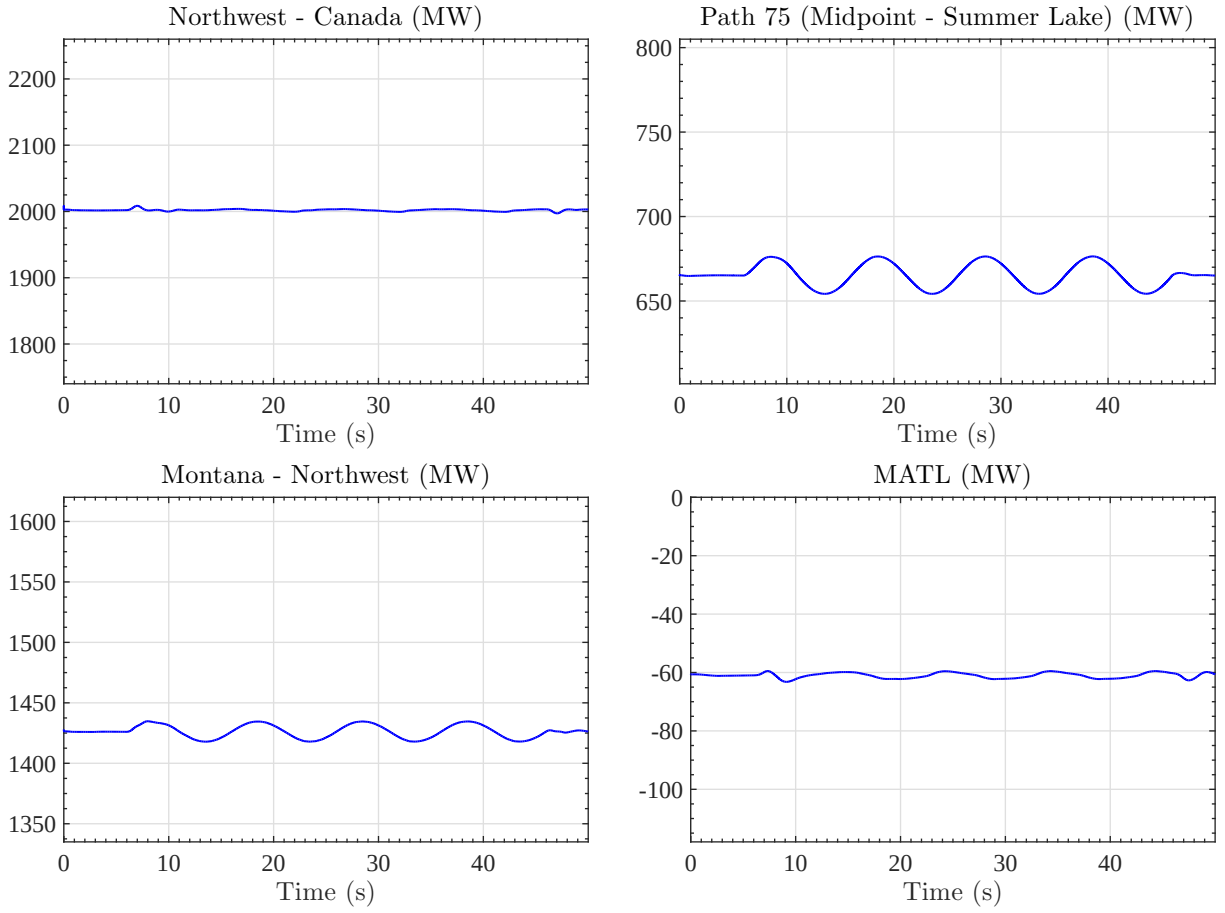


Figure 35. Active power flows. Event: SF 0.1/4x with amplitude of 125MW.

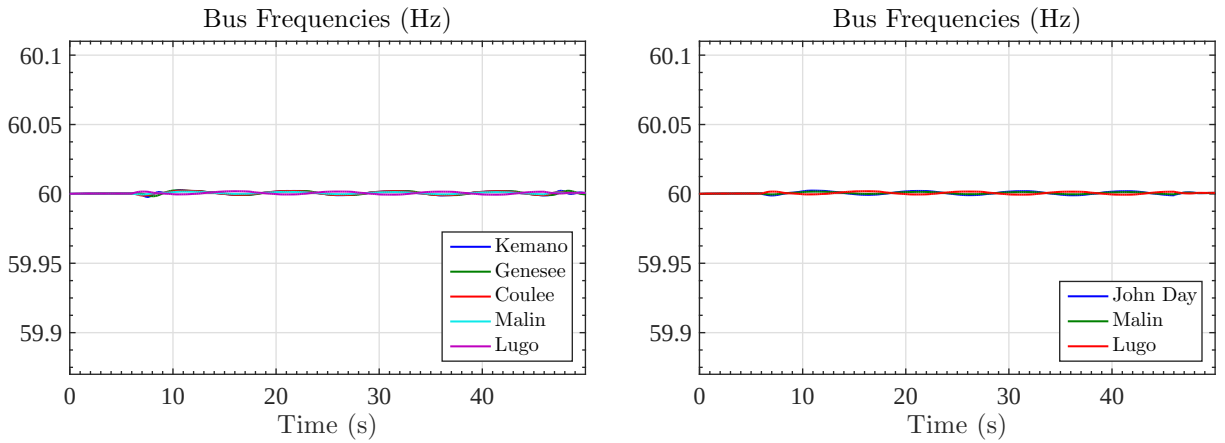


Figure 36. Bus frequencies. Event: SF 0.1/4x with amplitude of 125MW.

2.1.6. *Test System: Light Summer 2016. Controller Open Loop. Event: SF 0.3/4x with amplitude of 125MW*

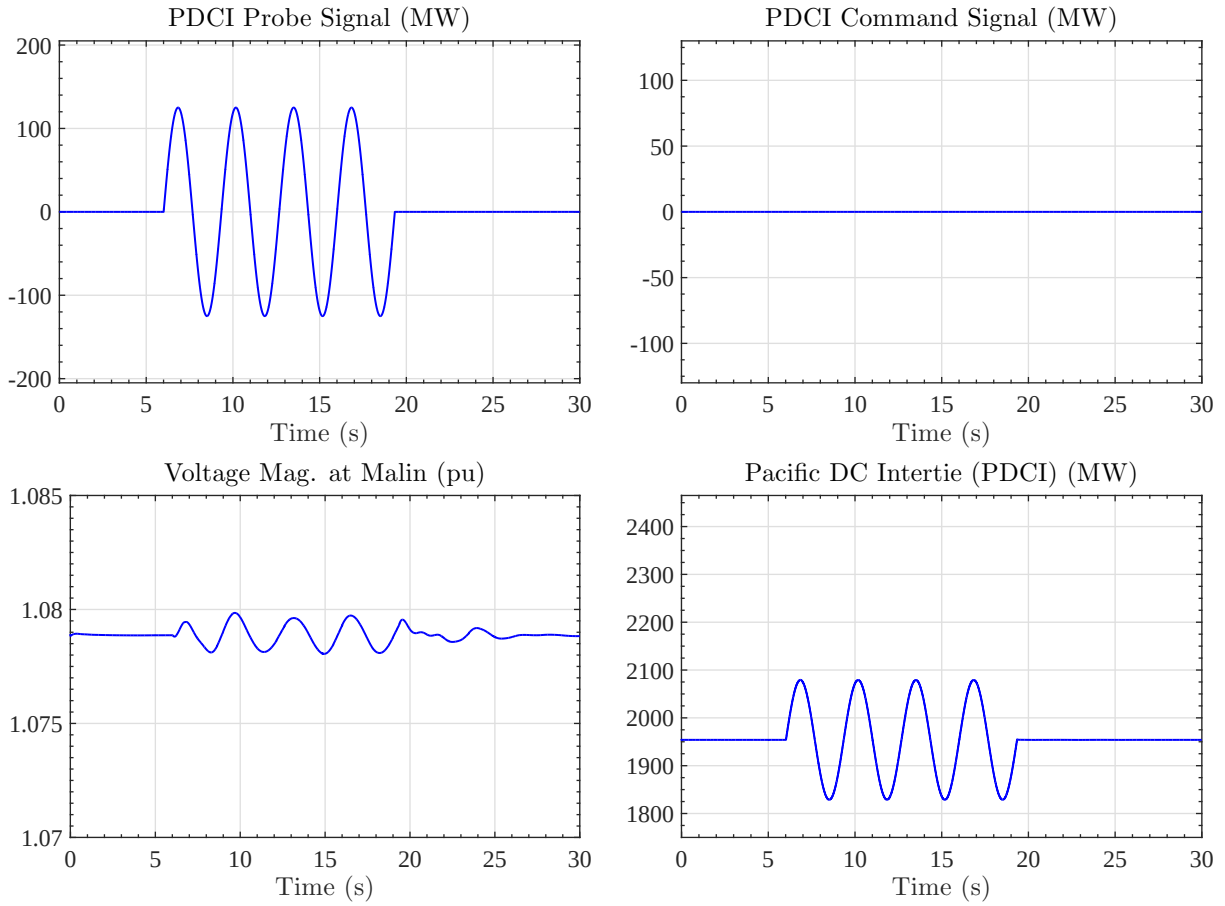


Figure 37. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 0.3/4x with amplitude of 125MW.

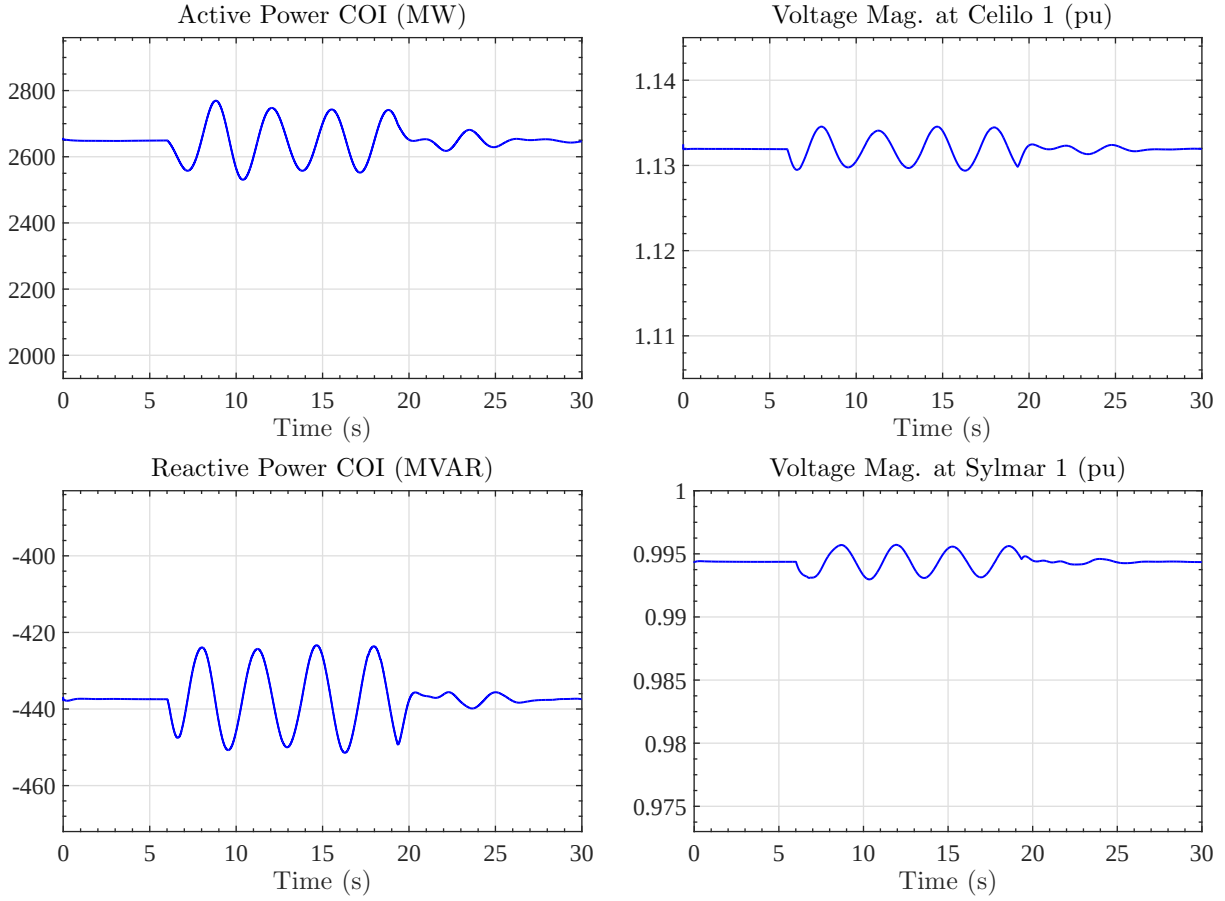


Figure 38. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 0.3/4x with amplitude of 125MW.

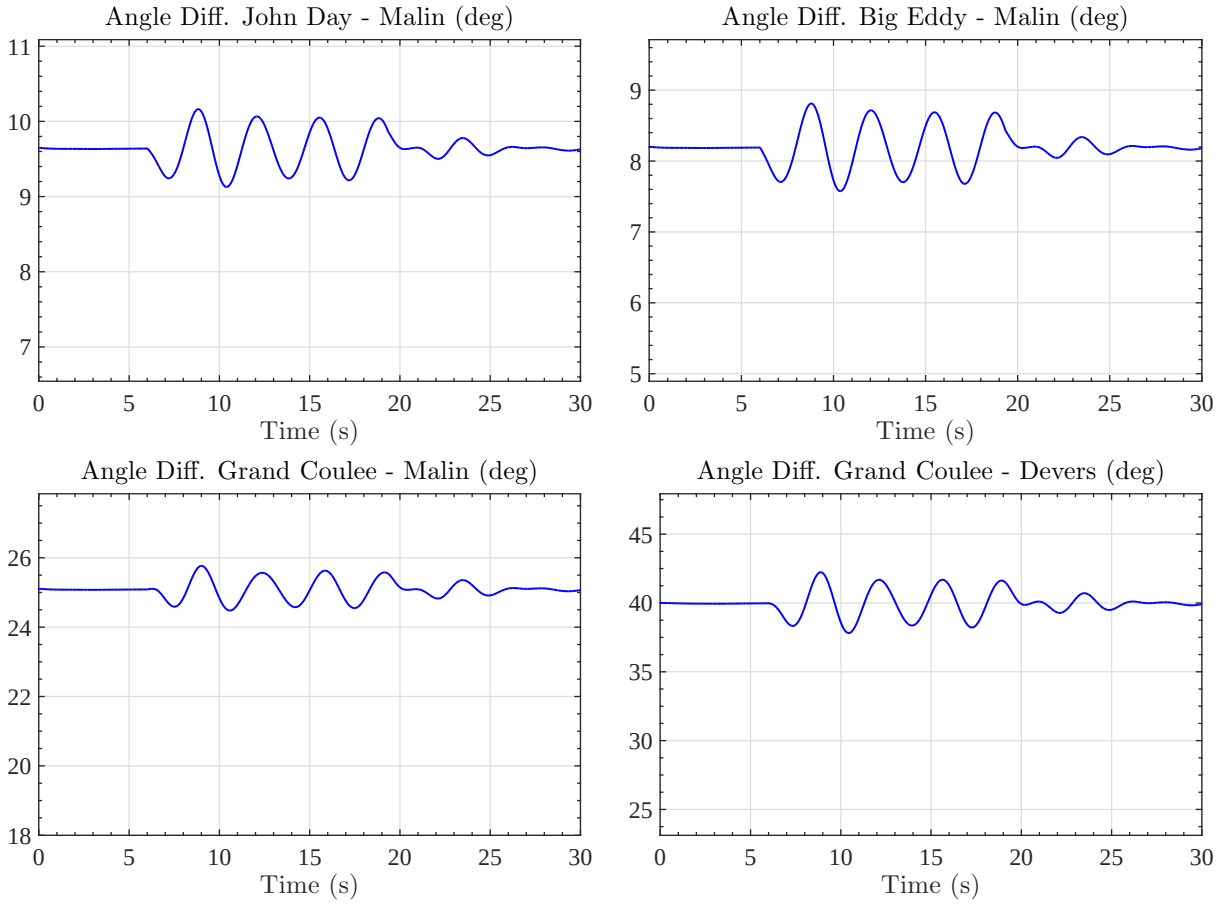


Figure 39. Angle differences. Event: SF 0.3/4x with amplitude of 125MW.

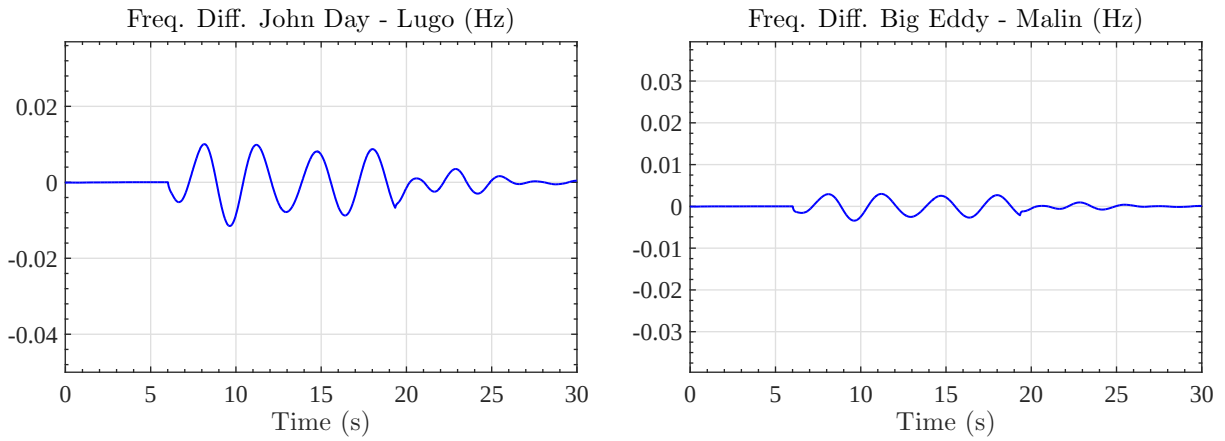


Figure 40. Frequency differences. Event: SF 0.3/4x with amplitude of 125MW.

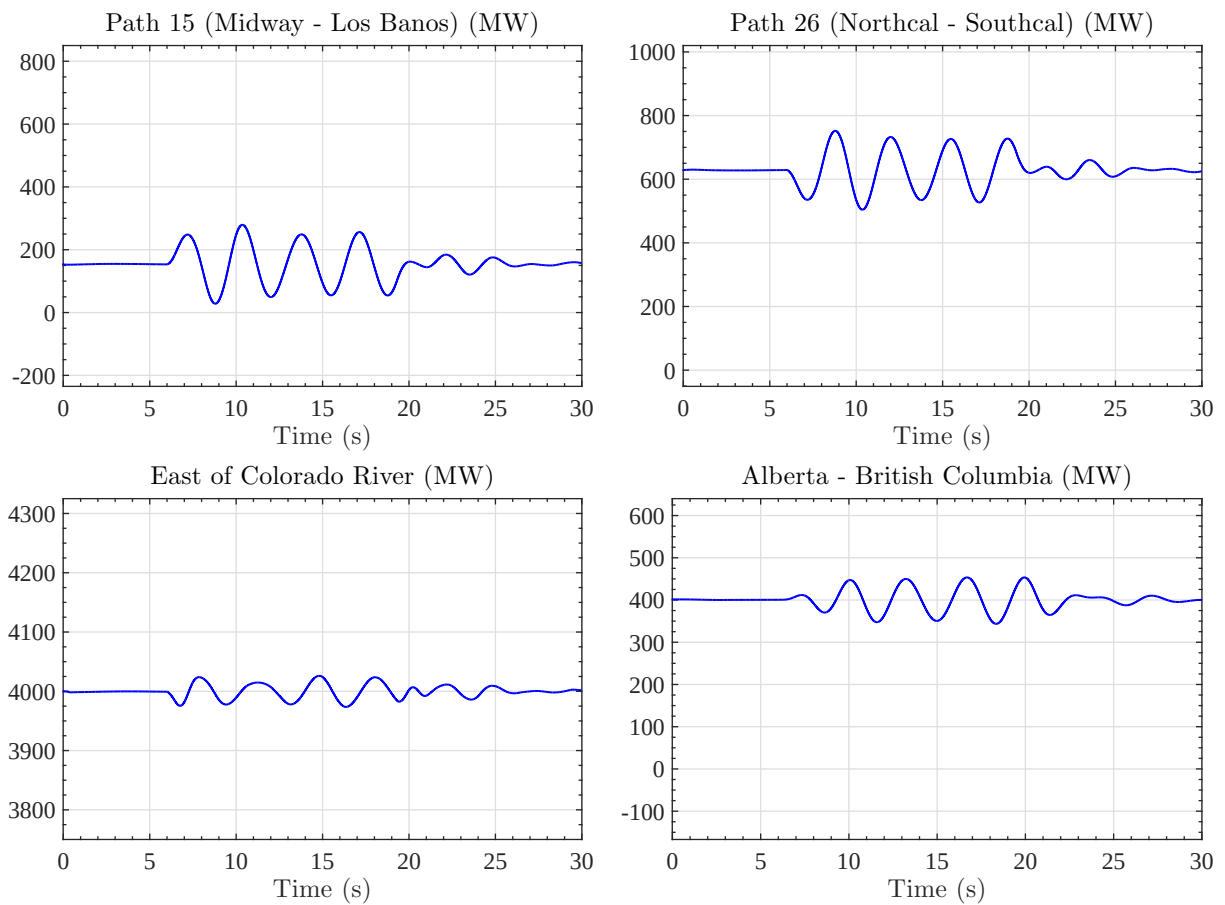


Figure 41. Active power flows. Event: SF 0.3/4x with amplitude of 125MW.

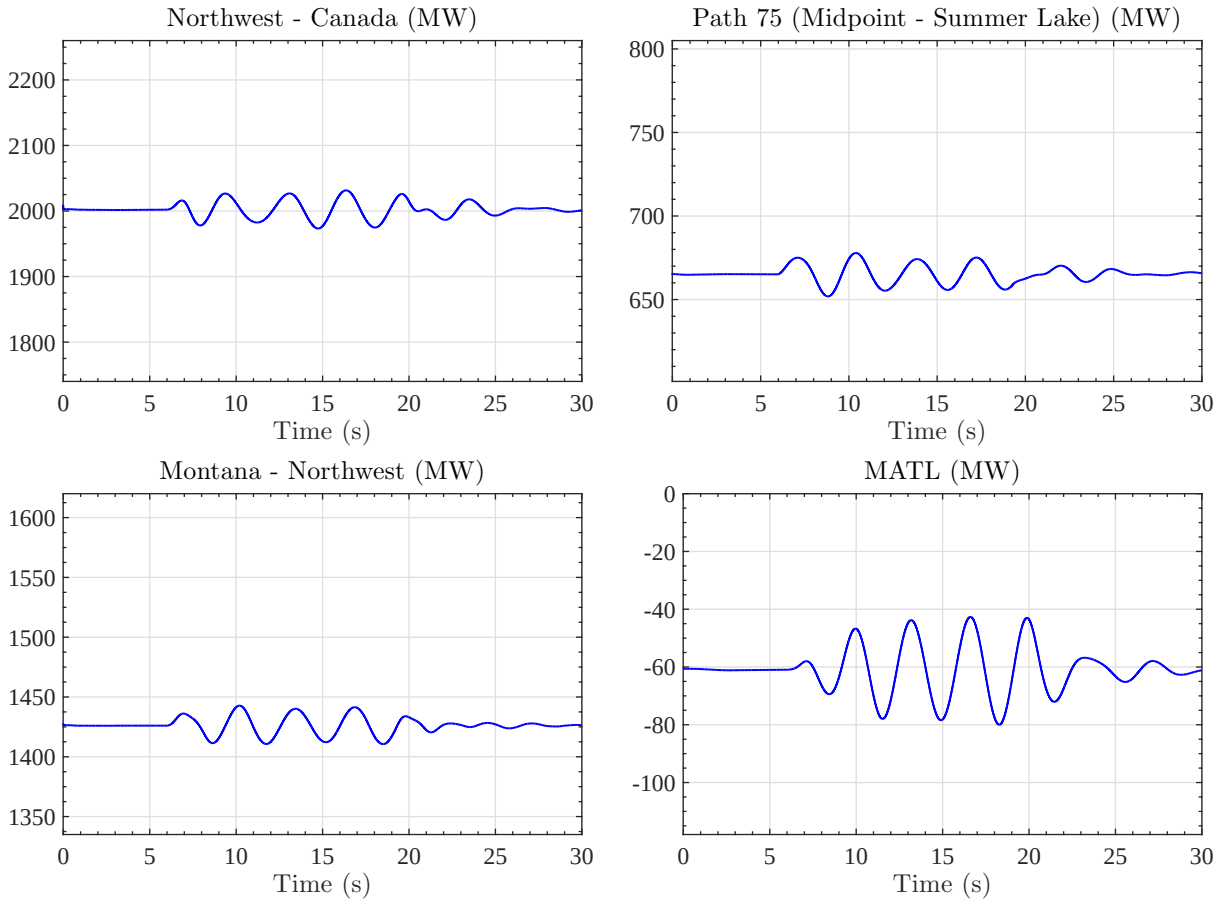


Figure 42. Active power flows. Event: SF 0.3/4x with amplitude of 125MW.

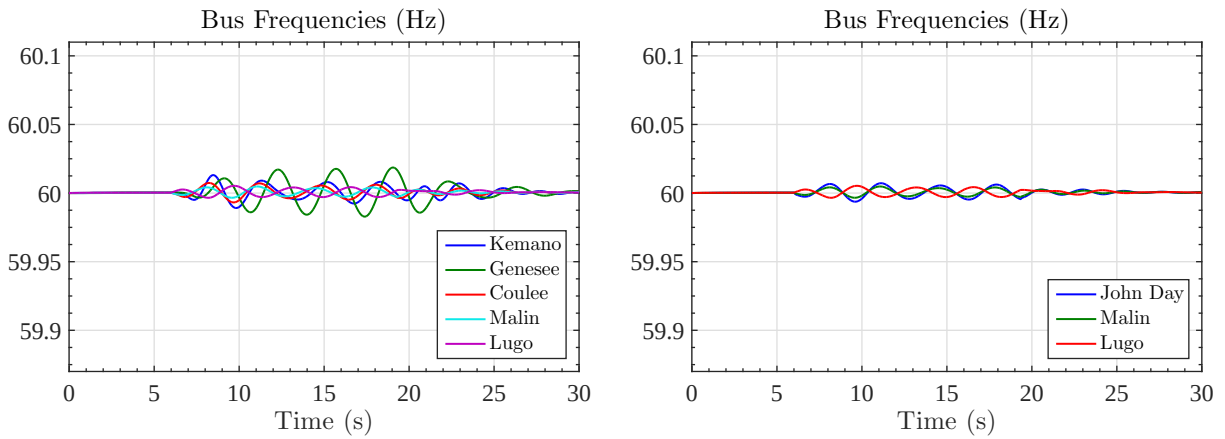


Figure 43. Bus frequencies. Event: SF 0.3/4x with amplitude of 125MW.

2.1.7. *Test System: Light Summer 2016. Controller Open Loop. Event: SF 1.0/4x with amplitude of 125MW*

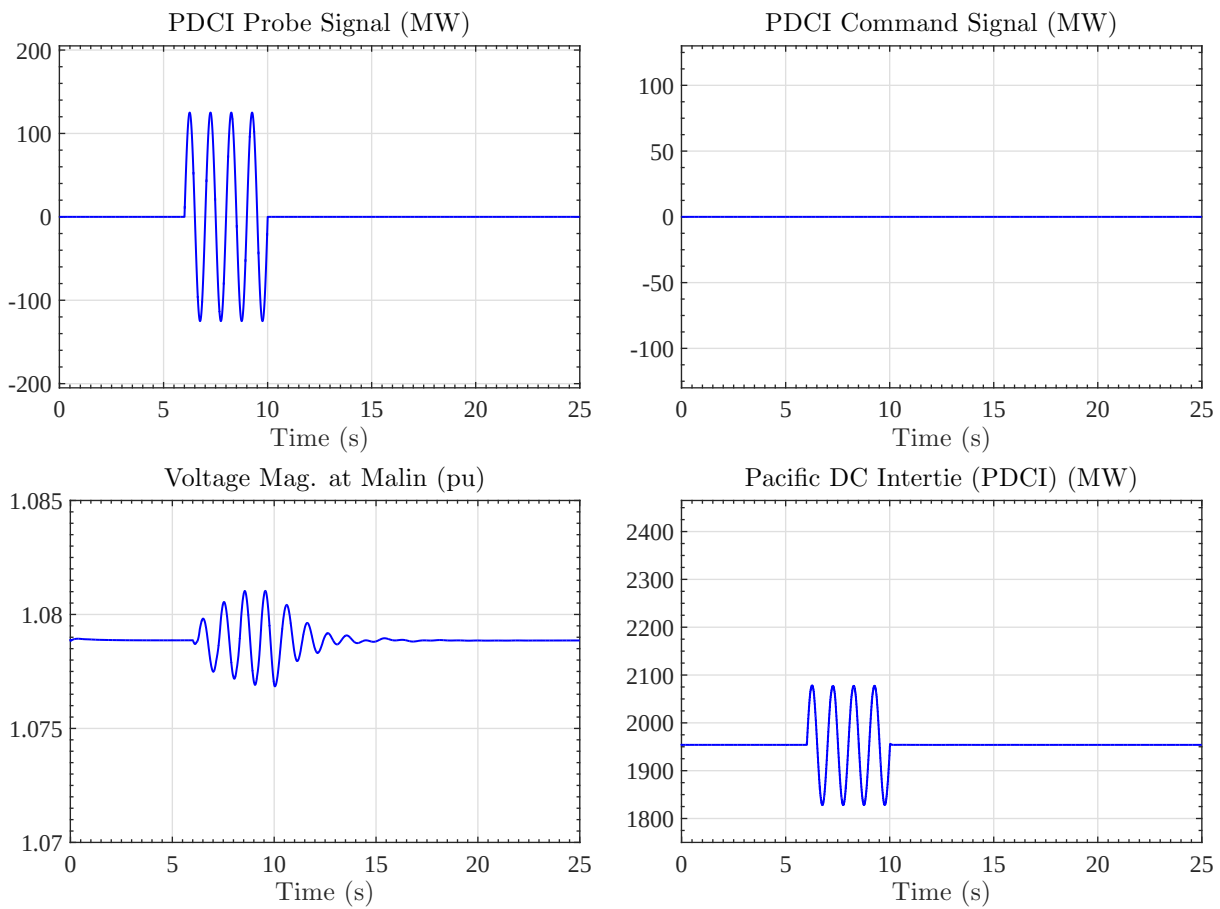


Figure 44. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 1.0/4x with amplitude of 125MW.

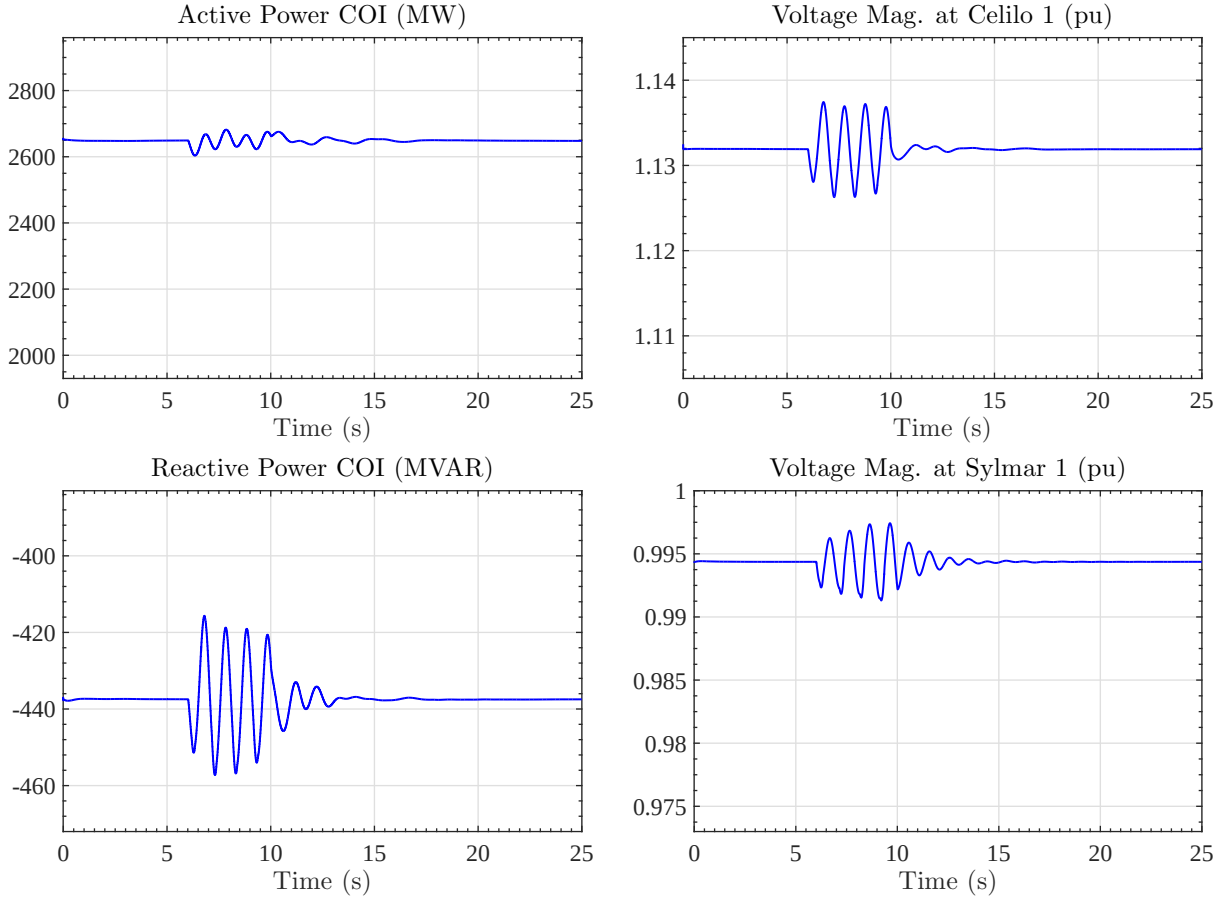


Figure 45. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 1.0/4x with amplitude of 125MW.

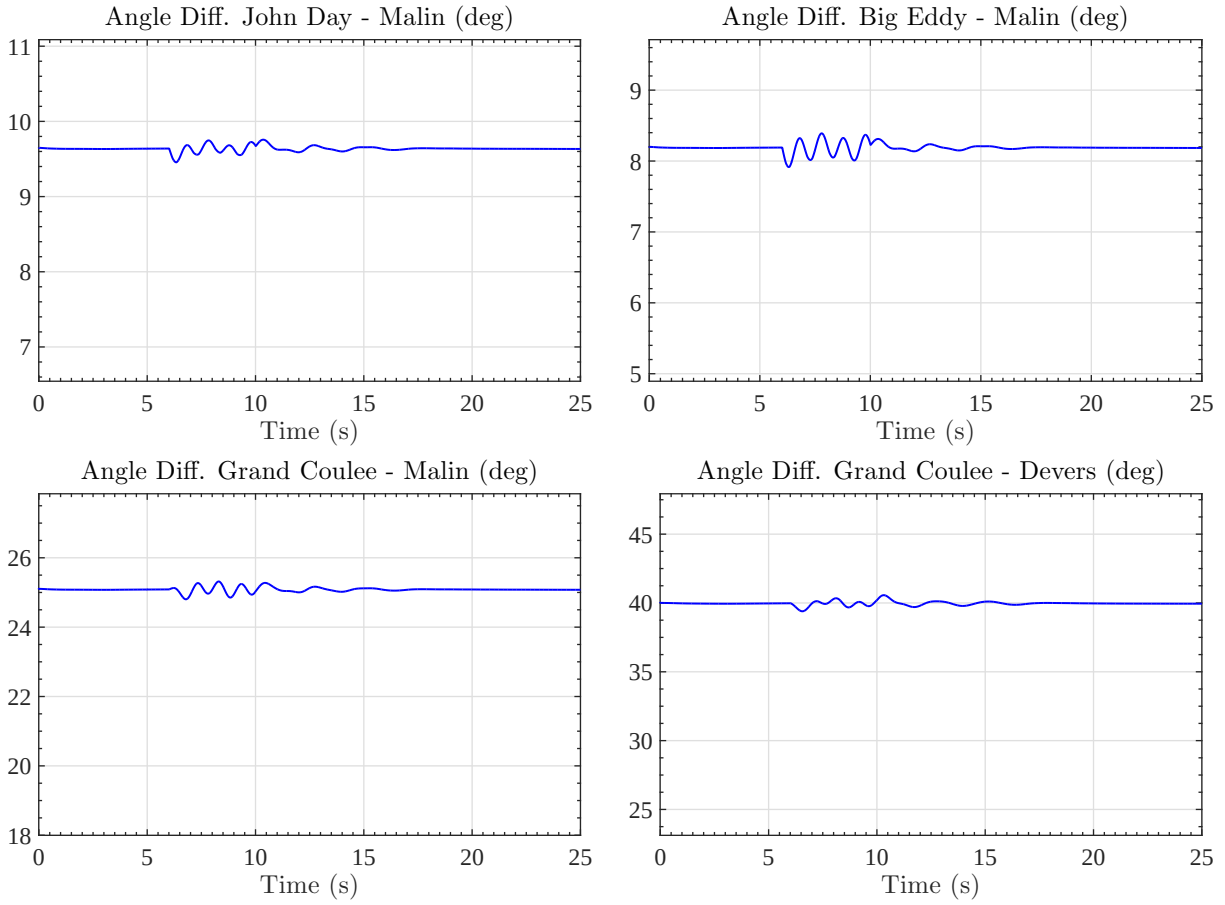


Figure 46. Angle differences. Event: SF 1.0/4x with amplitude of 125MW.

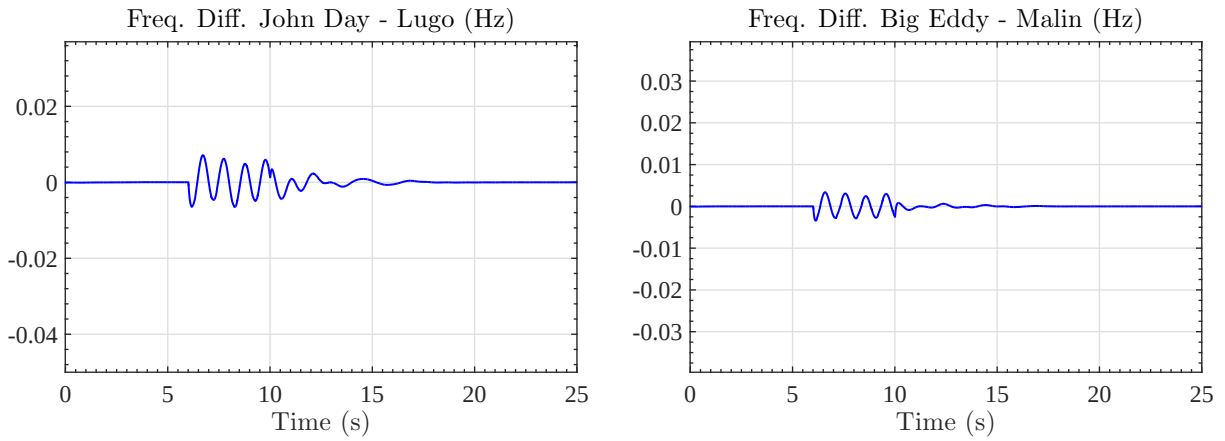


Figure 47. Frequency differences. Event: SF 1.0/4x with amplitude of 125MW.

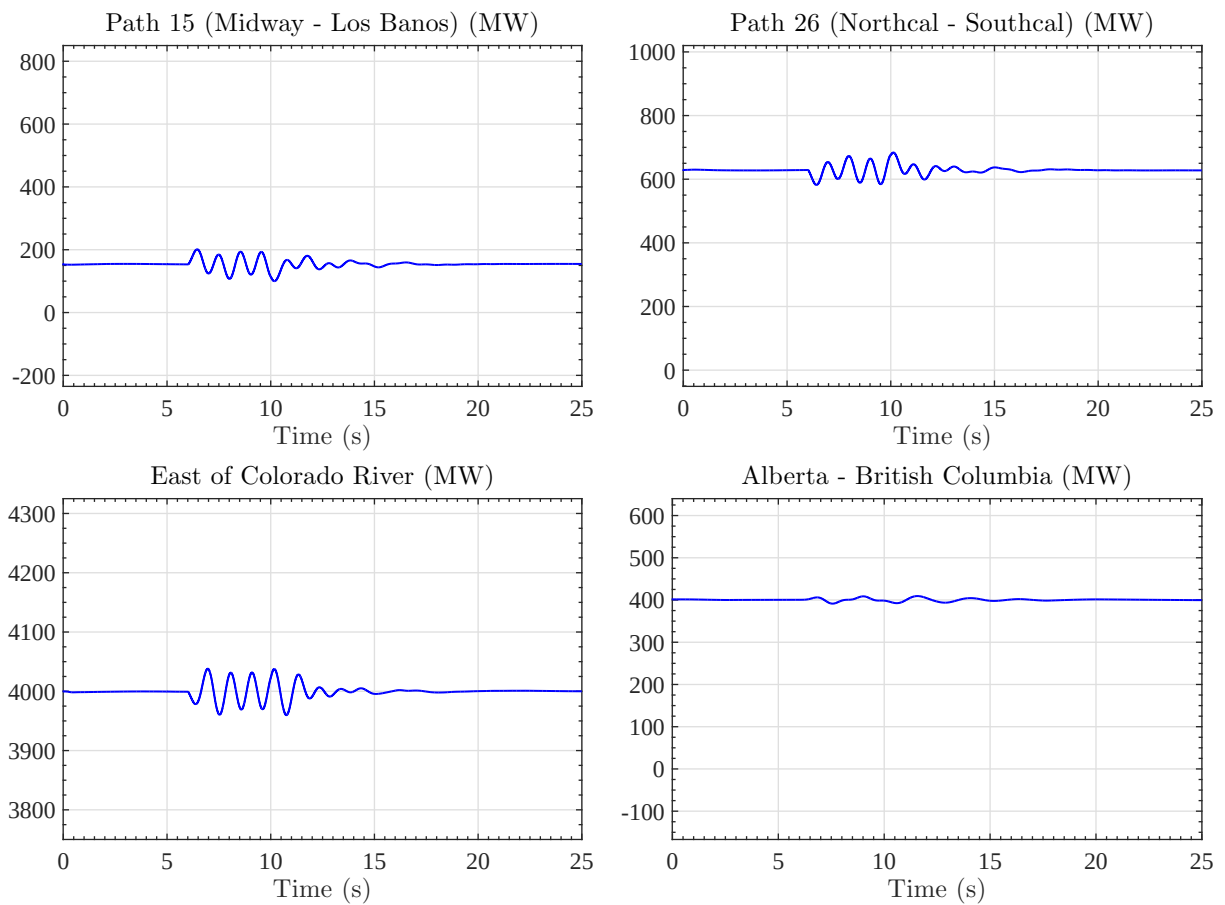


Figure 48. Active power flows. Event: SF 1.0/4x with amplitude of 125MW.

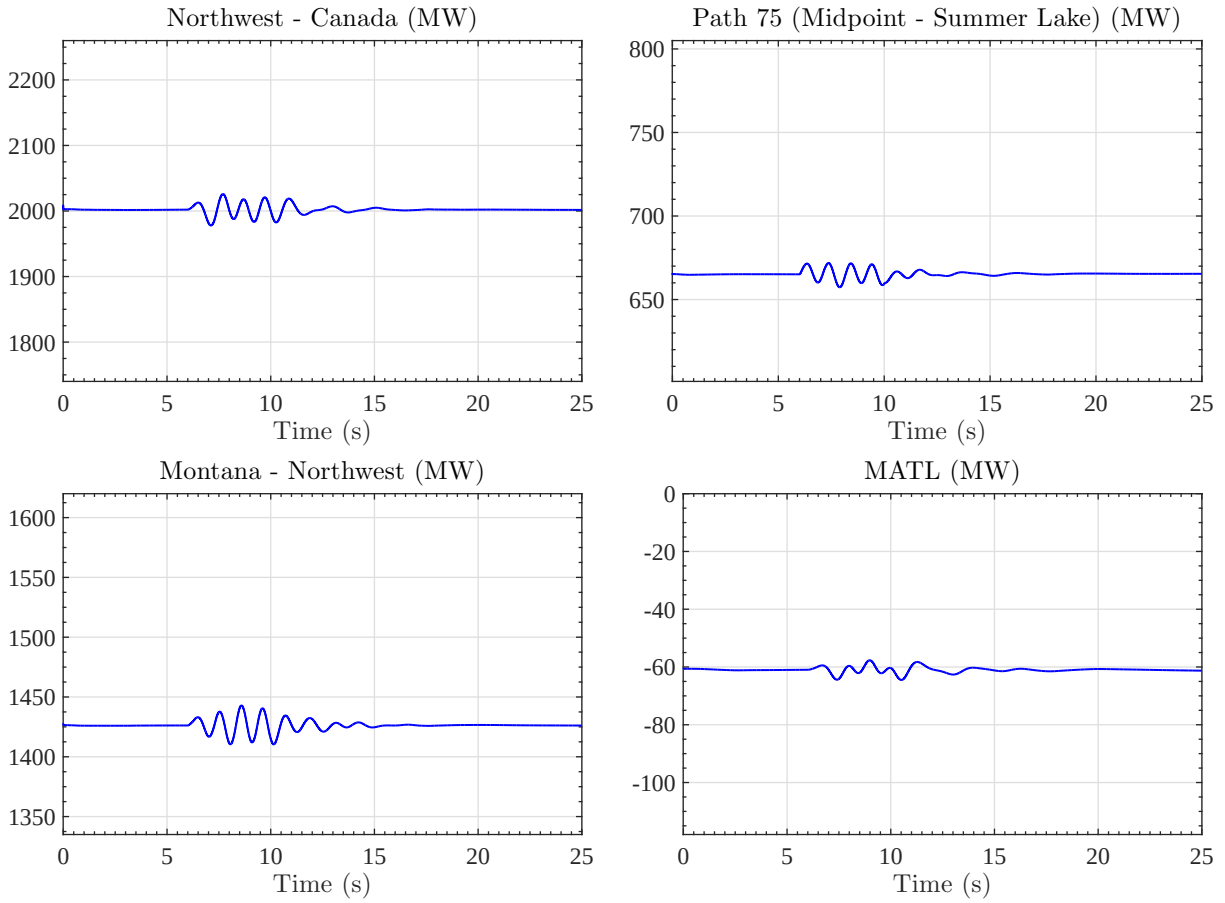


Figure 49. Active power flows. Event: SF 1.0/4x with amplitude of 125MW.

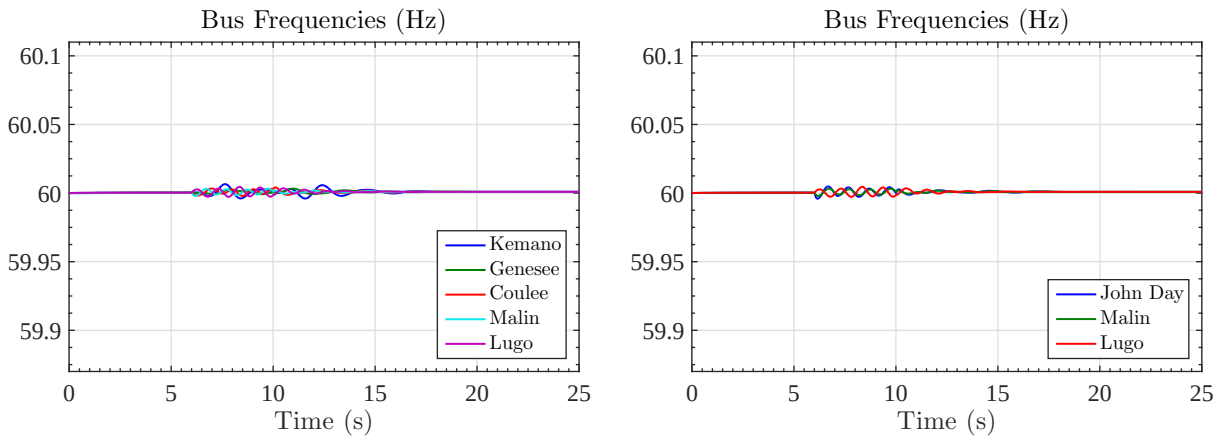


Figure 50. Bus frequencies. Event: SF 1.0/4x with amplitude of 125MW.

2.2. Closed Loop Testing

2.2.1. Test System: Light Summer 2016. Event: Chief Joe Brake

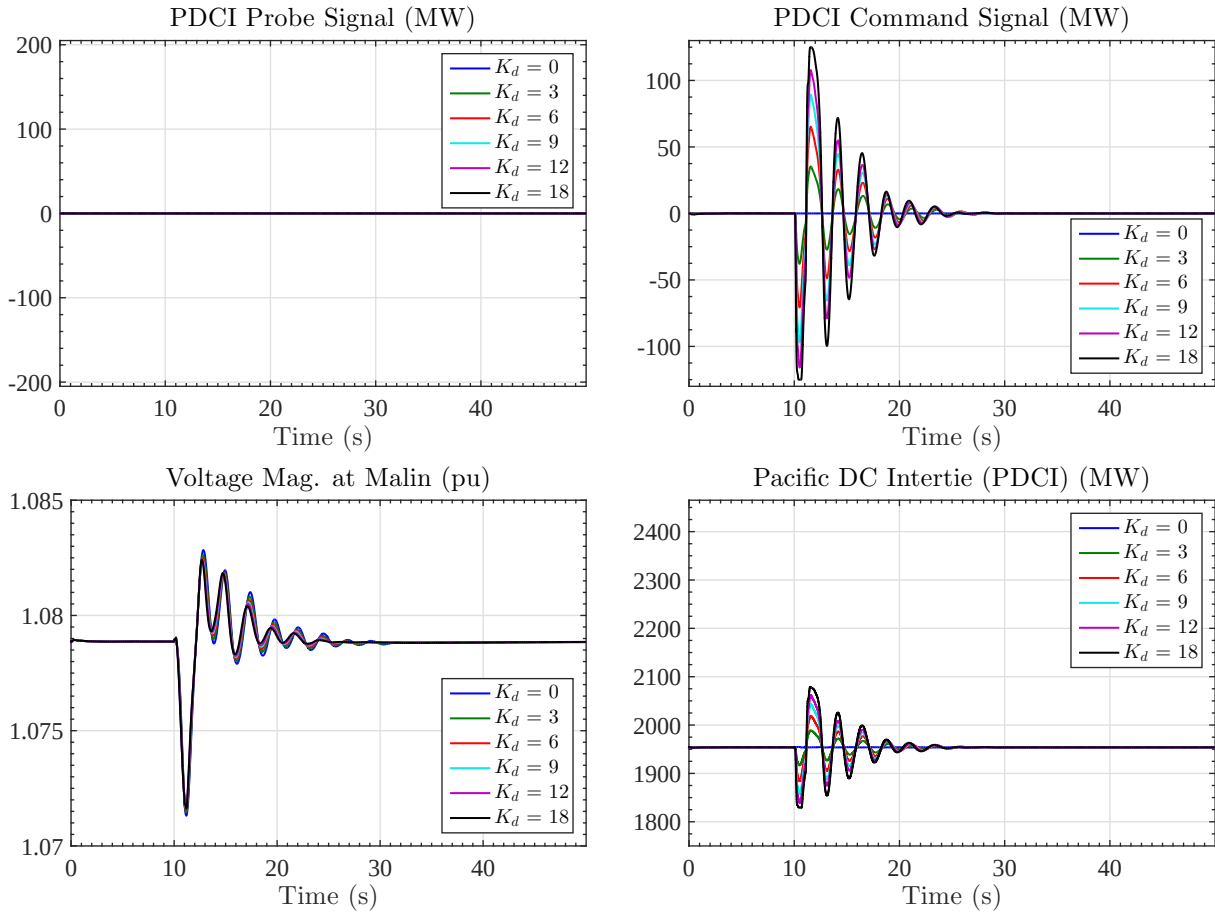


Figure 51. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake.

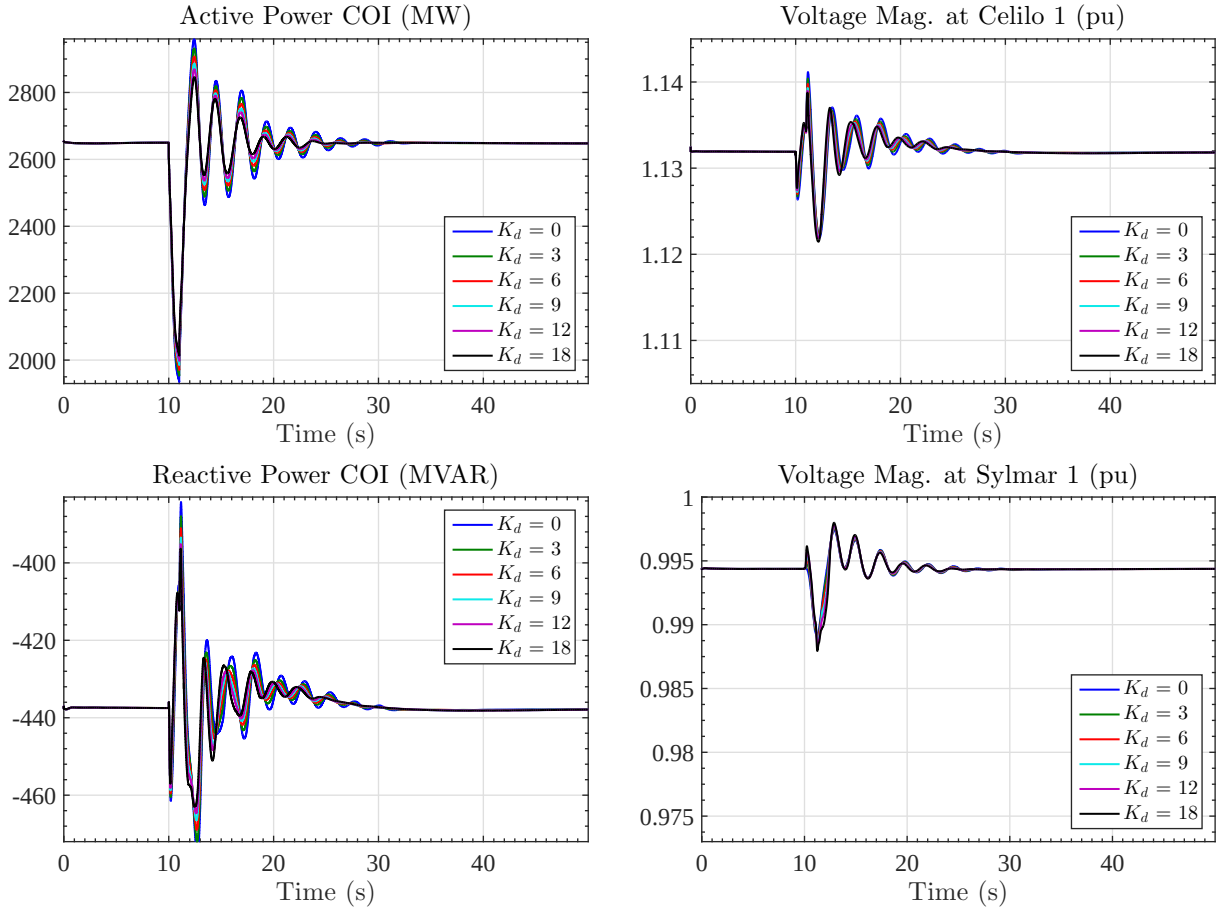


Figure 52. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake.

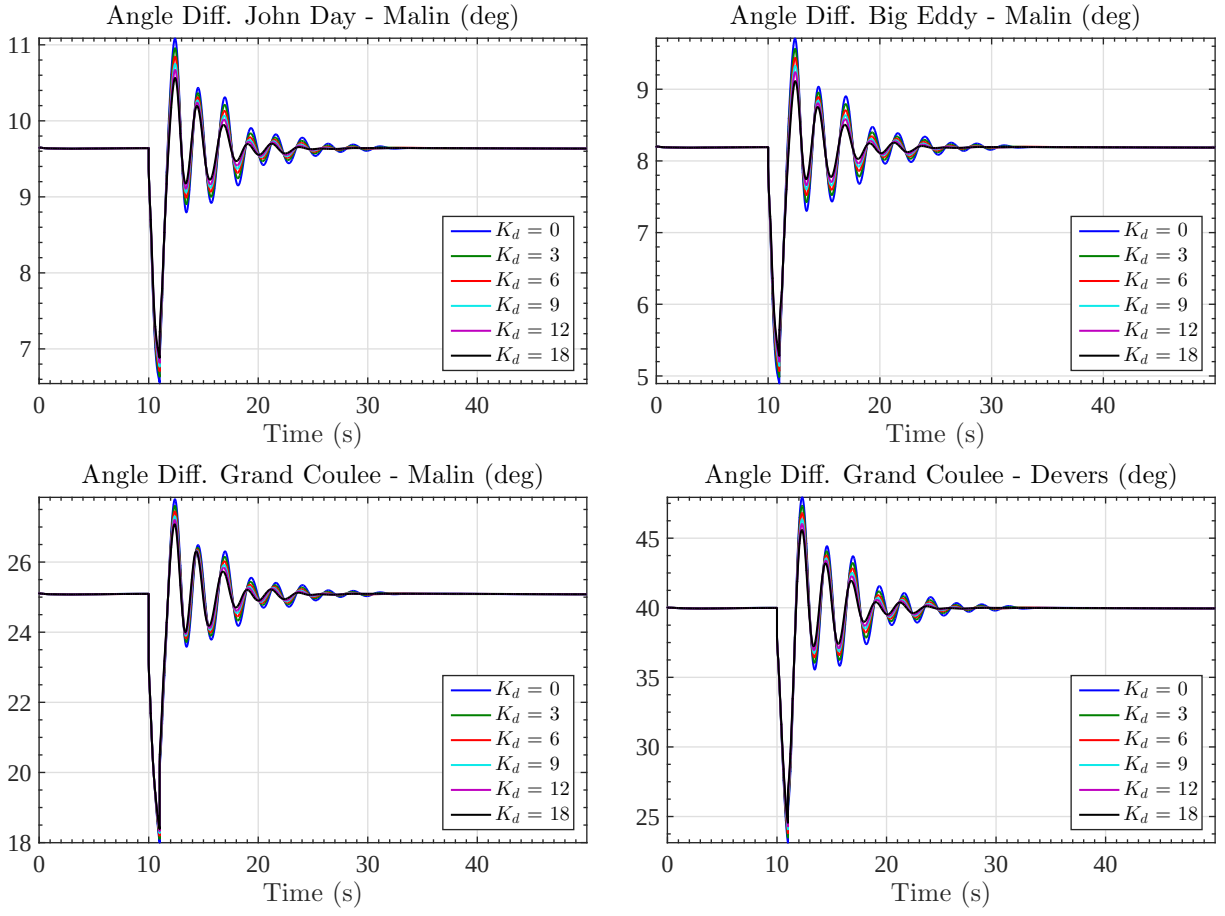


Figure 53. Angle differences. Event: Chief Joe Brake.

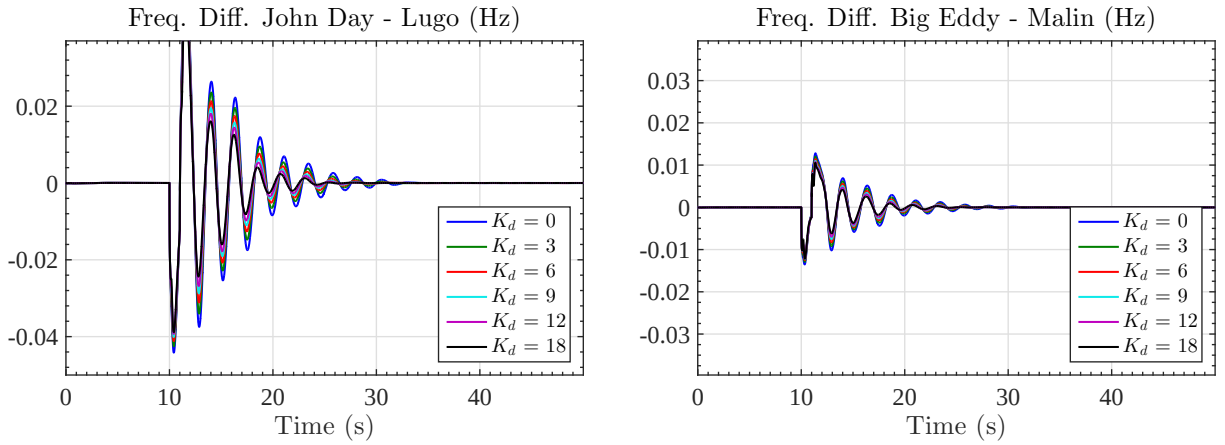


Figure 54. Frequency differences. Event: Chief Joe Brake.

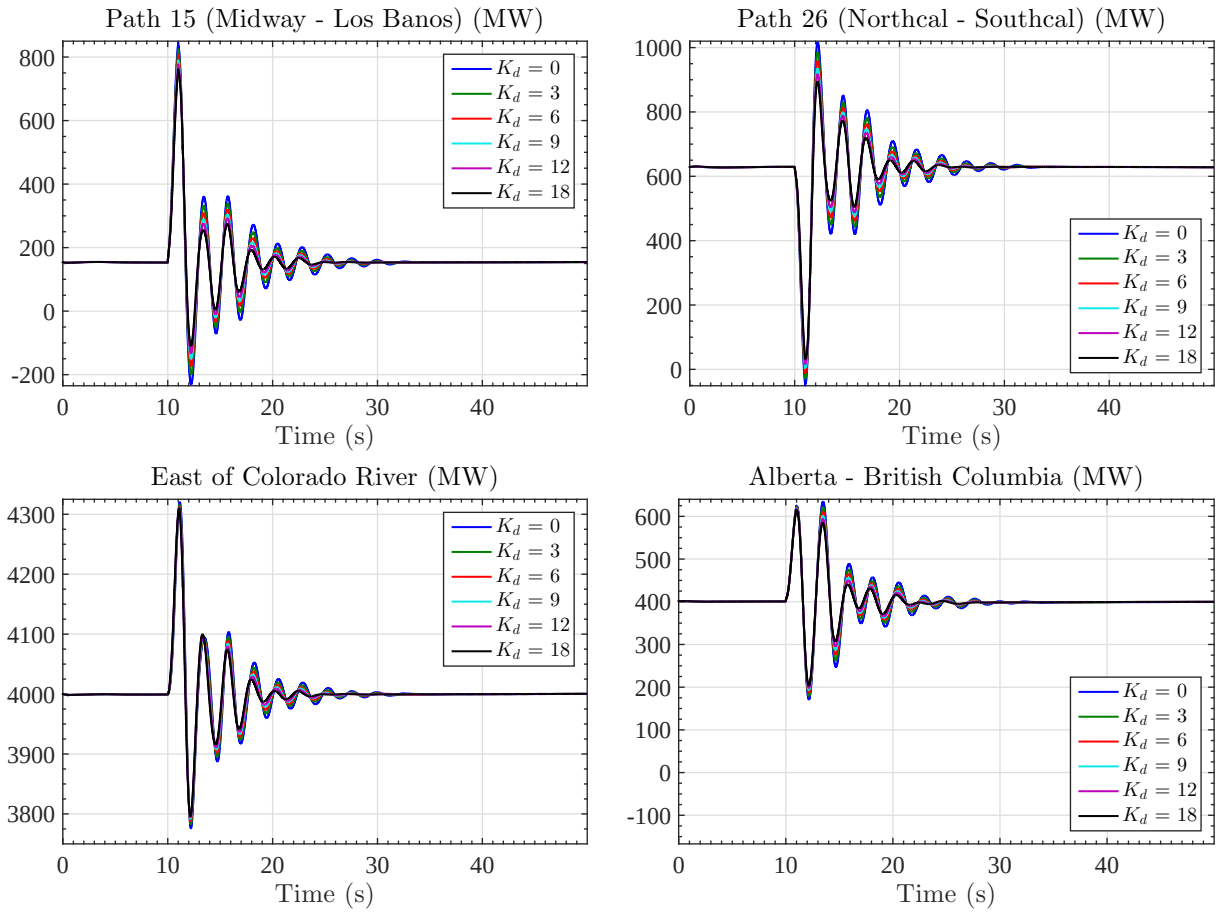


Figure 55. Active power flows. Event: Chief Joe Brake.

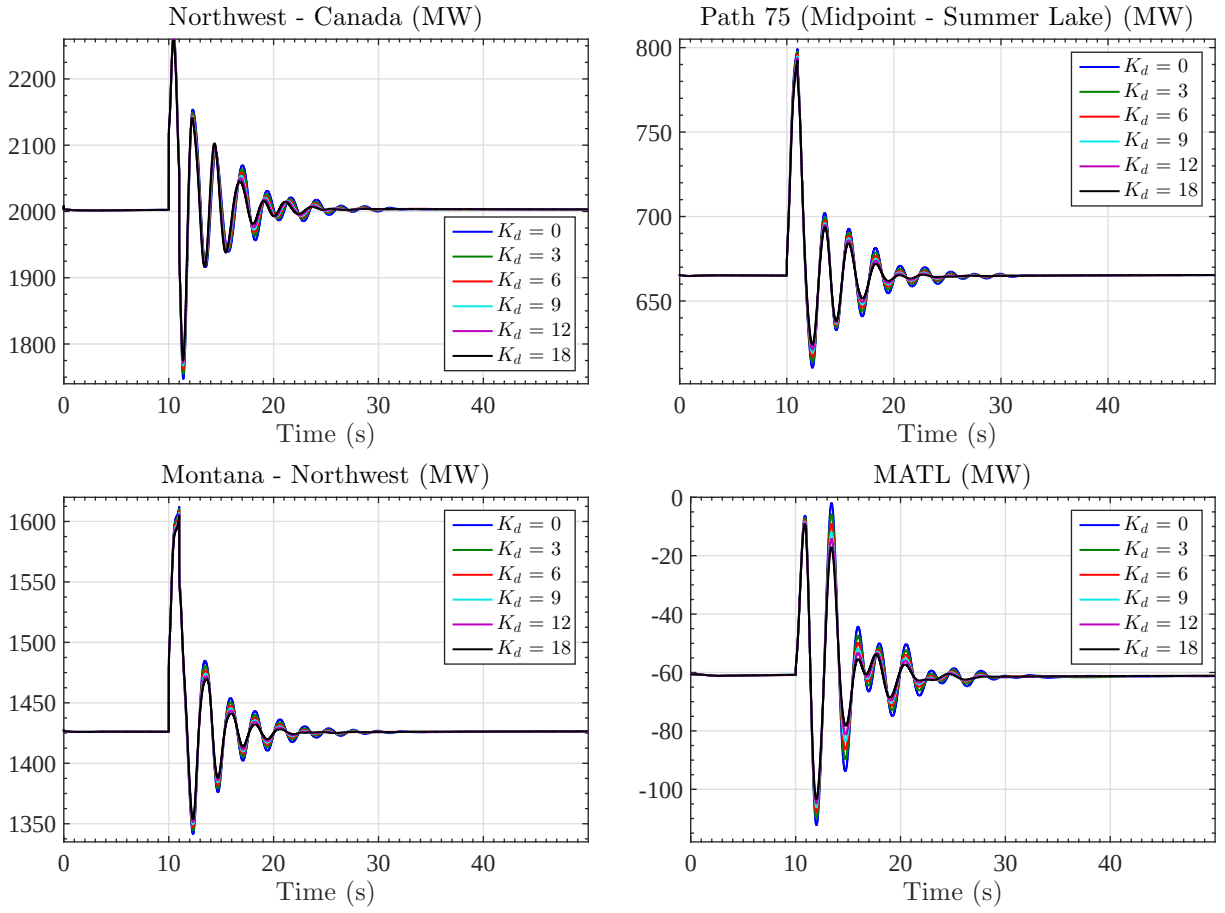


Figure 56. Active power flows. Event: Chief Joe Brake.

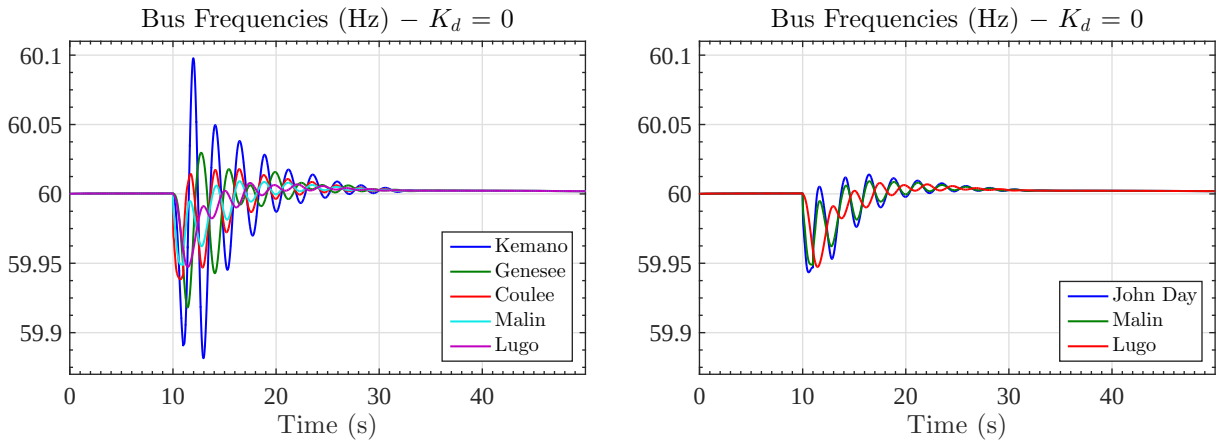


Figure 57. Bus frequencies. Event: Chief Joe Brake.

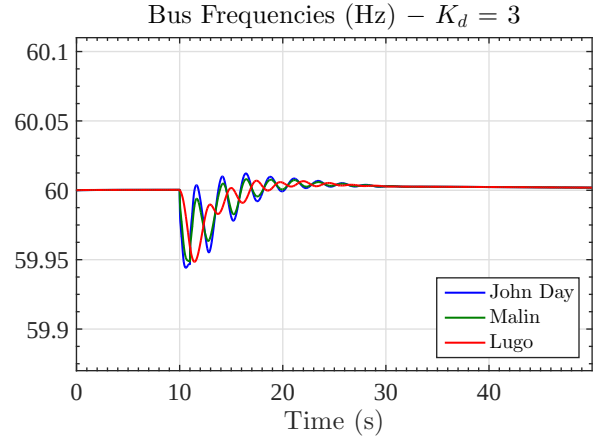
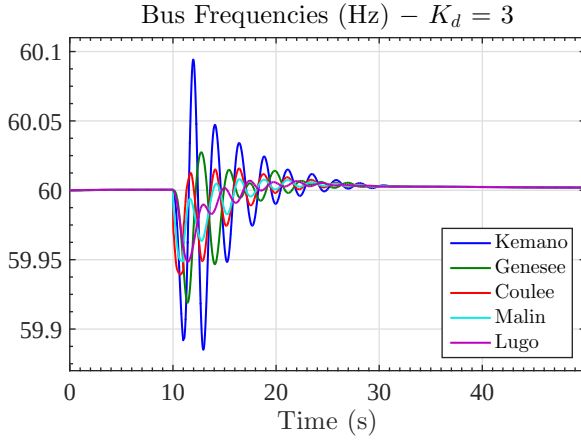


Figure 58. Bus frequencies. Event: Chief Joe Brake.

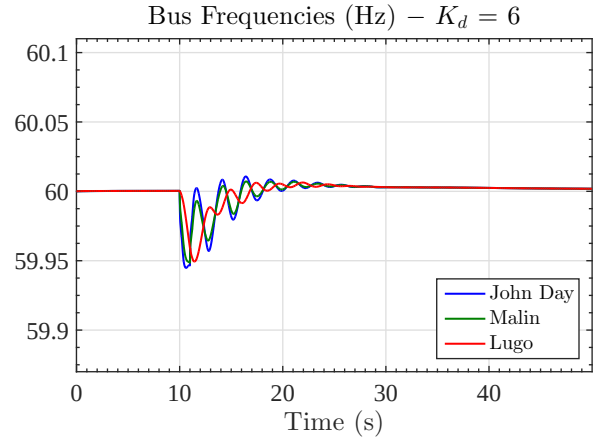
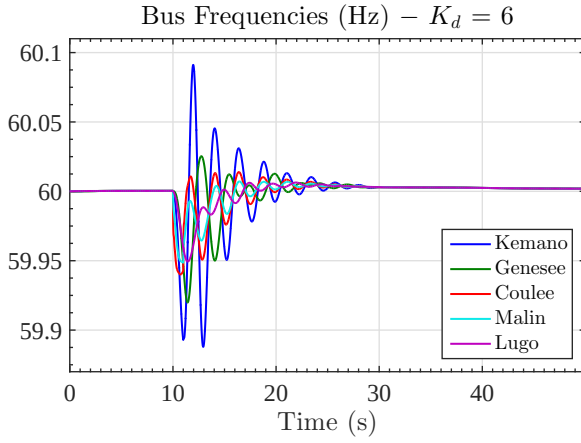


Figure 59. Bus frequencies. Event: Chief Joe Brake.

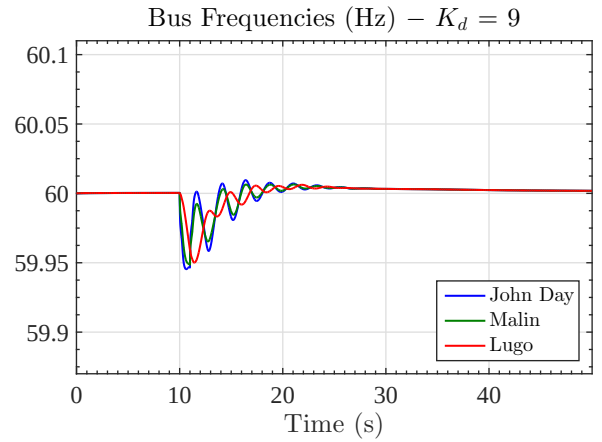
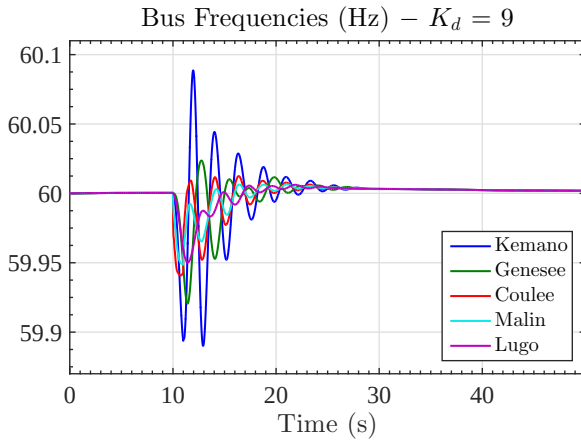


Figure 60. Bus frequencies. Event: Chief Joe Brake.

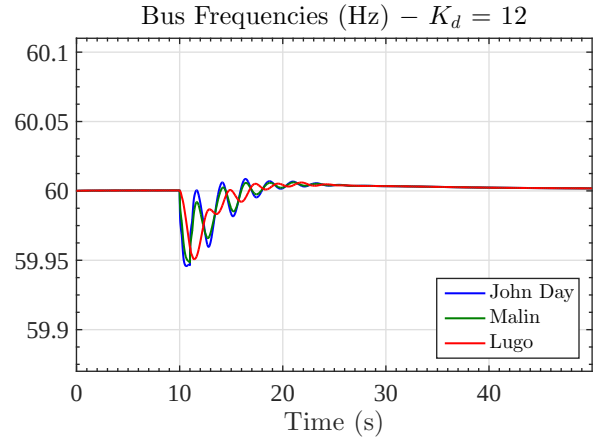
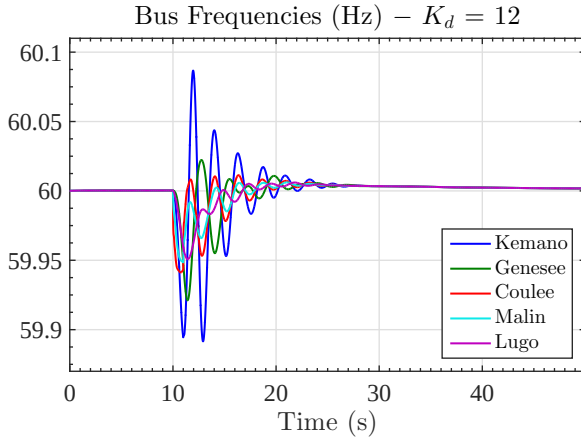


Figure 61. Bus frequencies. Event: Chief Joe Brake.

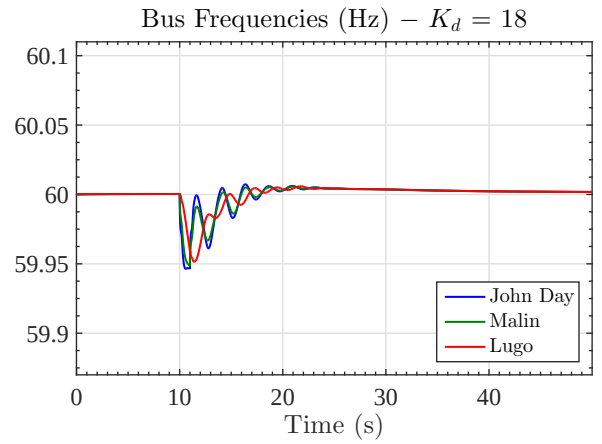
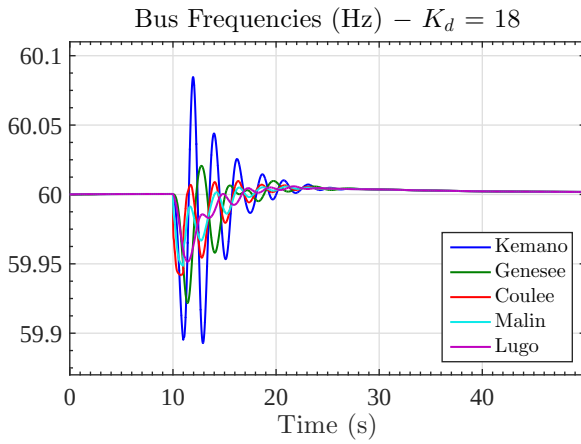


Figure 62. Bus frequencies. Event: Chief Joe Brake.

2.2.2. Test System: Light Summer 2016. Event: 200 MW pulses

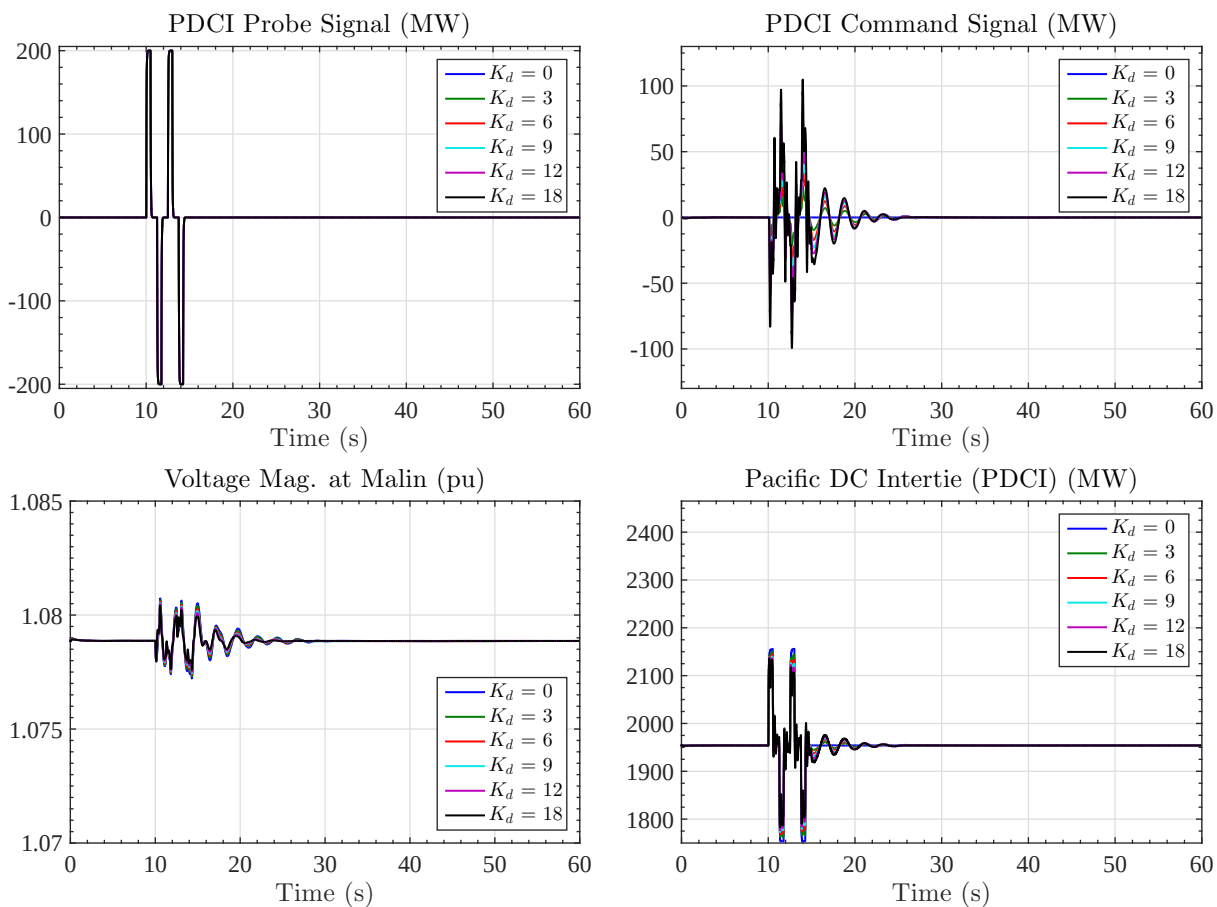


Figure 63. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses.

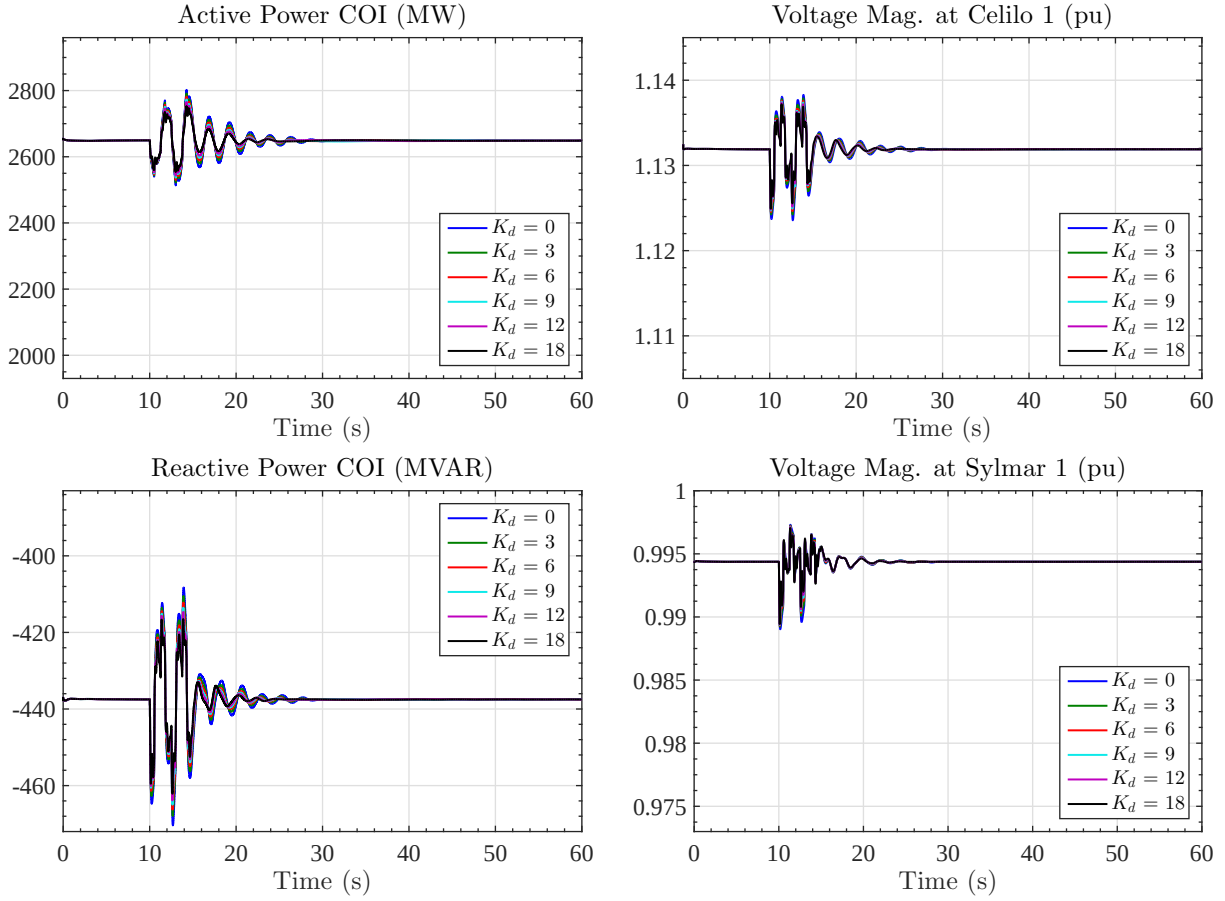


Figure 64. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses.

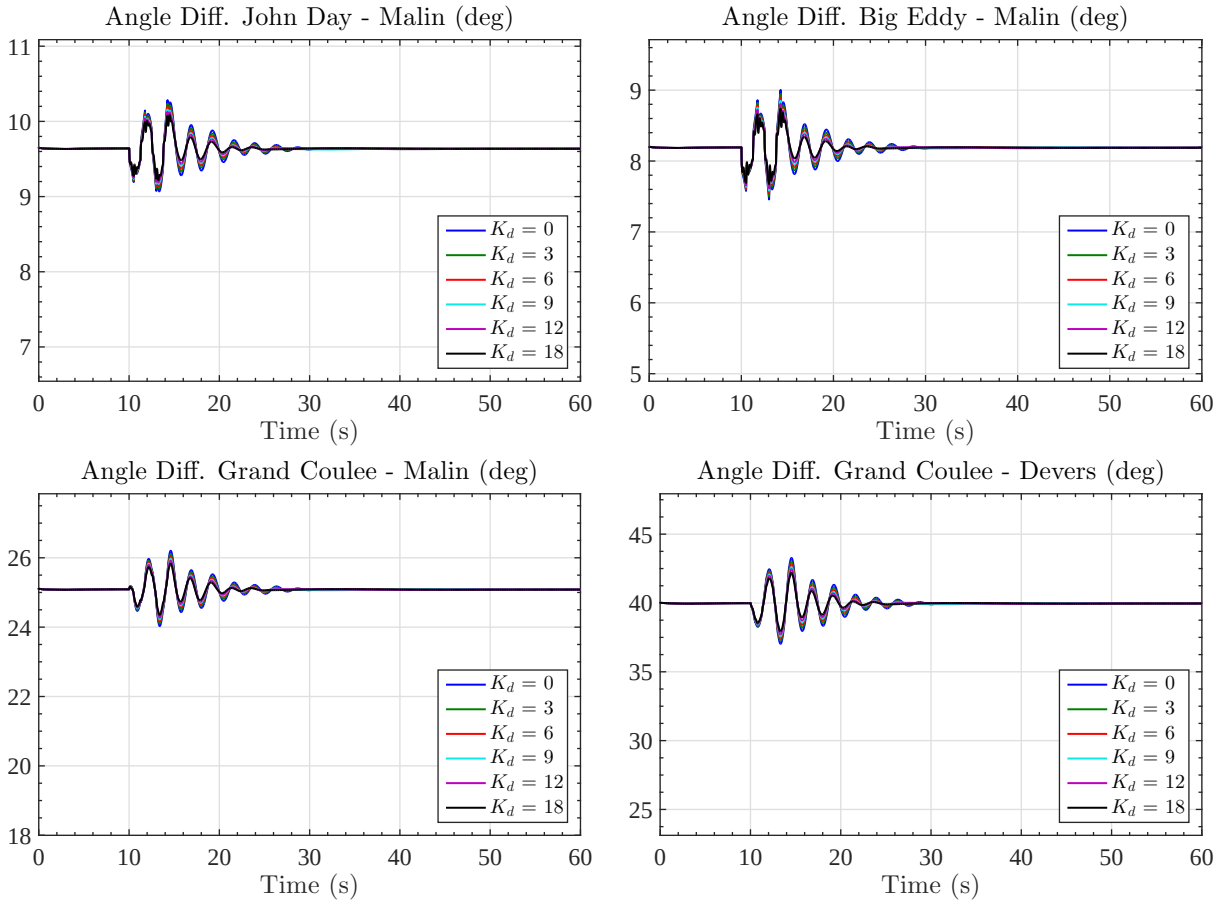


Figure 65. Angle differences. Event: 200 MW pulses.

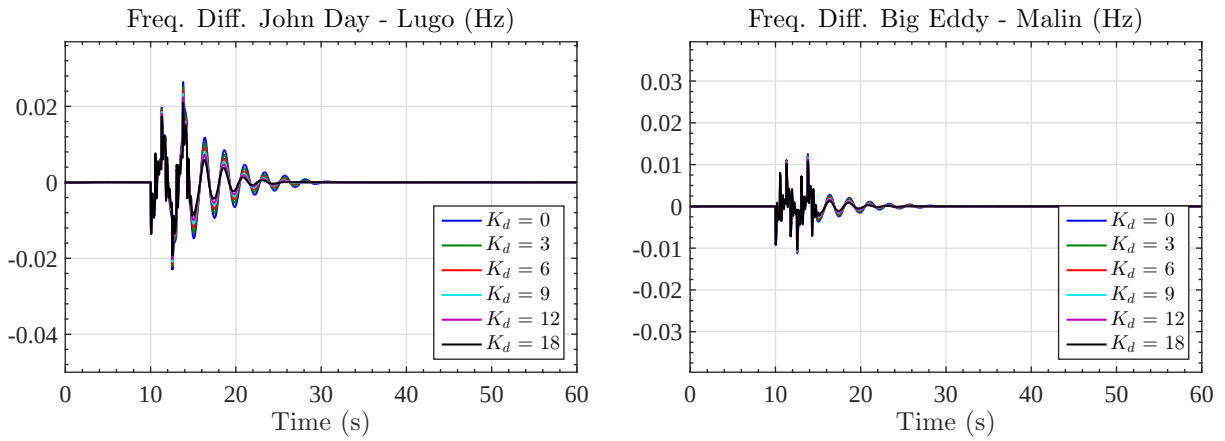


Figure 66. Frequency differences. Event: 200 MW pulses.

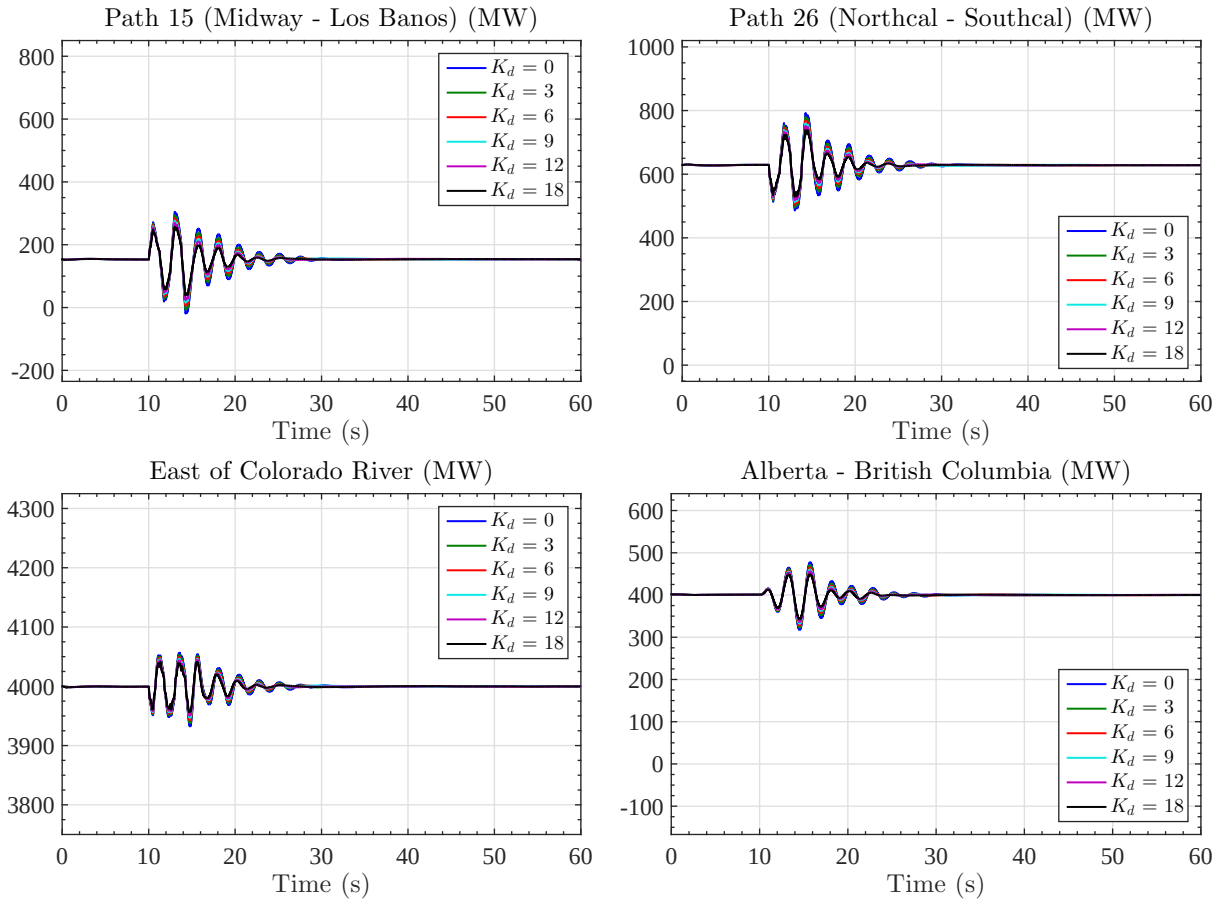


Figure 67. Active power flows. Event: 200 MW pulses.

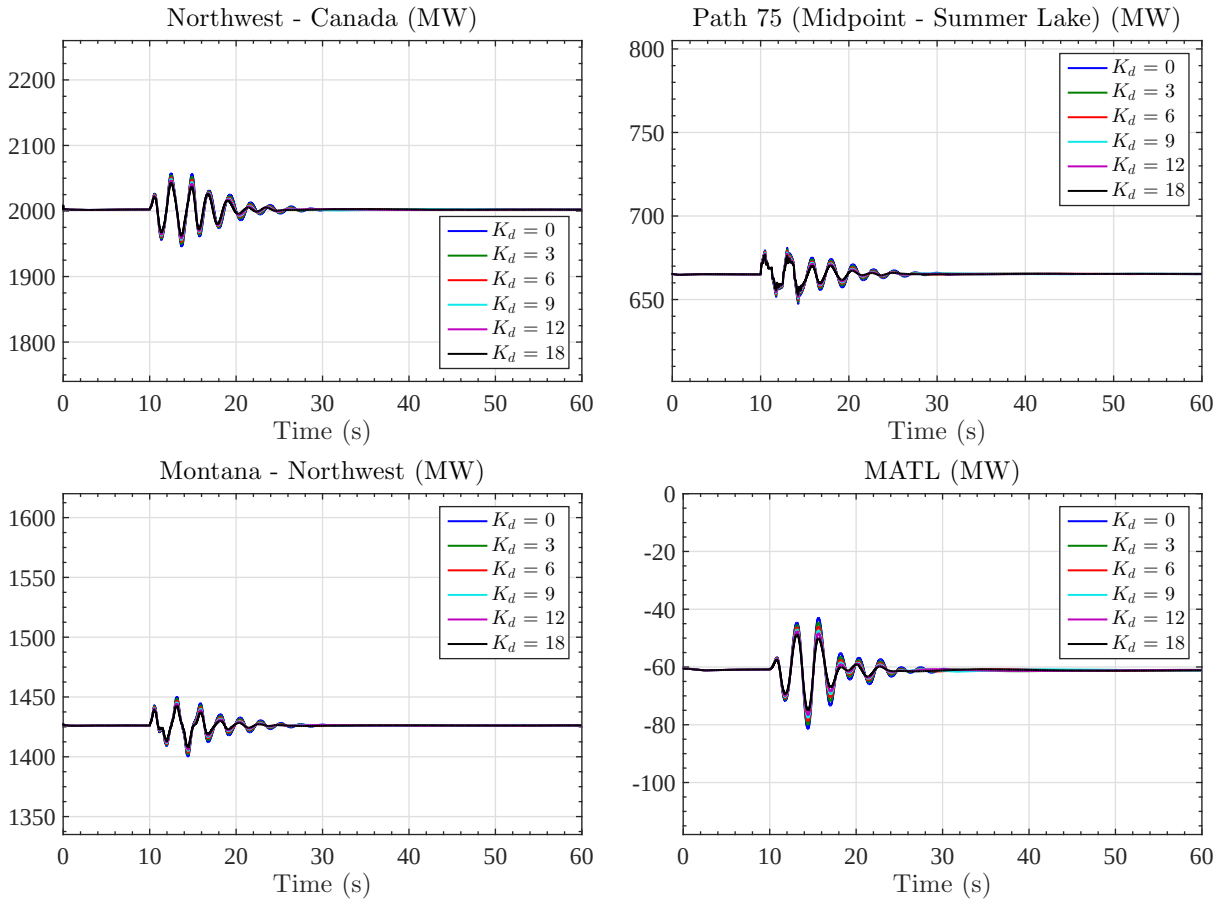


Figure 68. Active power flows. Event: 200 MW pulses.

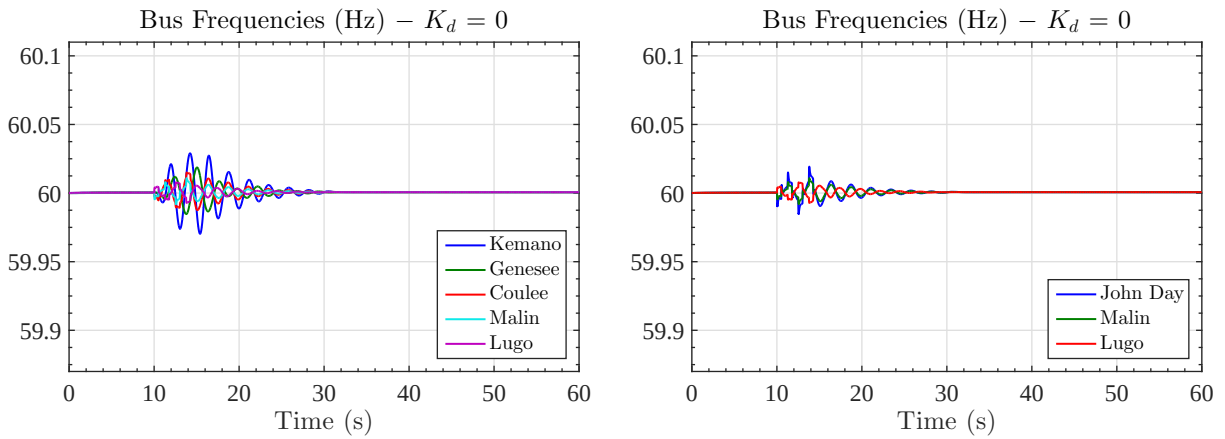


Figure 69. Bus frequencies. Event: 200 MW pulses.

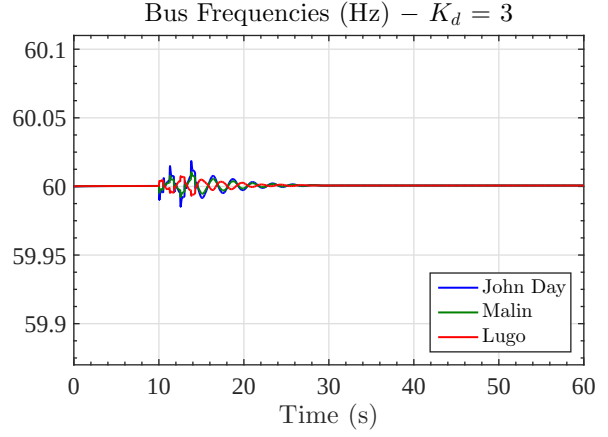
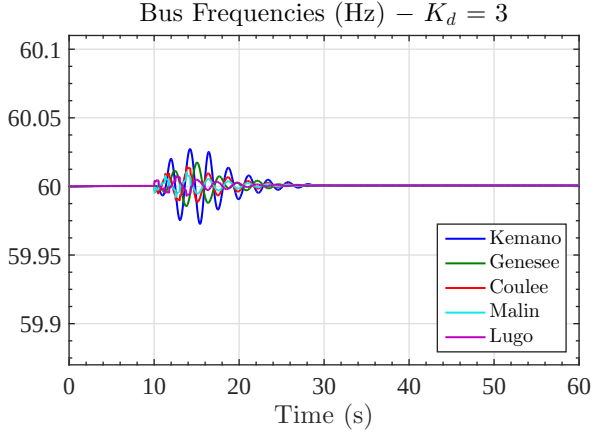


Figure 70. Bus frequencies. Event: 200 MW pulses.

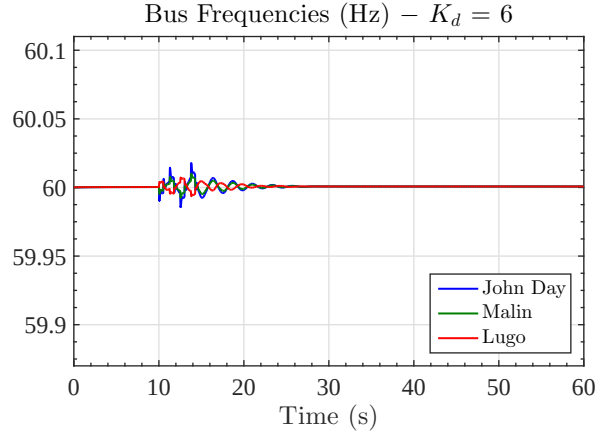
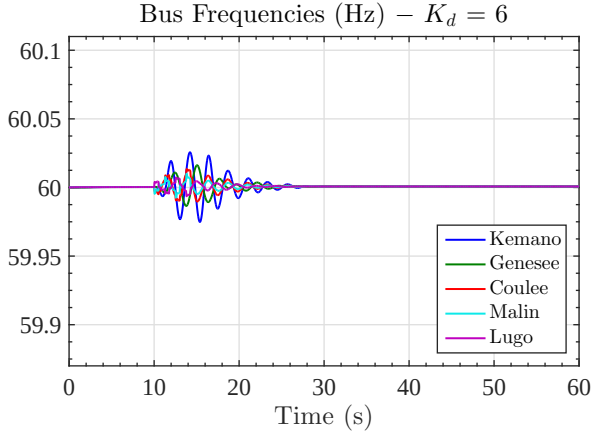


Figure 71. Bus frequencies. Event: 200 MW pulses.

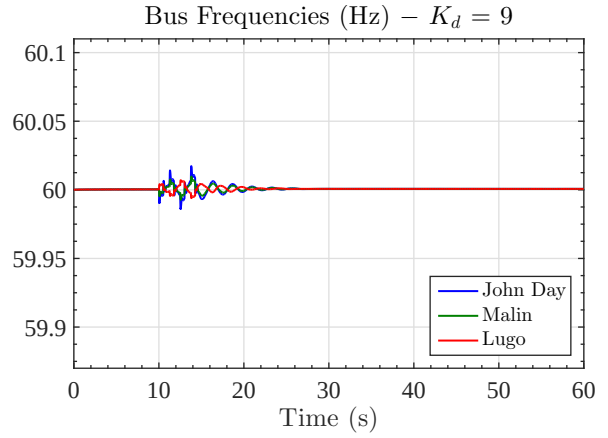
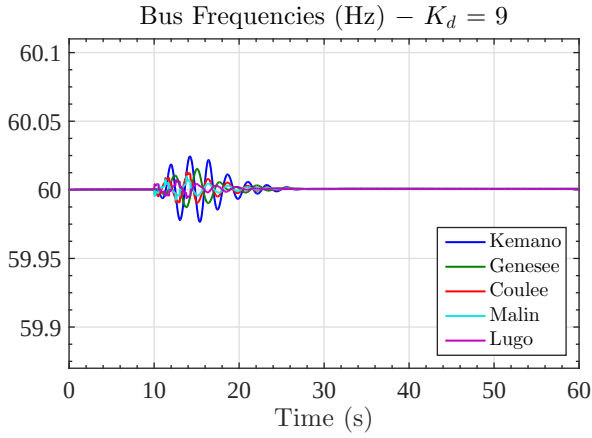


Figure 72. Bus frequencies. Event: 200 MW pulses.

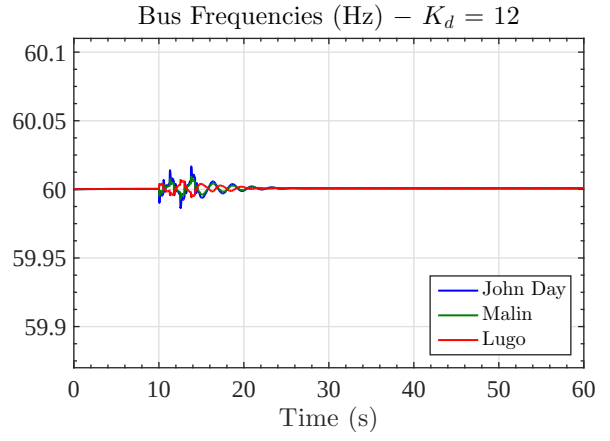
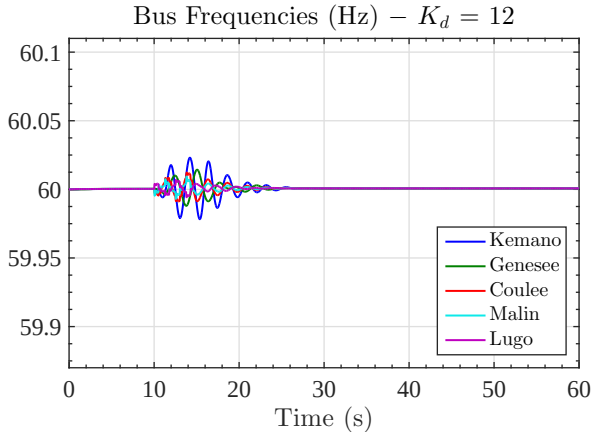


Figure 73. Bus frequencies. Event: 200 MW pulses.

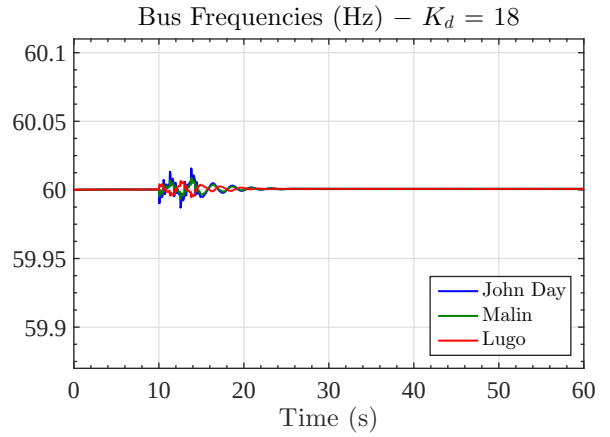
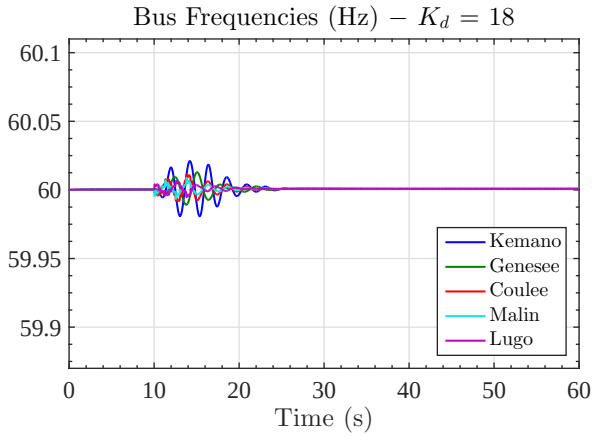


Figure 74. Bus frequencies. Event: 200 MW pulses.

2.2.3. Test System: Light Summer 2016. Event: 200 MW pulses with control limit of 50 MW

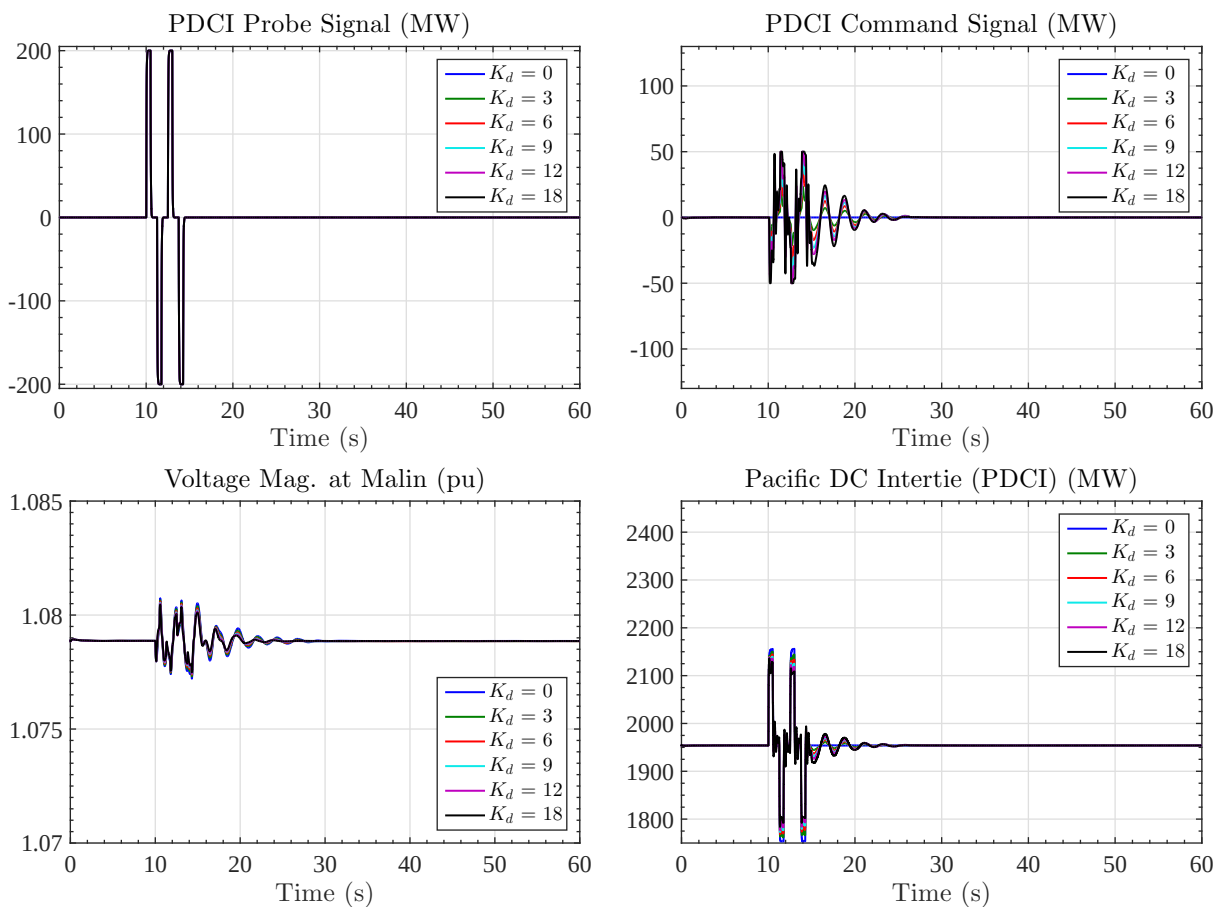


Figure 75. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses with control limit of 50 MW.

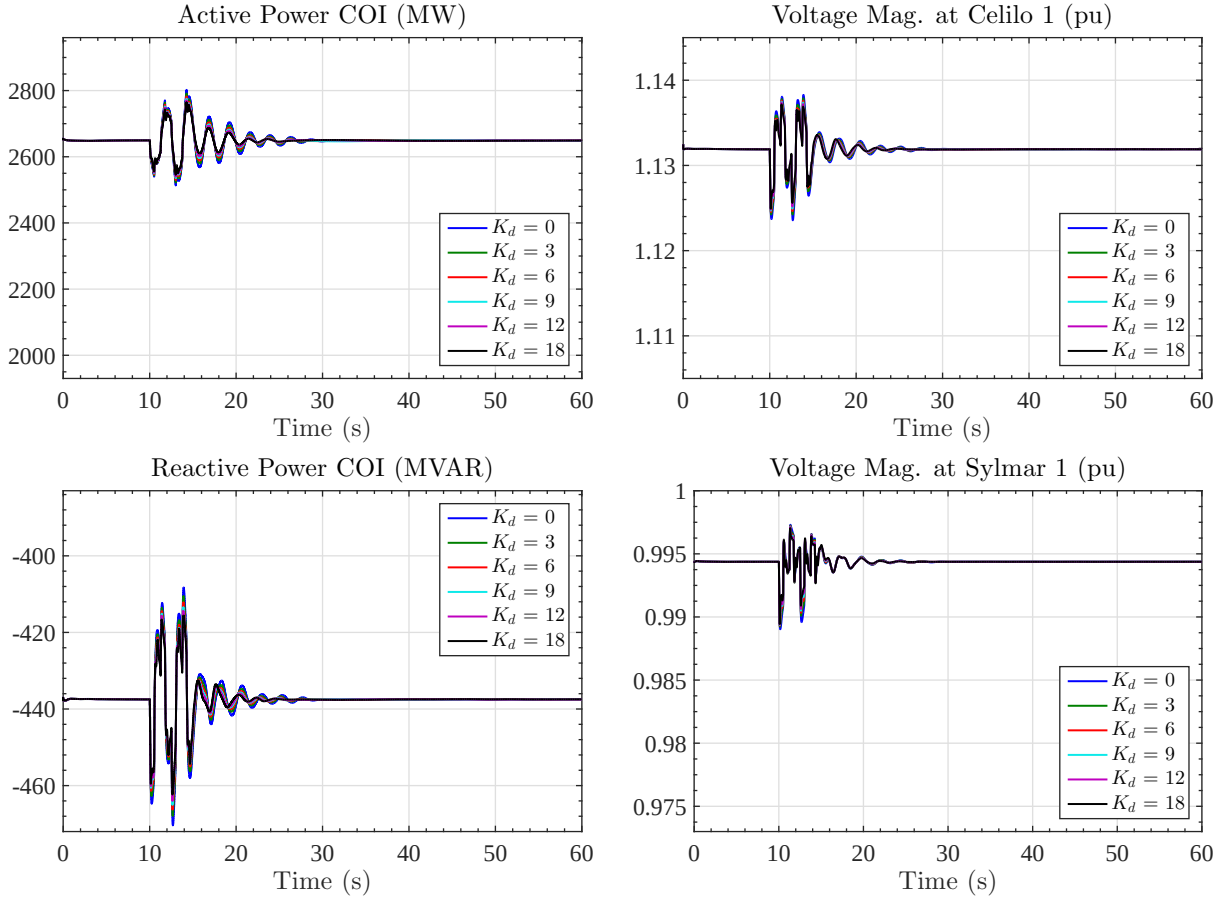


Figure 76. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses with control limit of 50 MW.

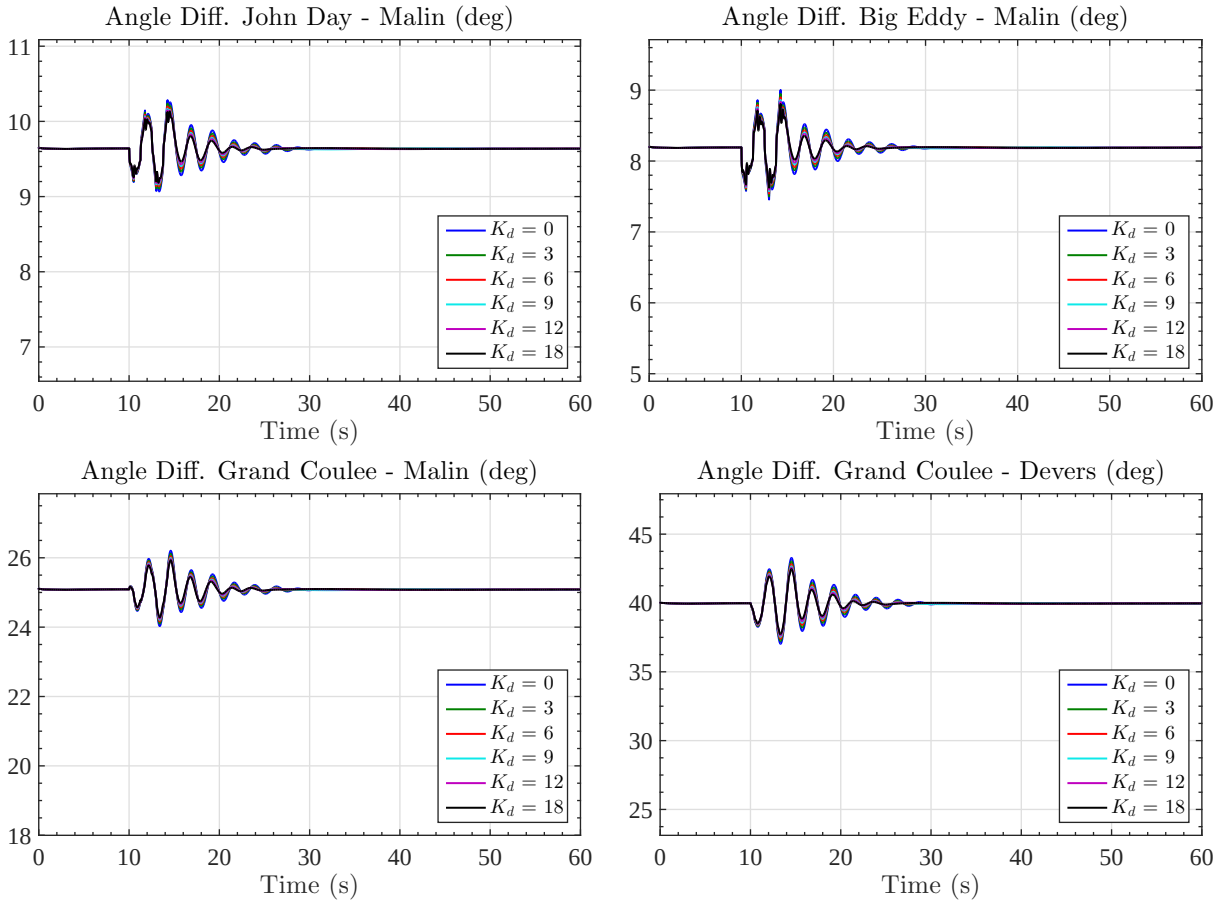


Figure 77. Angle differences. Event: 200 MW pulses with control limit of 50 MW.

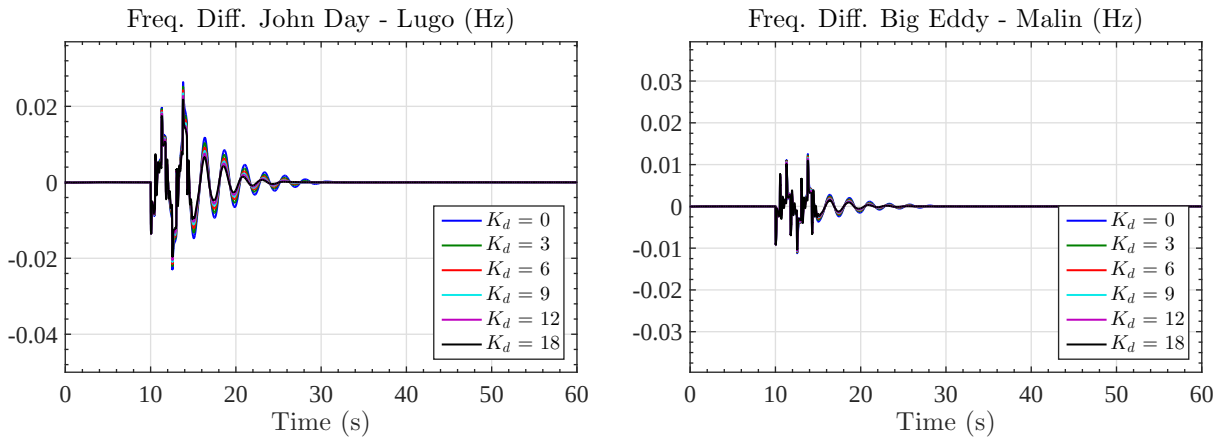


Figure 78. Frequency differences. Event: 200 MW pulses with control limit of 50 MW.

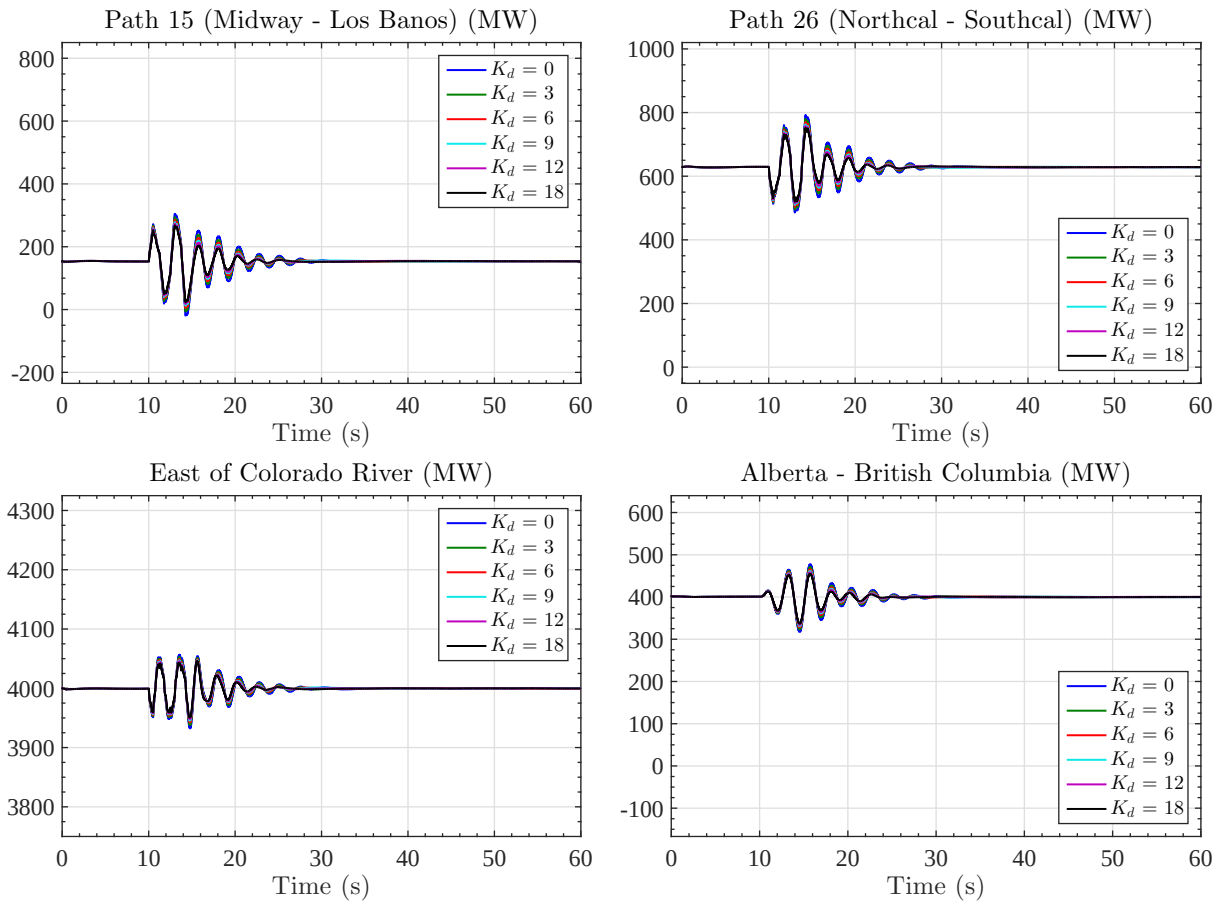


Figure 79. Active power flows. Event: 200 MW pulses with control limit of 50 MW.

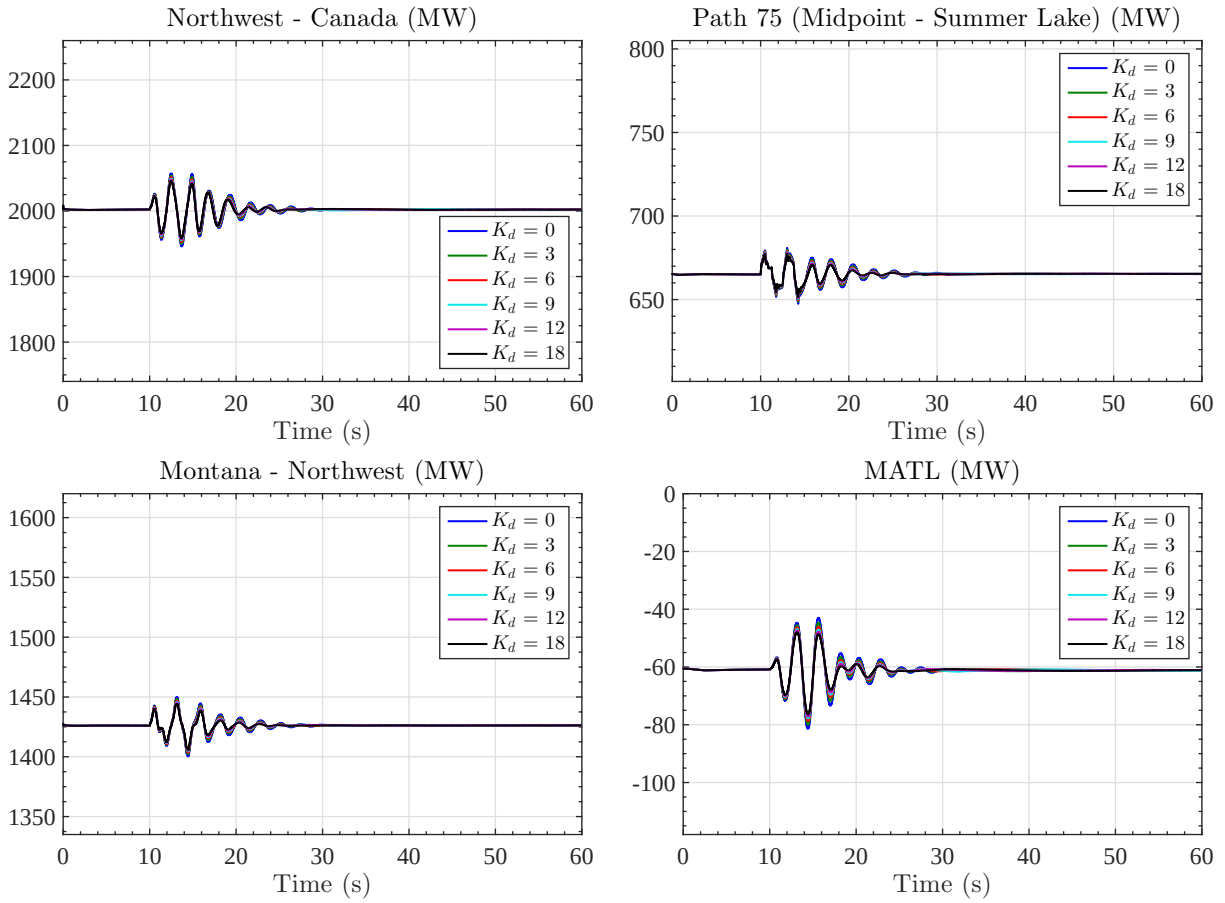


Figure 80. Active power flows. Event: 200 MW pulses with control limit of 50 MW.

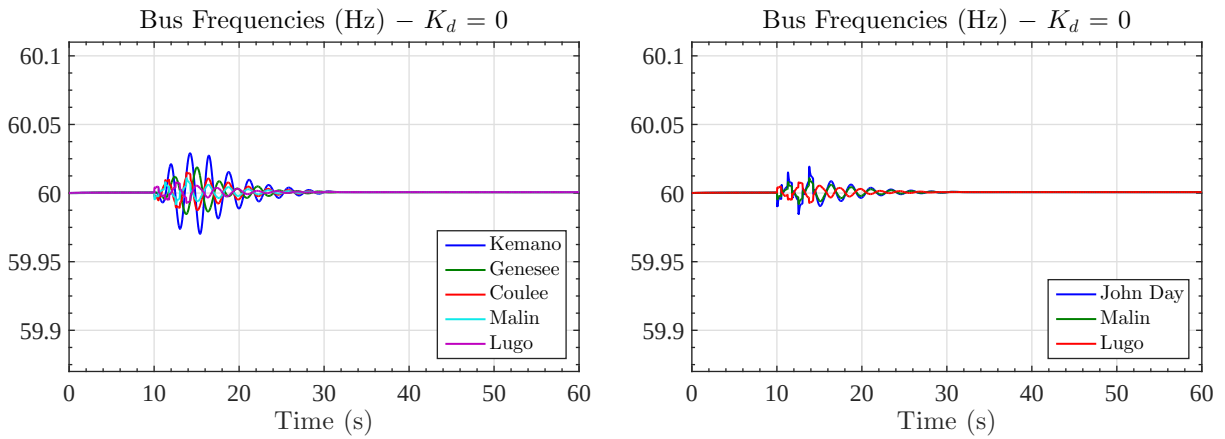


Figure 81. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

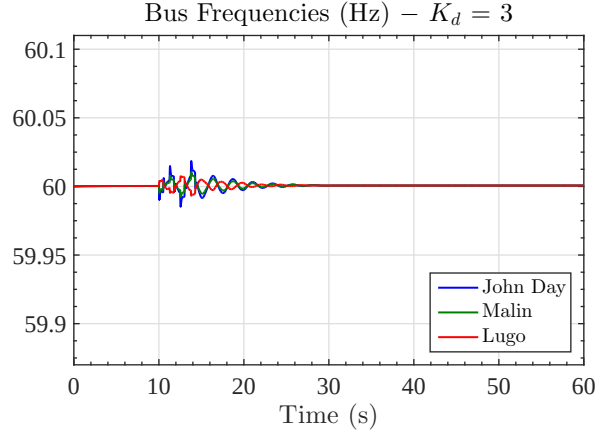
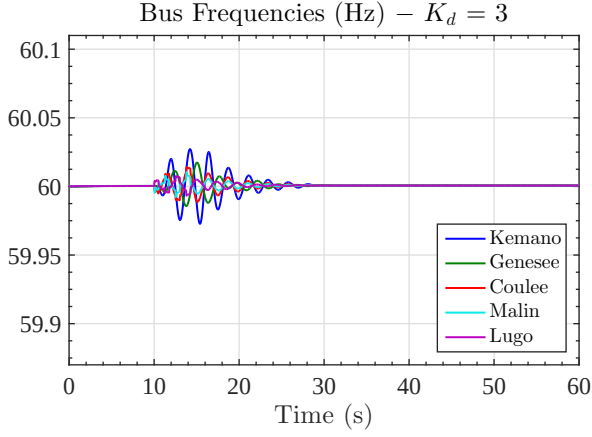


Figure 82. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

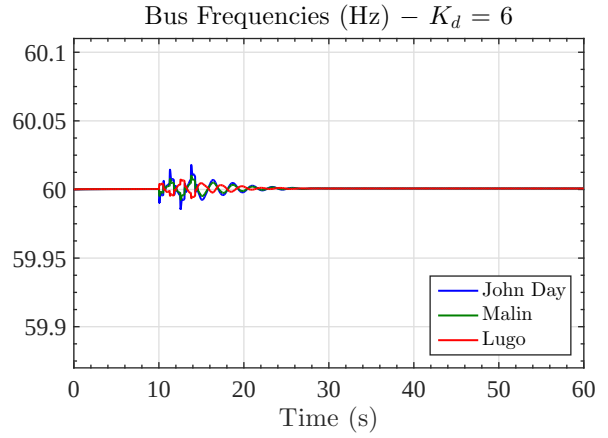
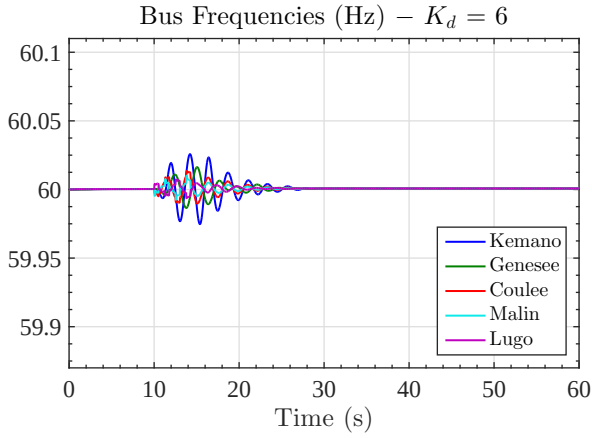


Figure 83. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

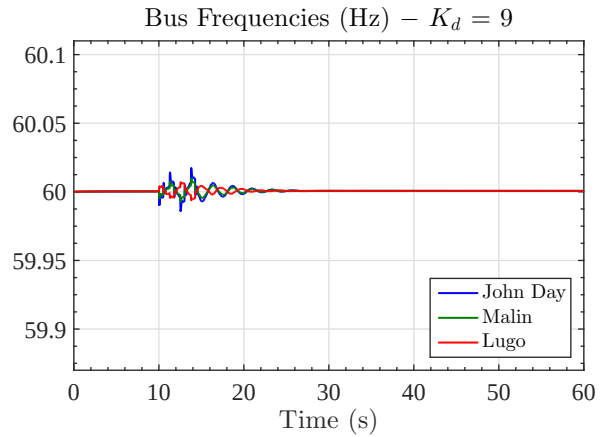
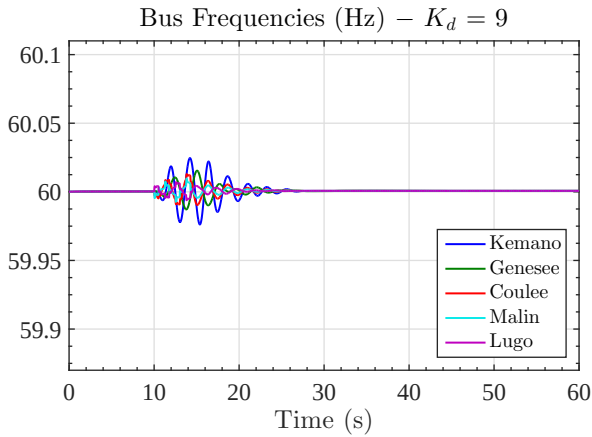


Figure 84. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

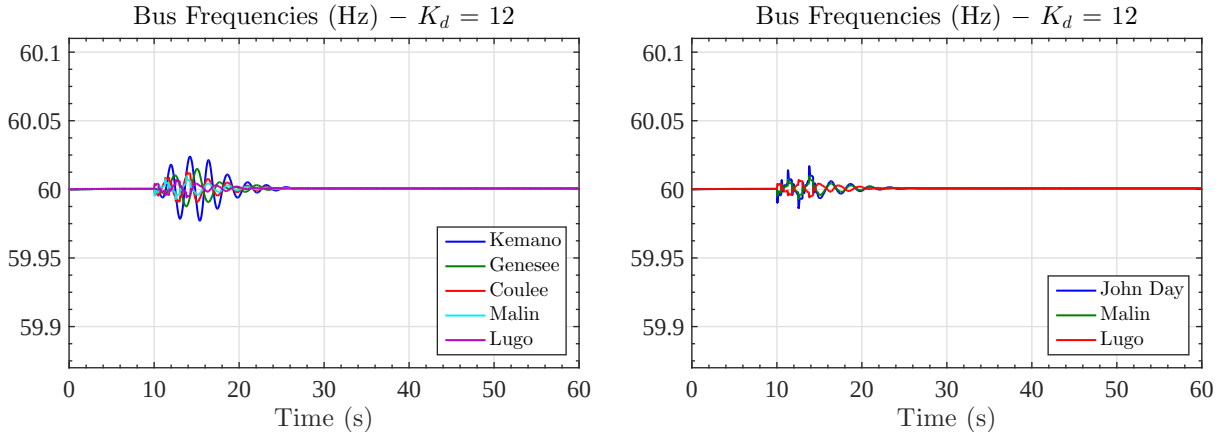


Figure 85. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

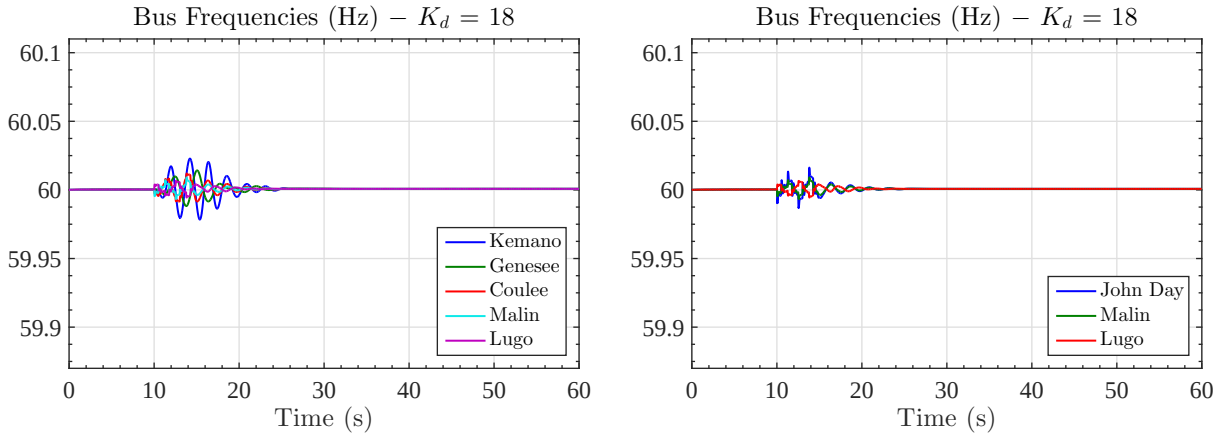


Figure 86. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

2.2.4. Test System: Light Summer 2016. Event: 200 MW pulses with control limit of 35 MW

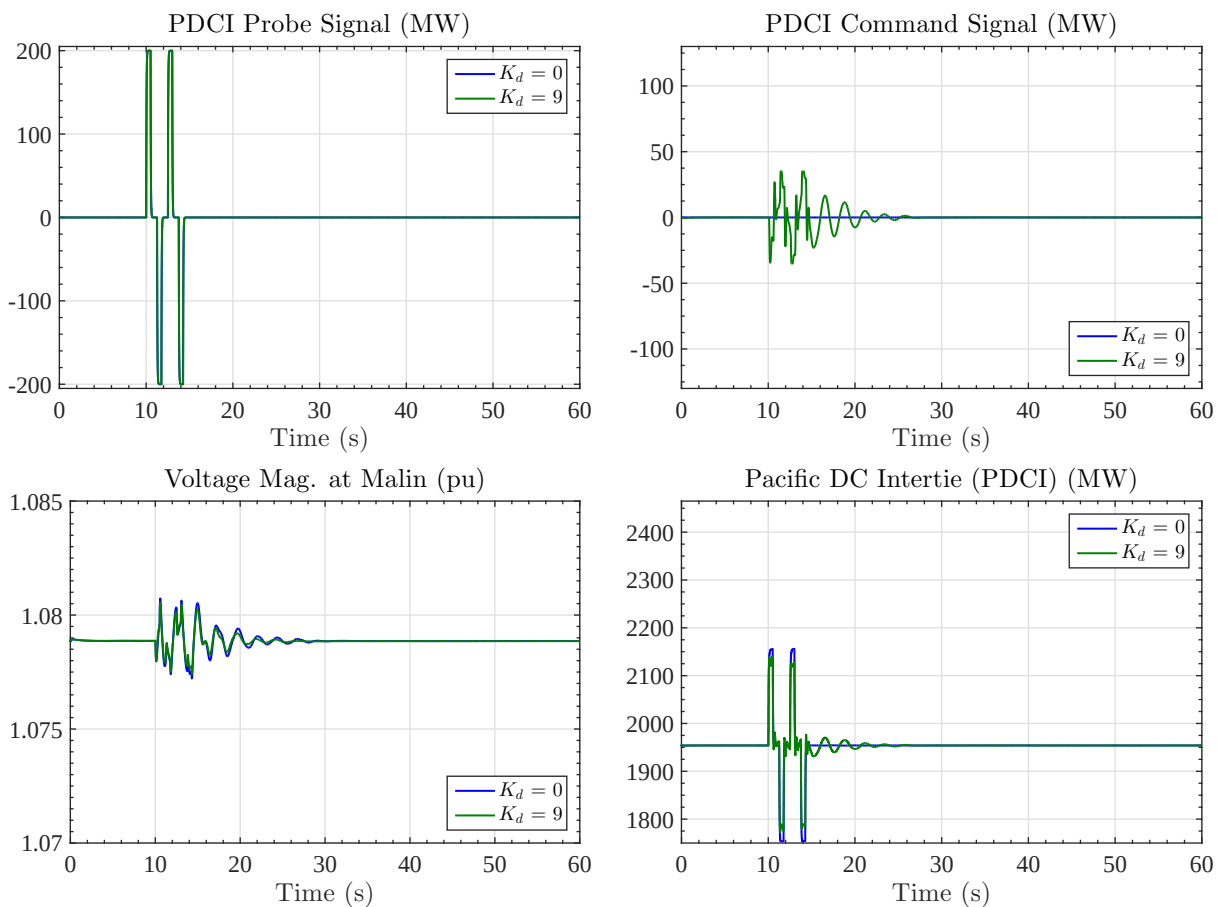


Figure 87. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses with control limit of 35 MW.

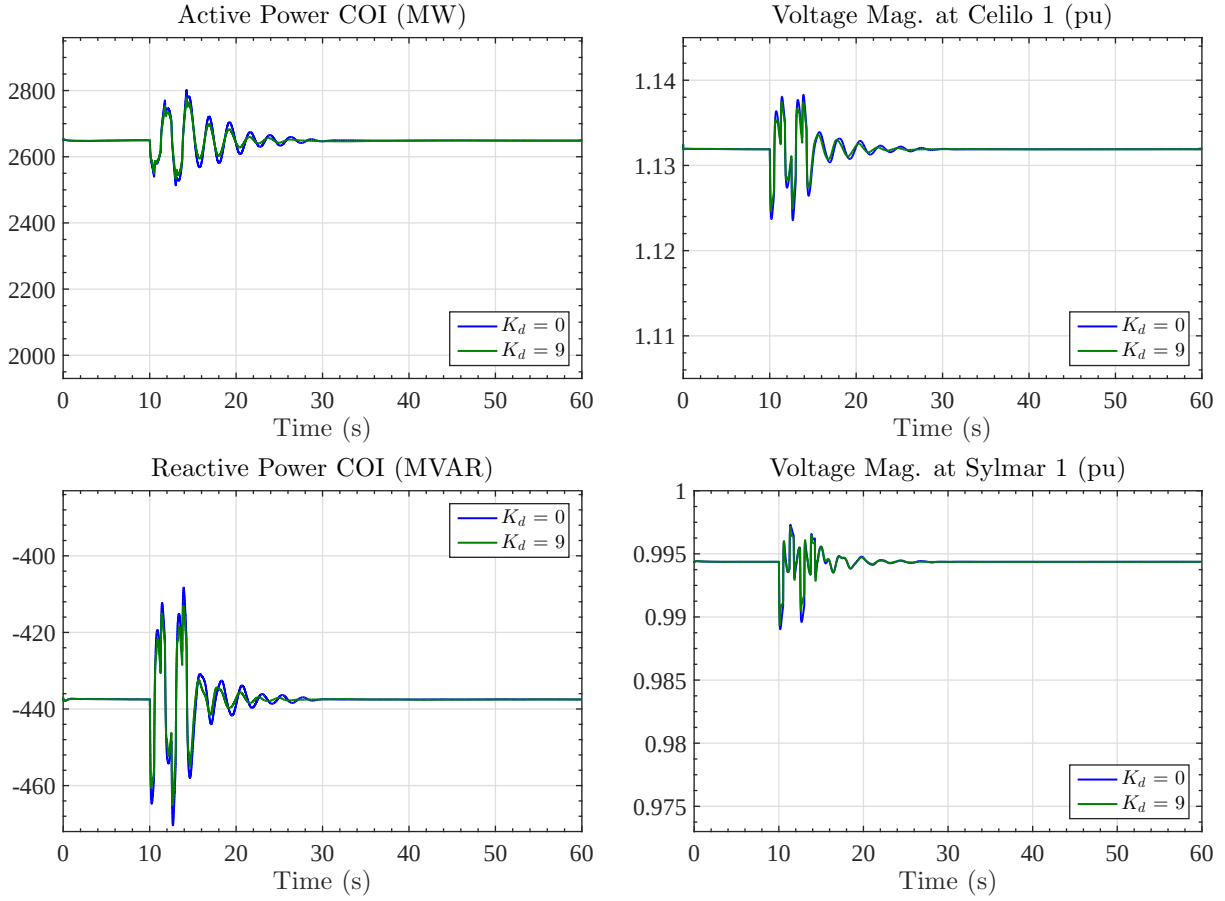


Figure 88. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses with control limit of 35 MW.

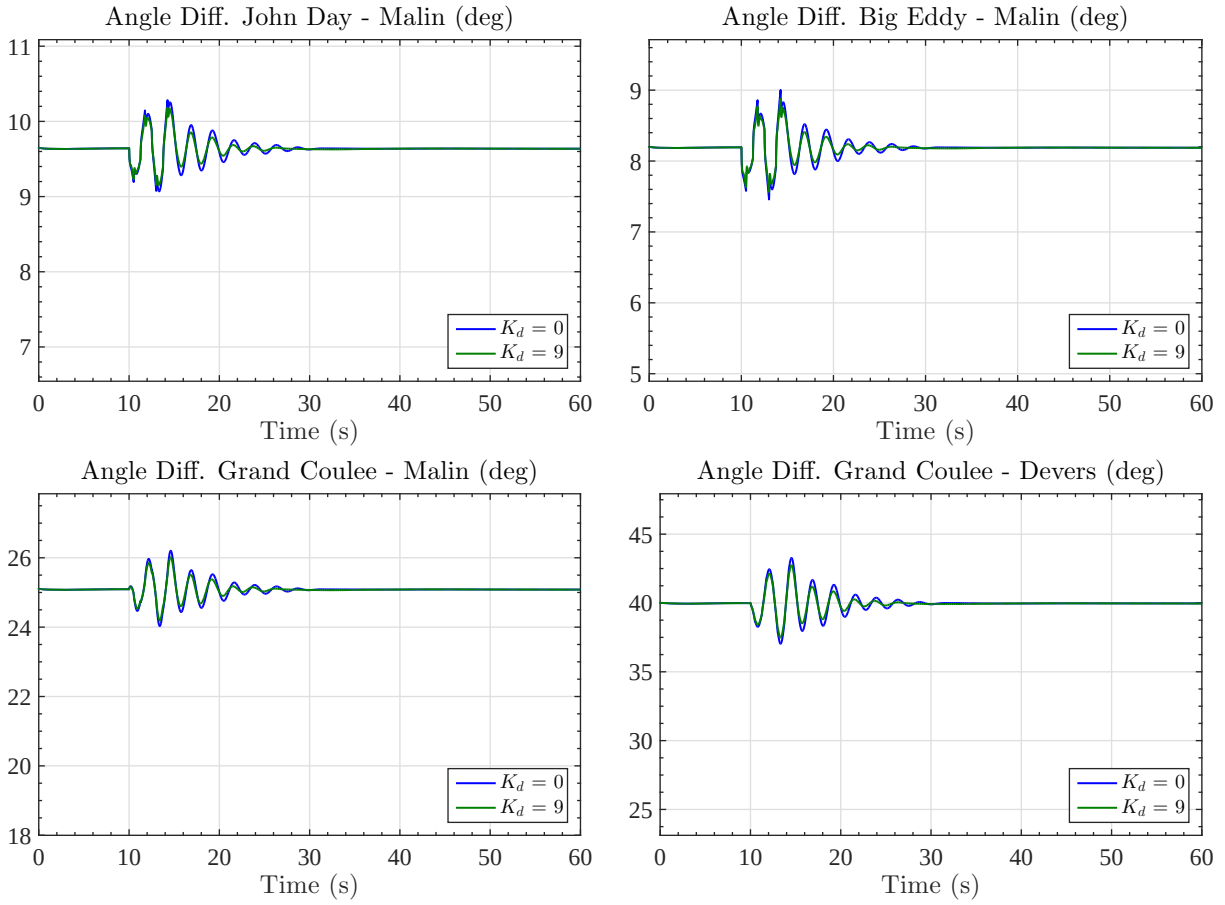


Figure 89. Angle differences. Event: 200 MW pulses with control limit of 35 MW.

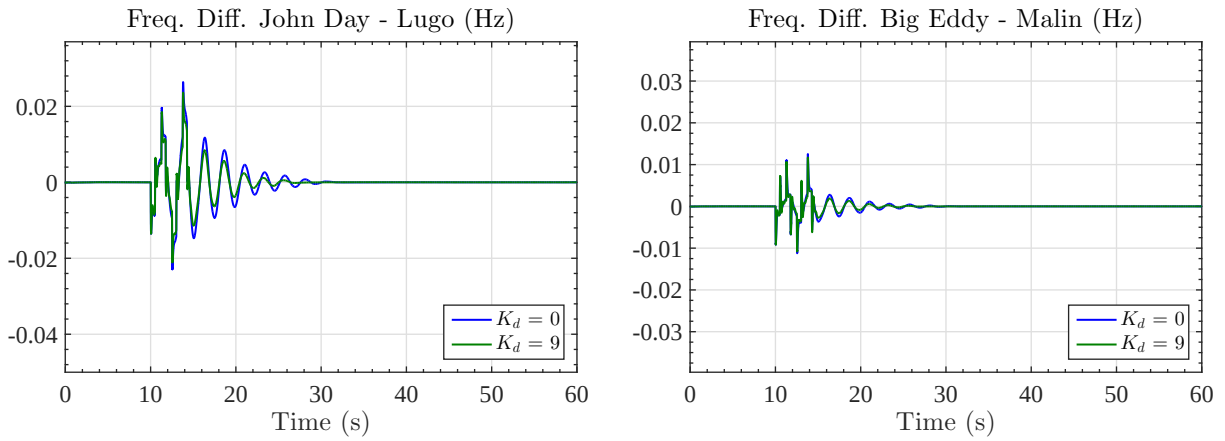


Figure 90. Frequency differences. Event: 200 MW pulses with control limit of 35 MW.

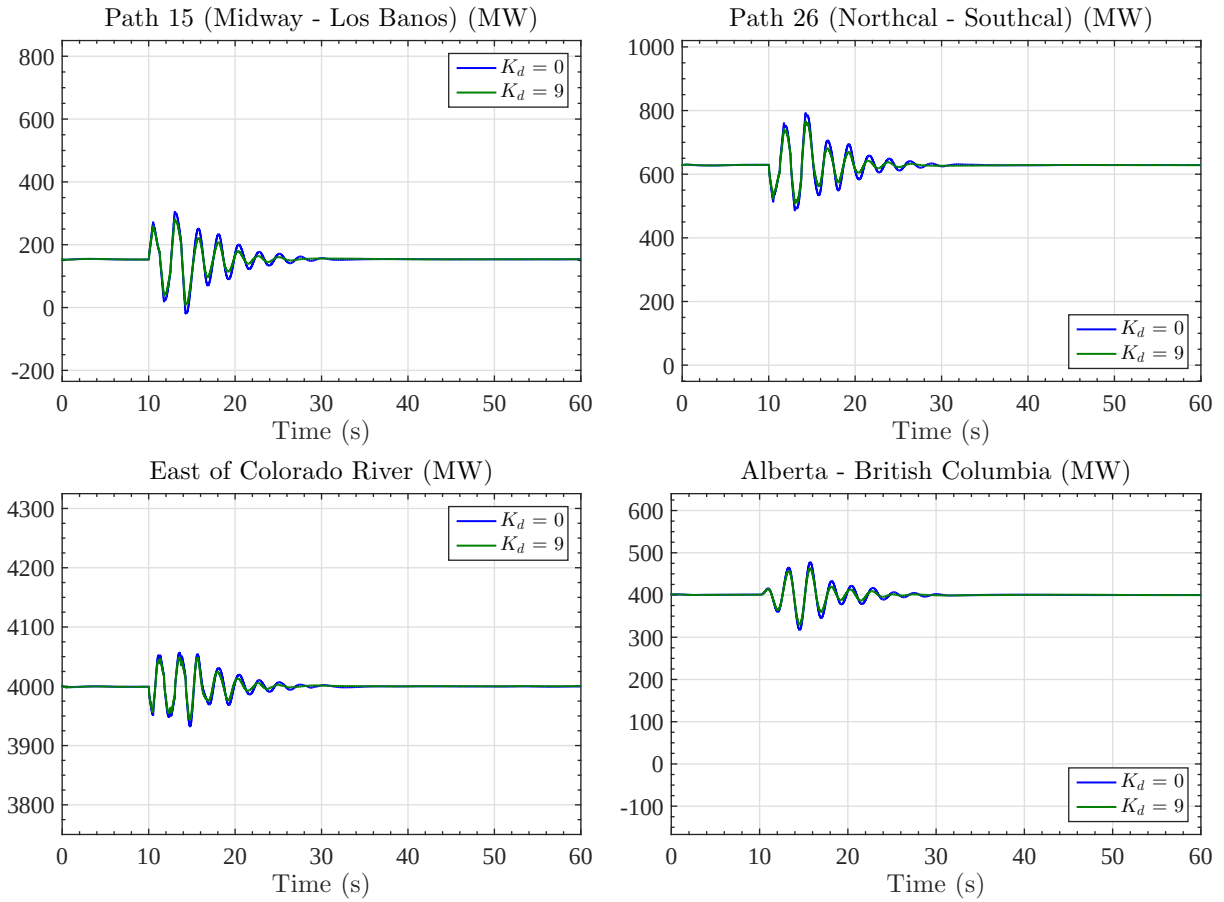


Figure 91. Active power flows. Event: 200 MW pulses with control limit of 35 MW.

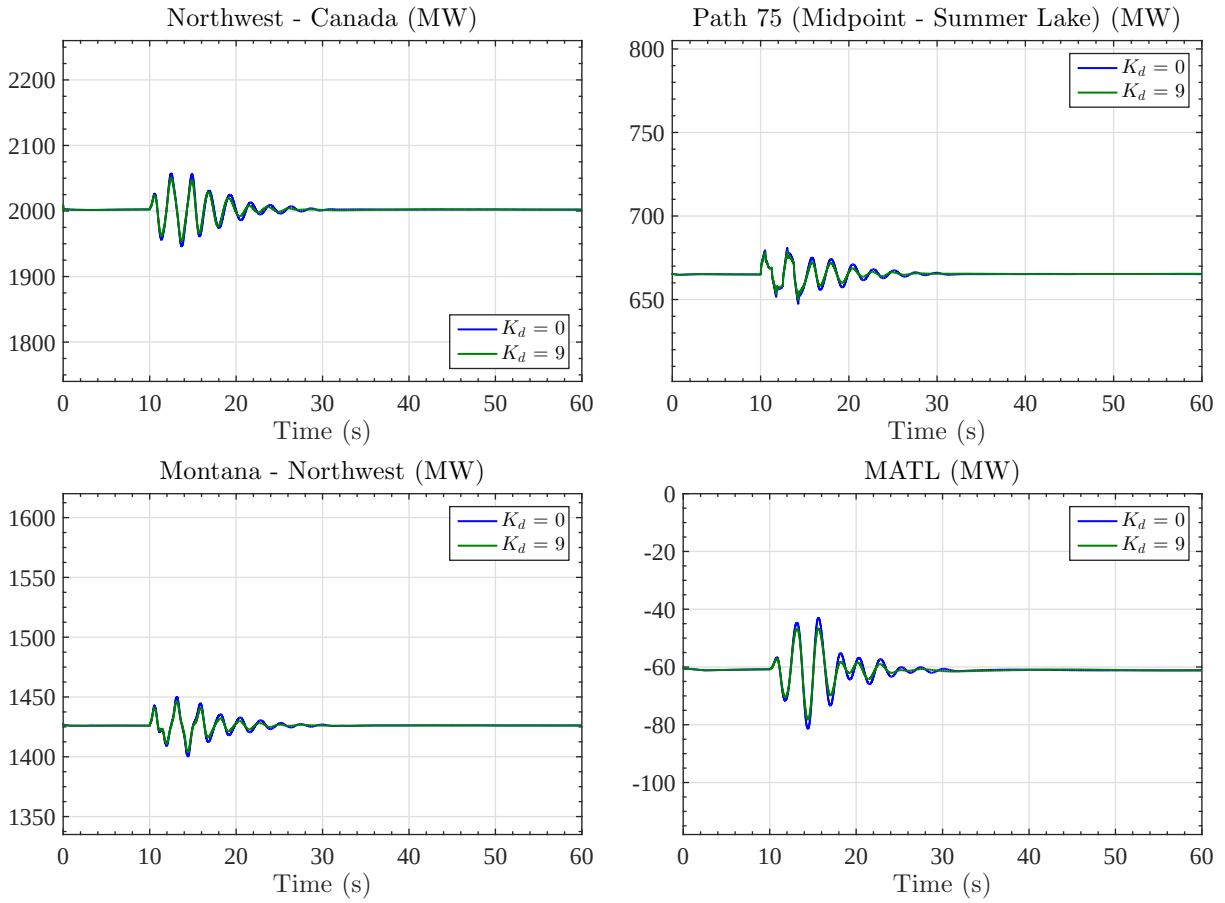


Figure 92. Active power flows. Event: 200 MW pulses with control limit of 35 MW.

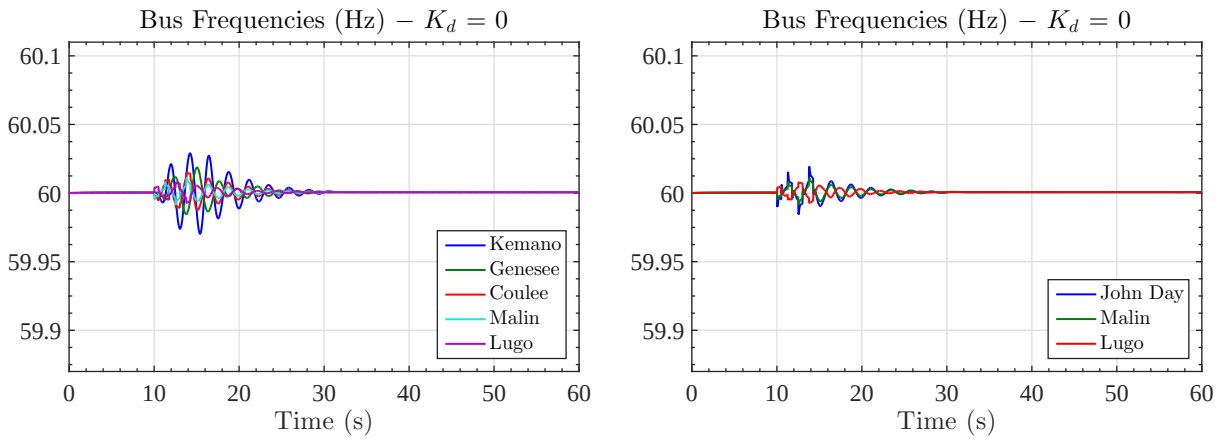


Figure 93. Bus frequencies. Event: 200 MW pulses with control limit of 35 MW.

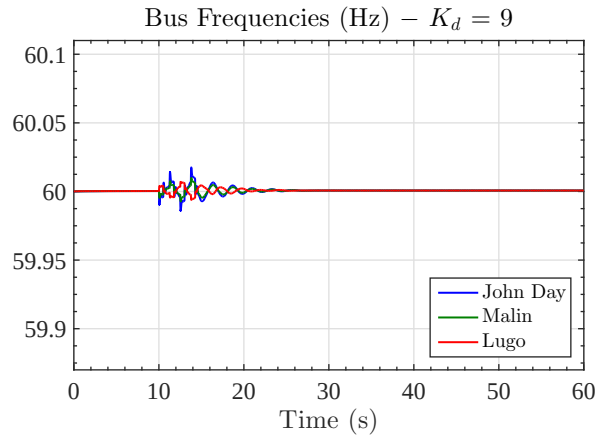
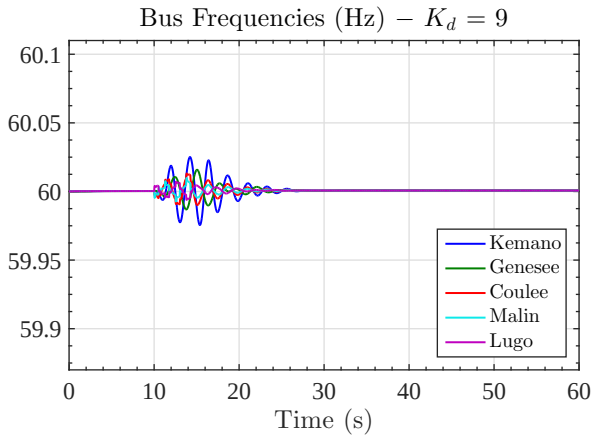


Figure 94. Bus frequencies. Event: 200 MW pulses with control limit of 35 MW.

2.2.5. Test System: Light Summer 2016. Event: MSF 1/30/1/100 with amplitude of 20MW

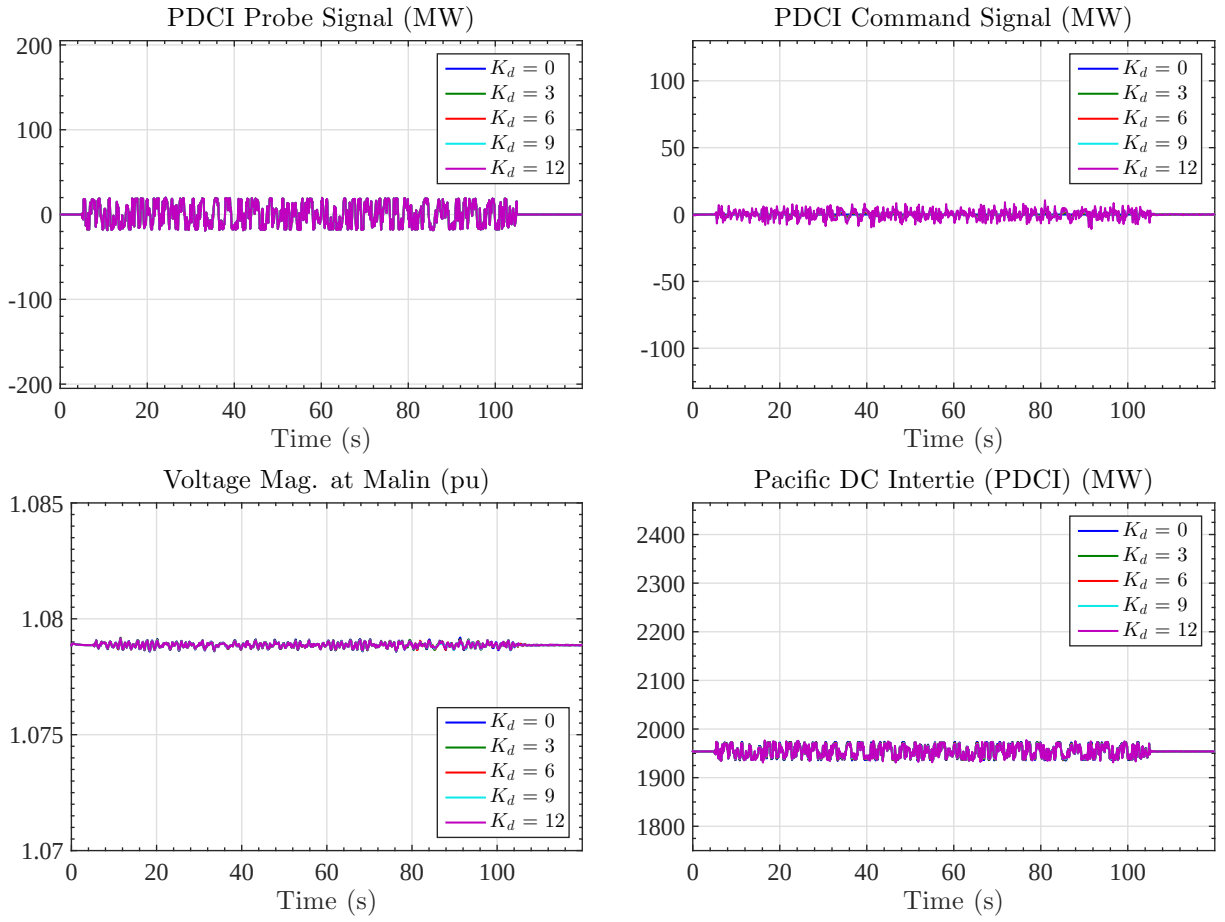


Figure 95. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 1/30/1/100 with amplitude of 20MW.

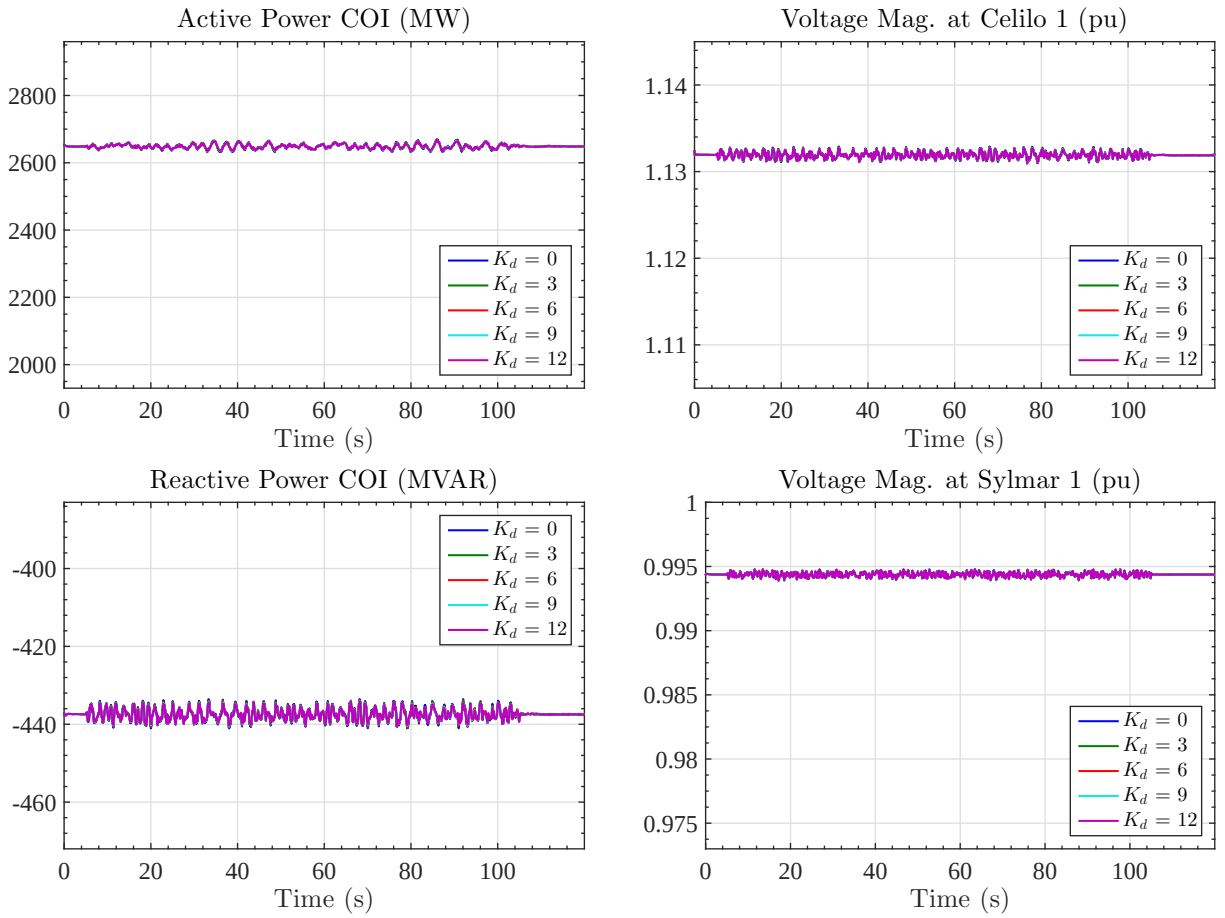


Figure 96. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 1/30/1/100 with amplitude of 20MW.

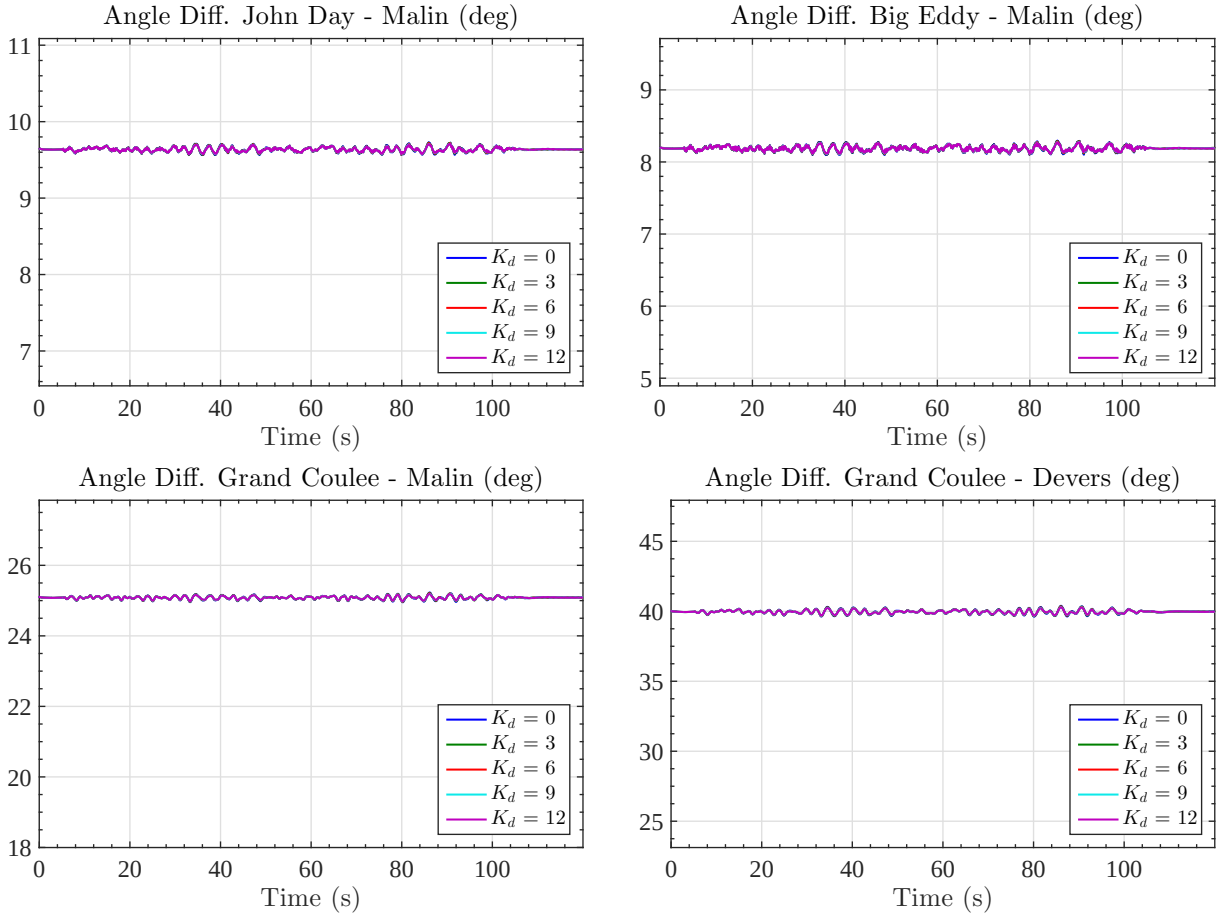


Figure 97. Angle differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

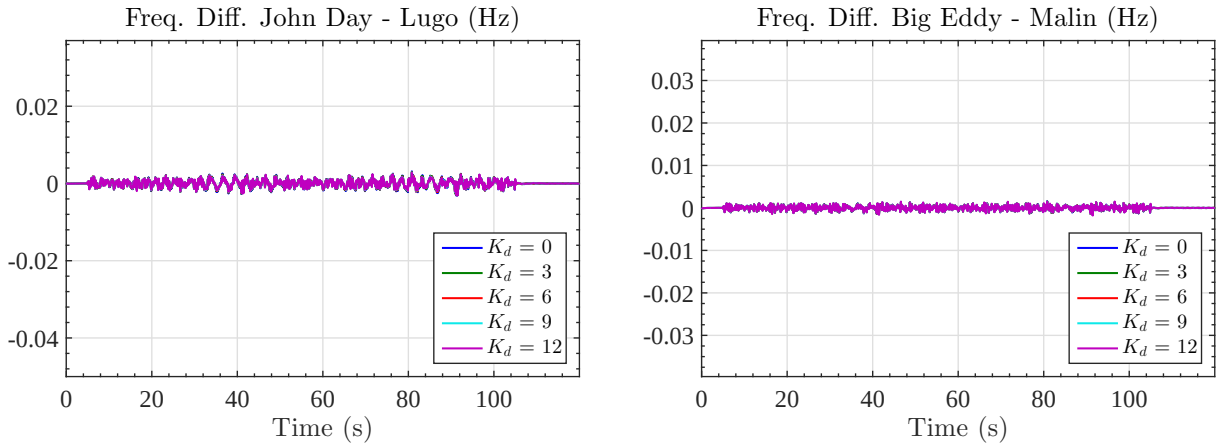


Figure 98. Frequency differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

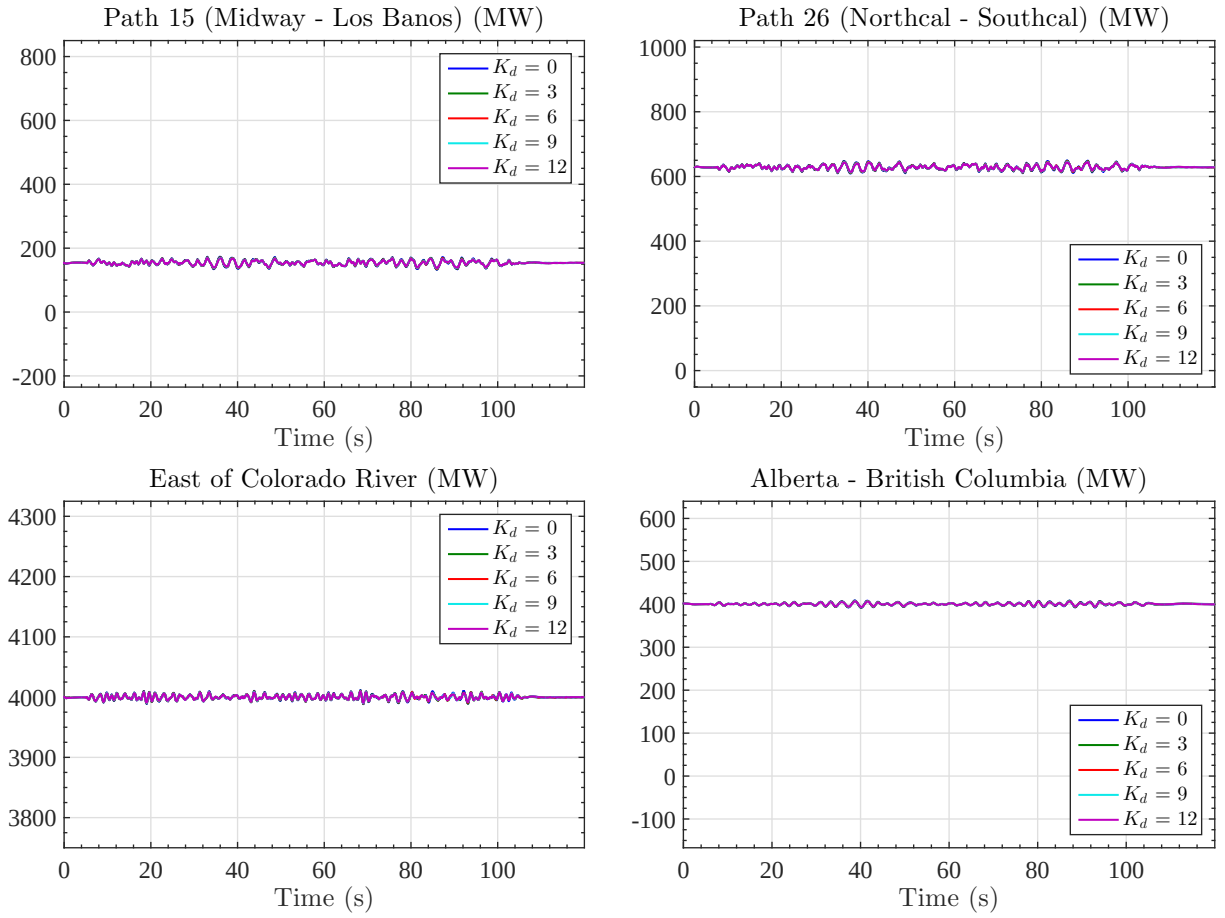


Figure 99. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

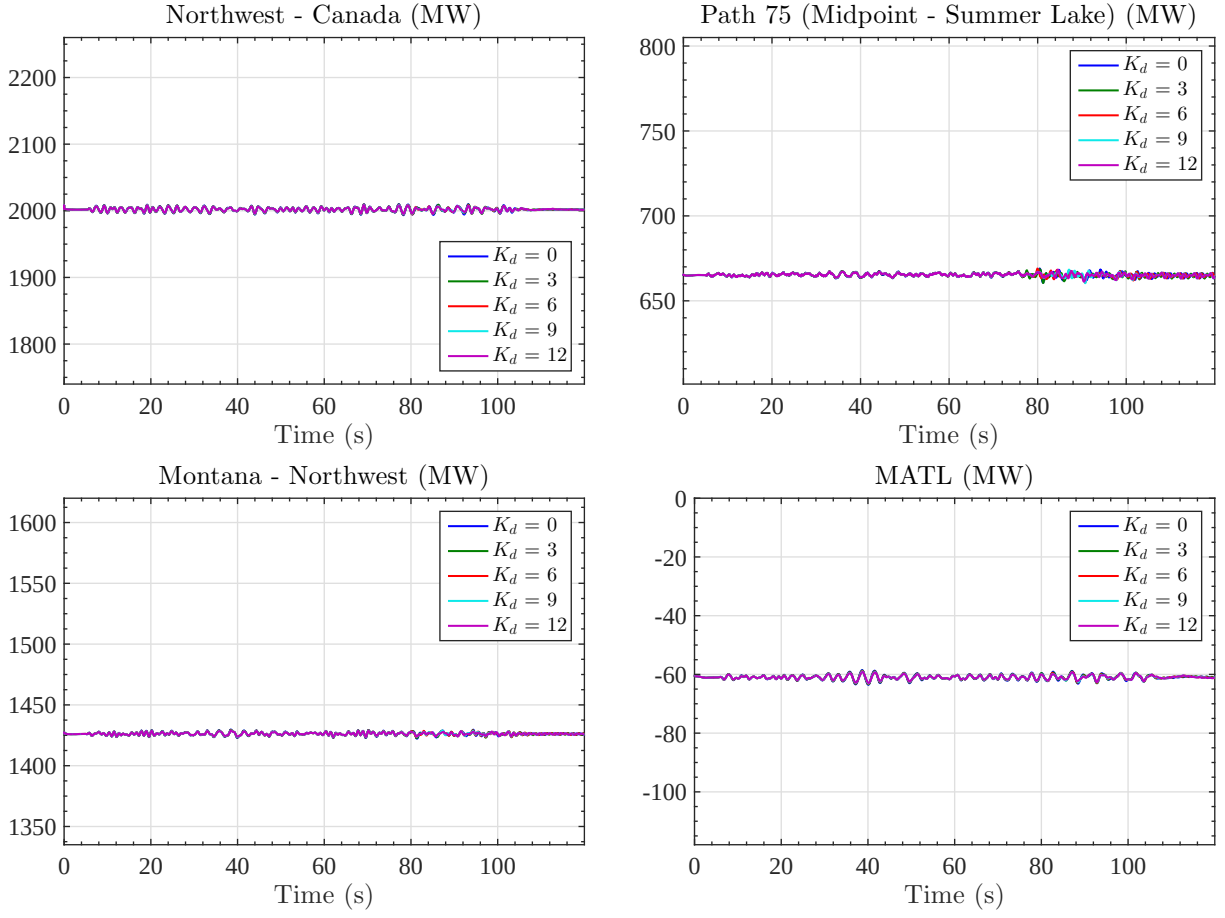


Figure 100. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

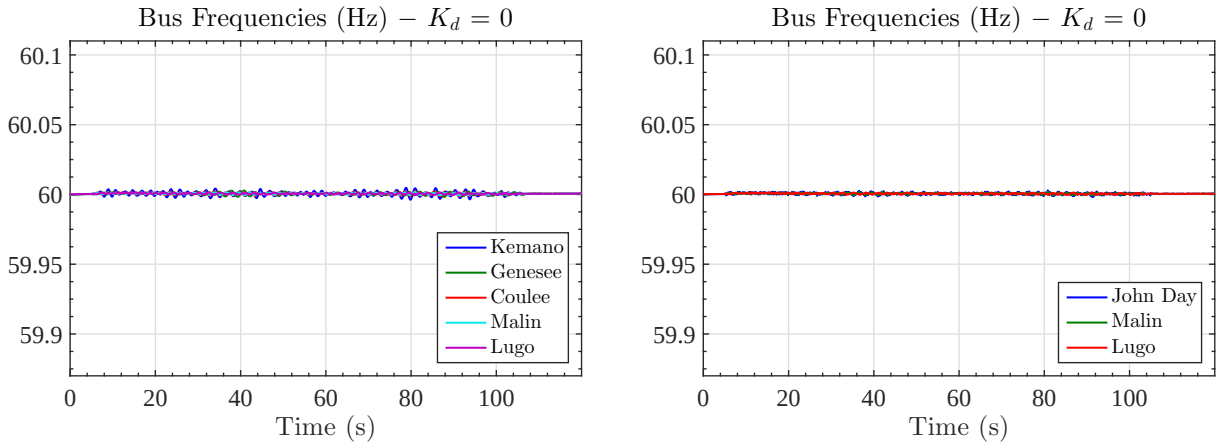


Figure 101. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

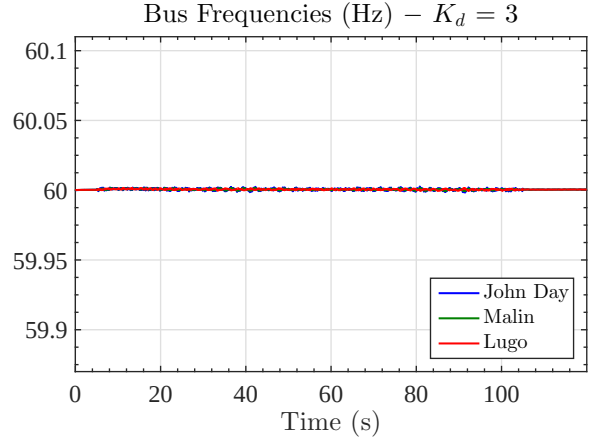
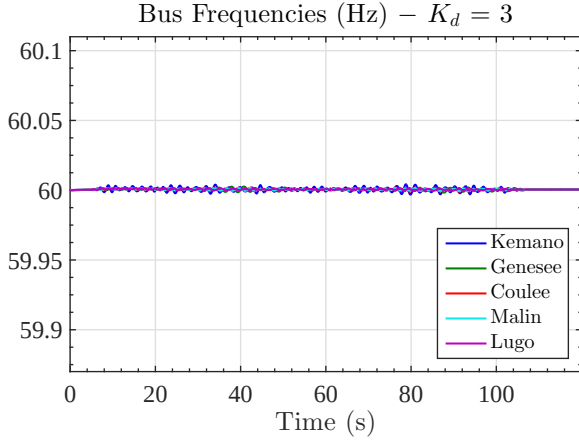


Figure 102. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

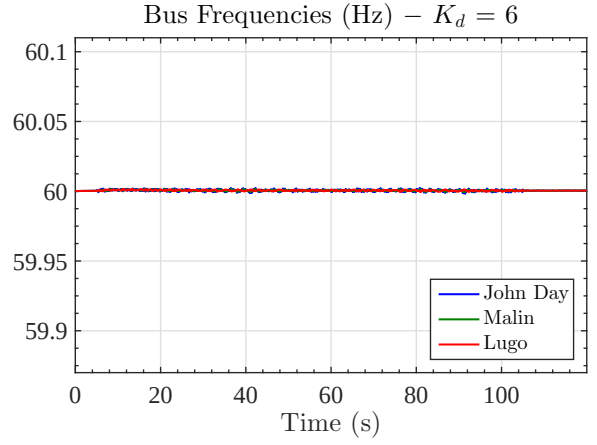
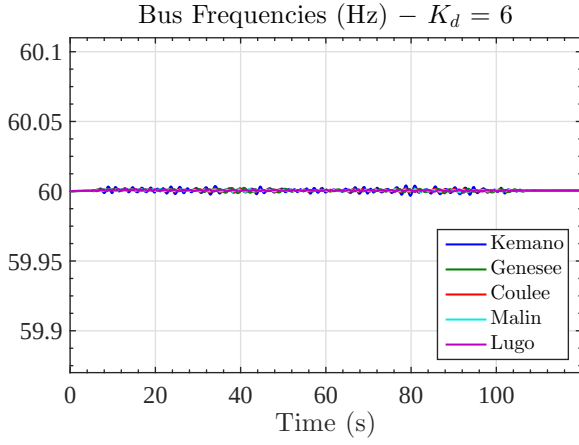


Figure 103. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

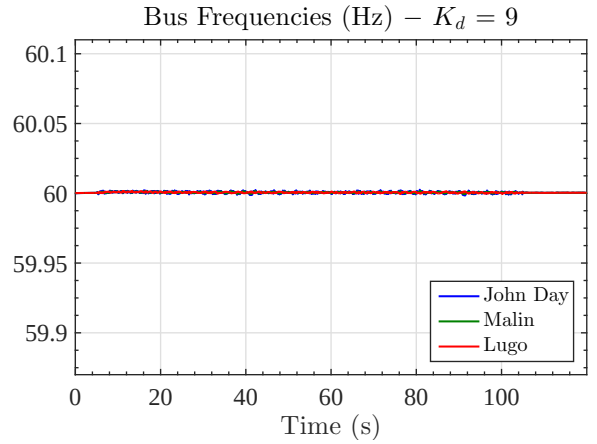
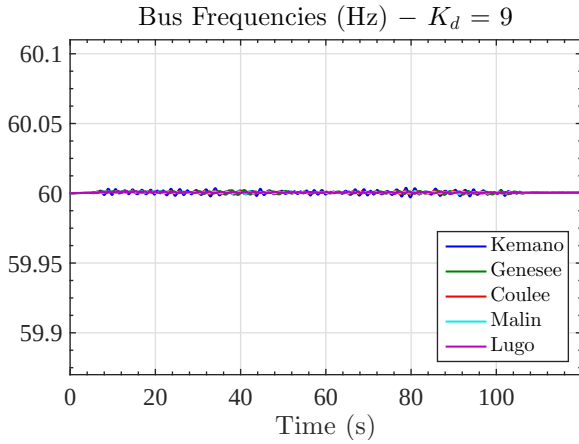


Figure 104. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

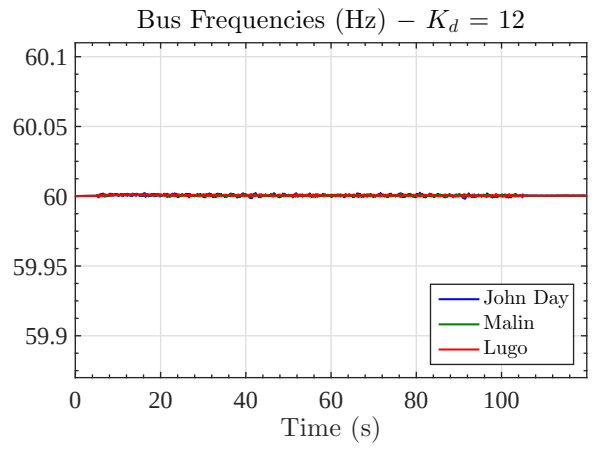
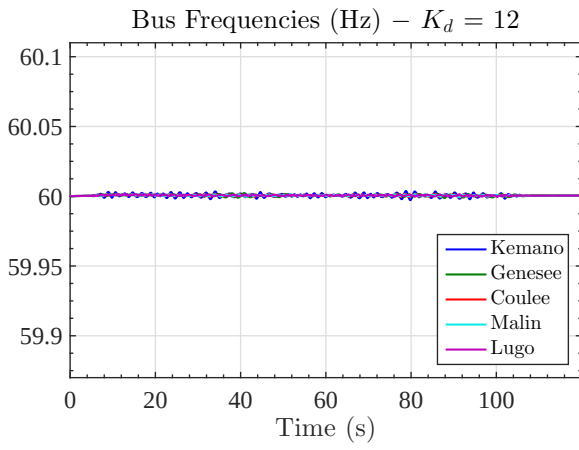


Figure 105. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

2.2.6. *Test System: Light Summer 2016. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW*

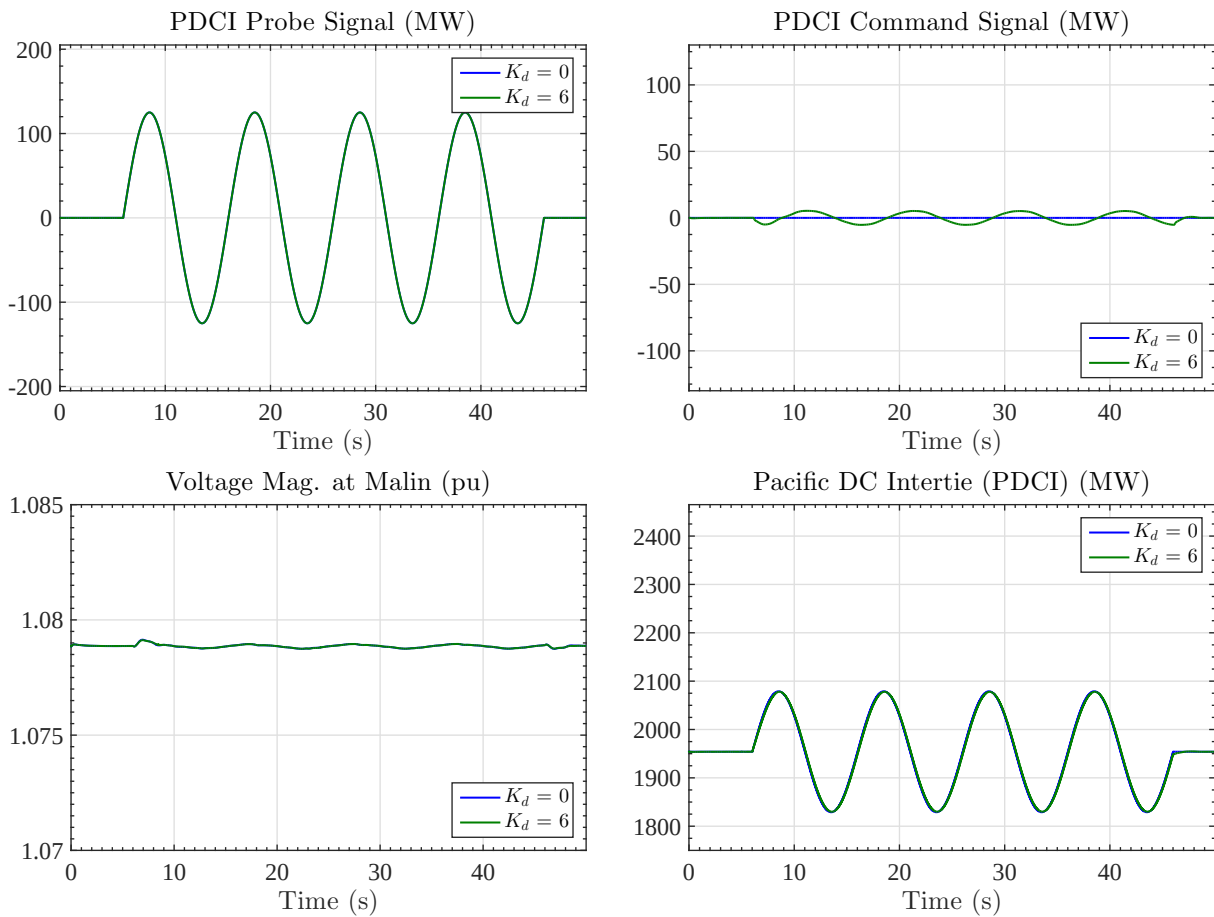


Figure 106. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

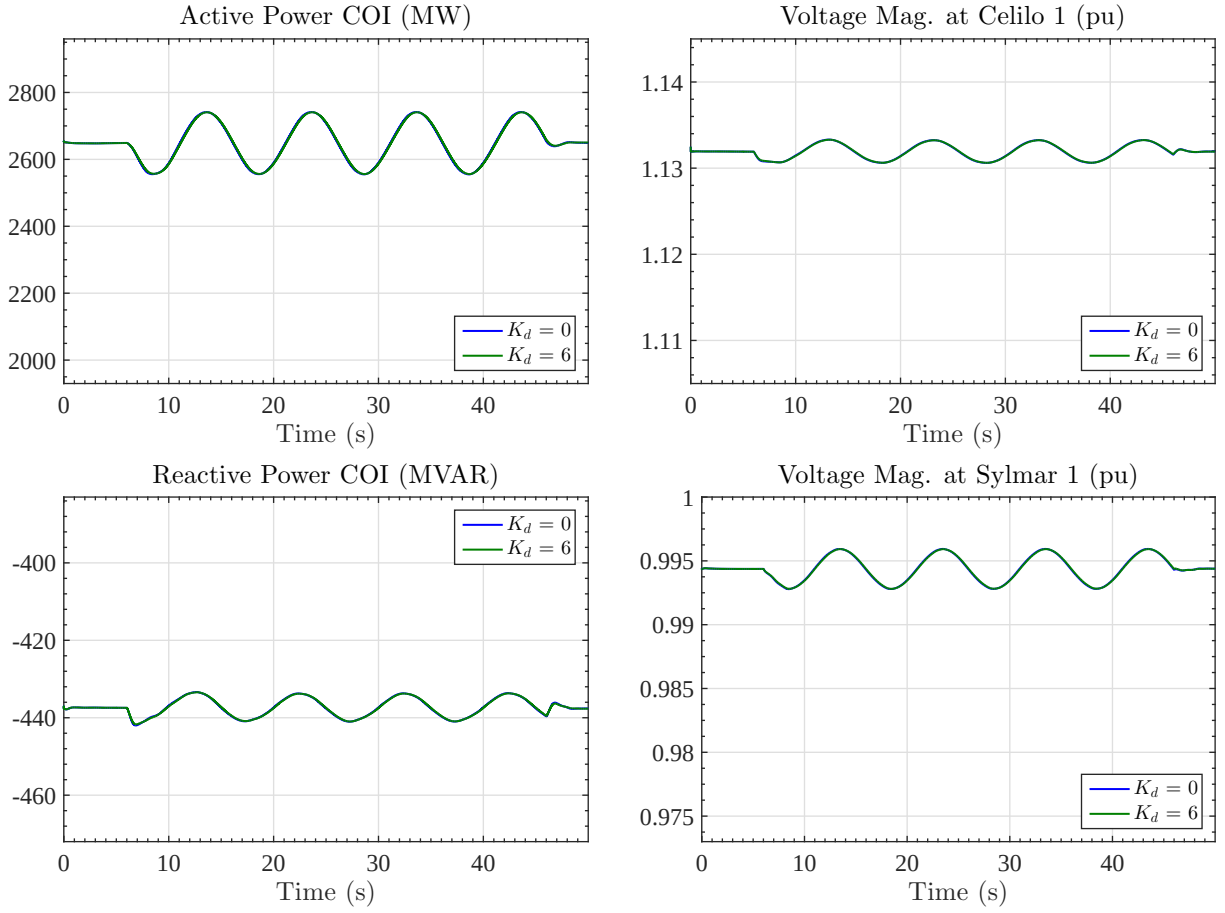


Figure 107. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

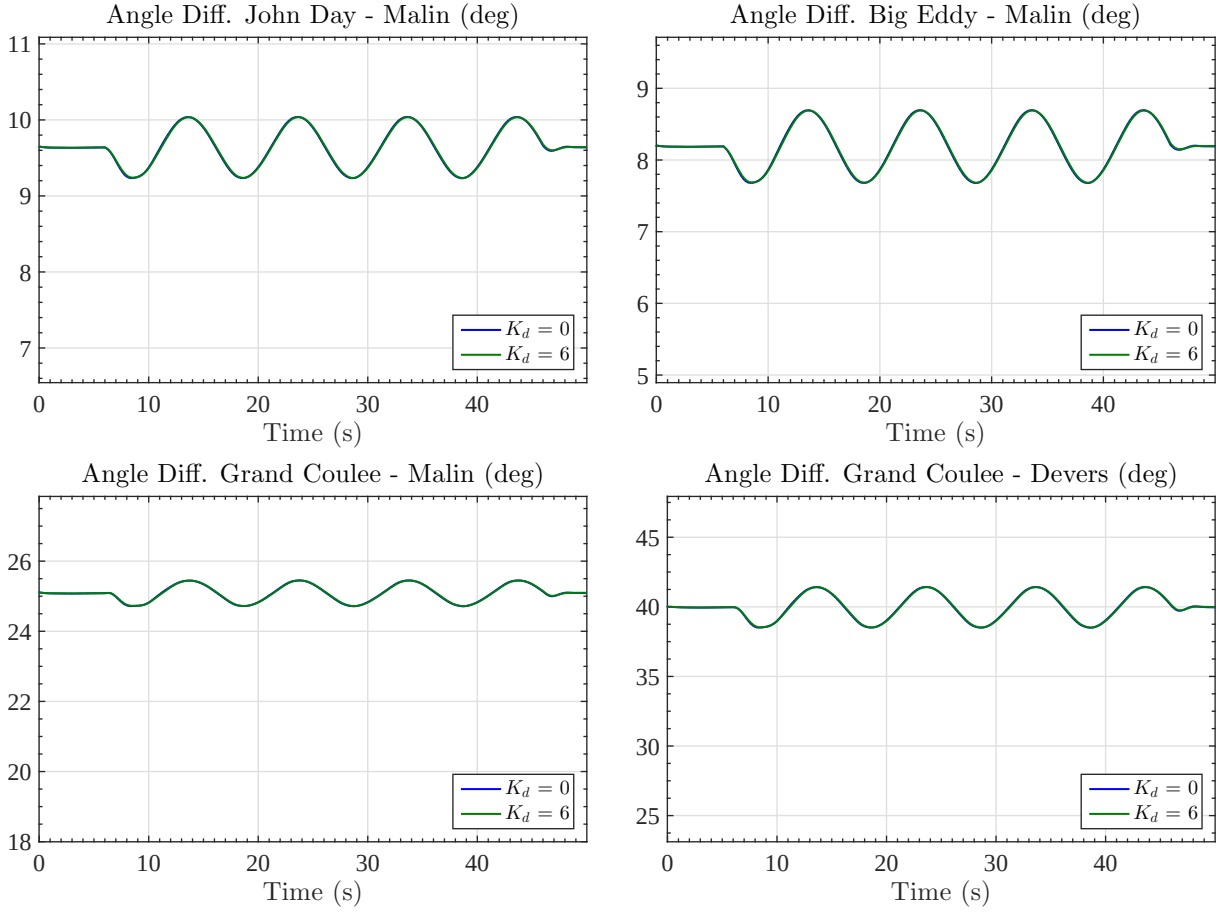


Figure 108. Angle differences. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

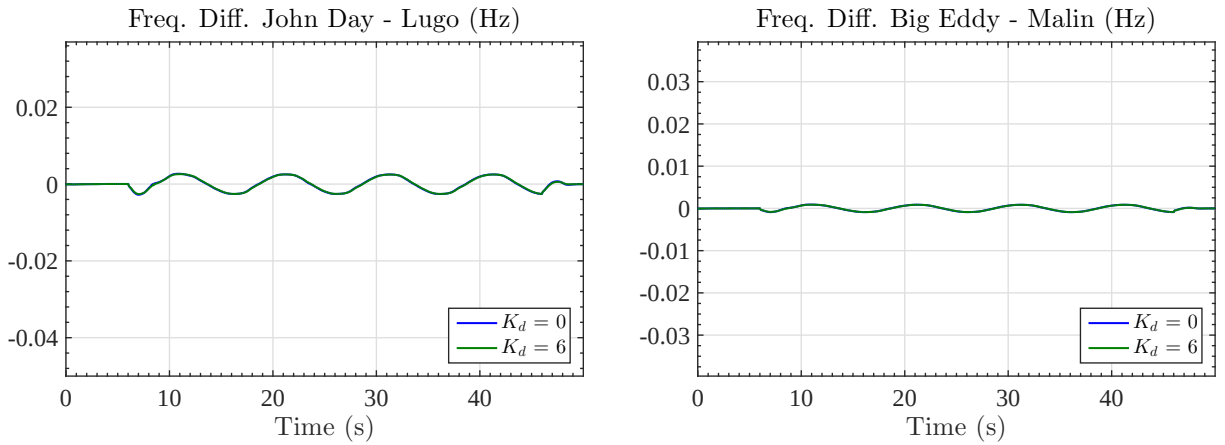


Figure 109. Frequency differences. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

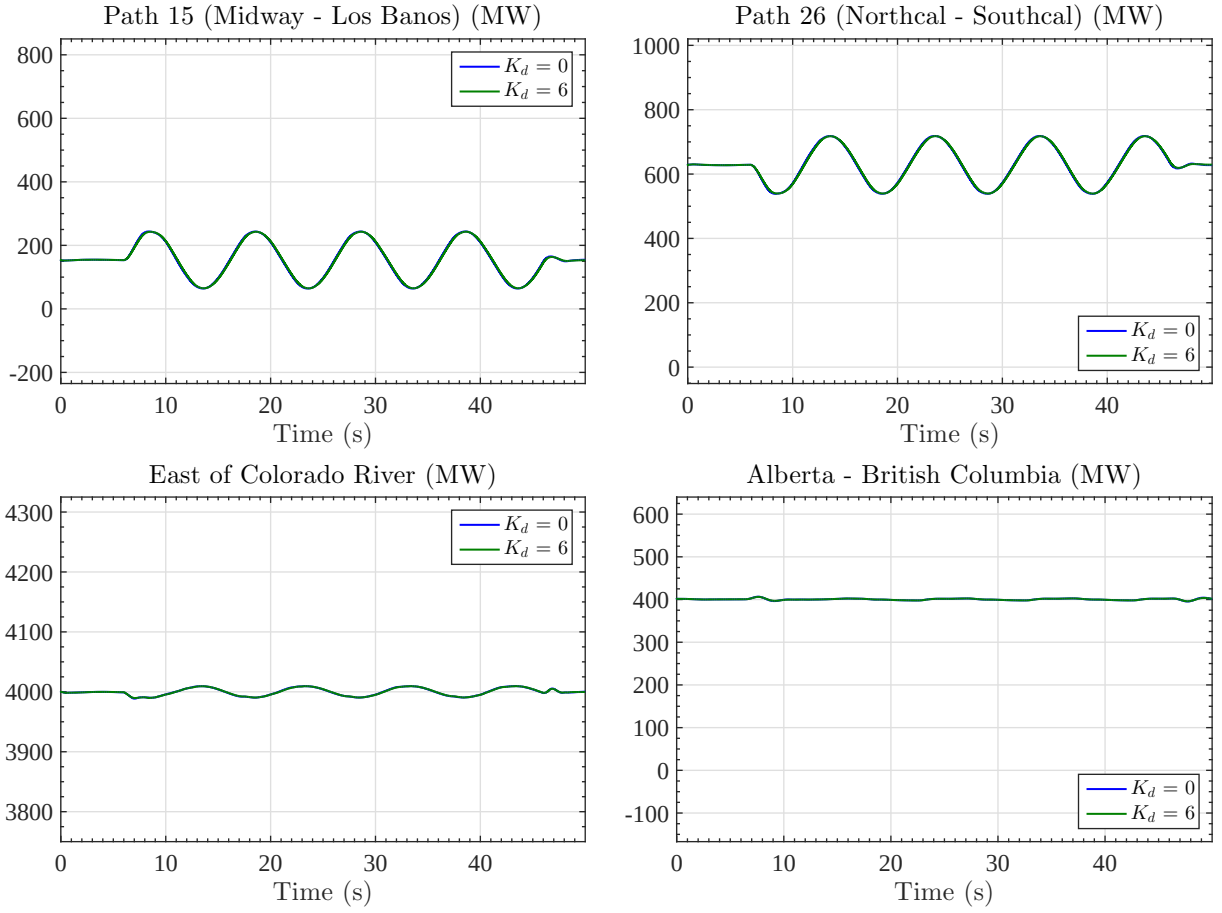


Figure 110. Active power flows. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

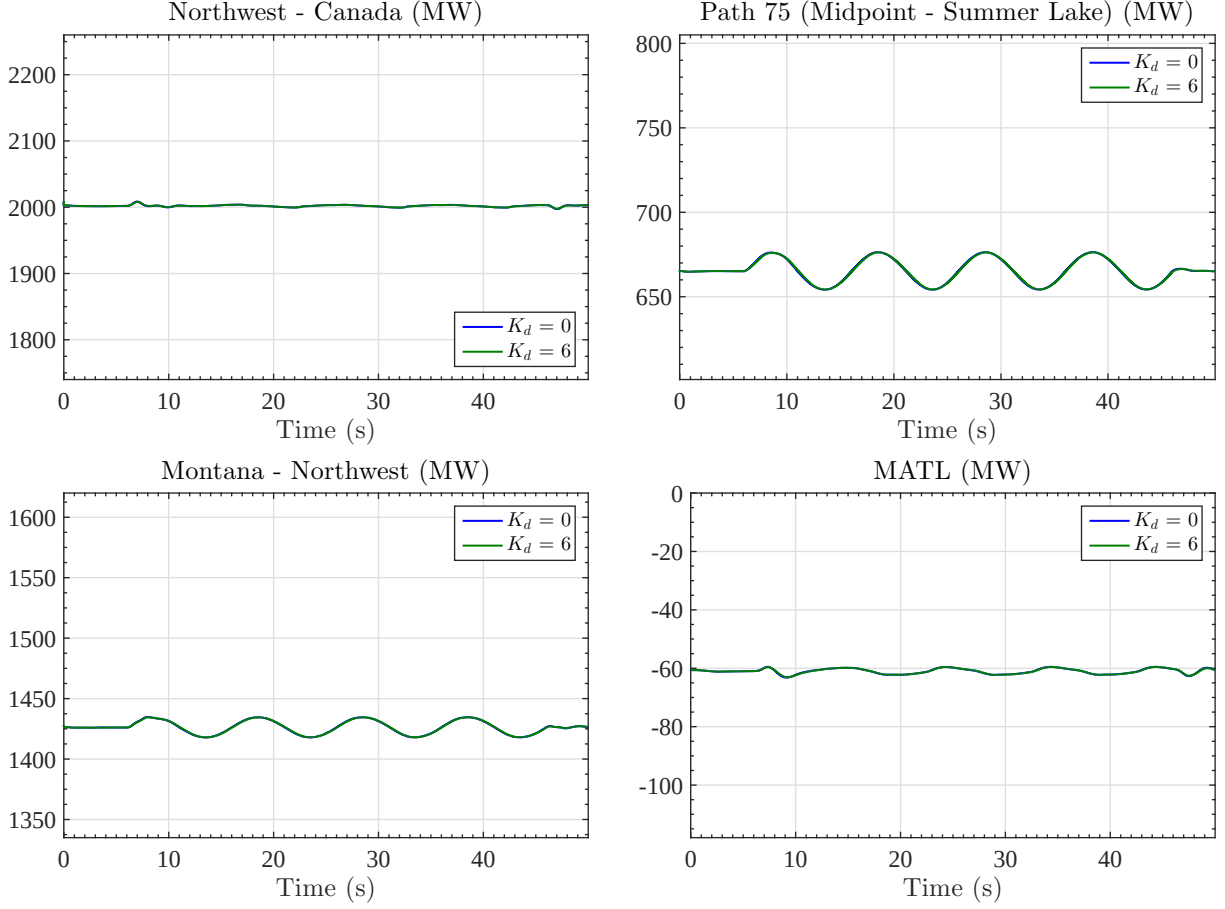


Figure 111. Active power flows. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

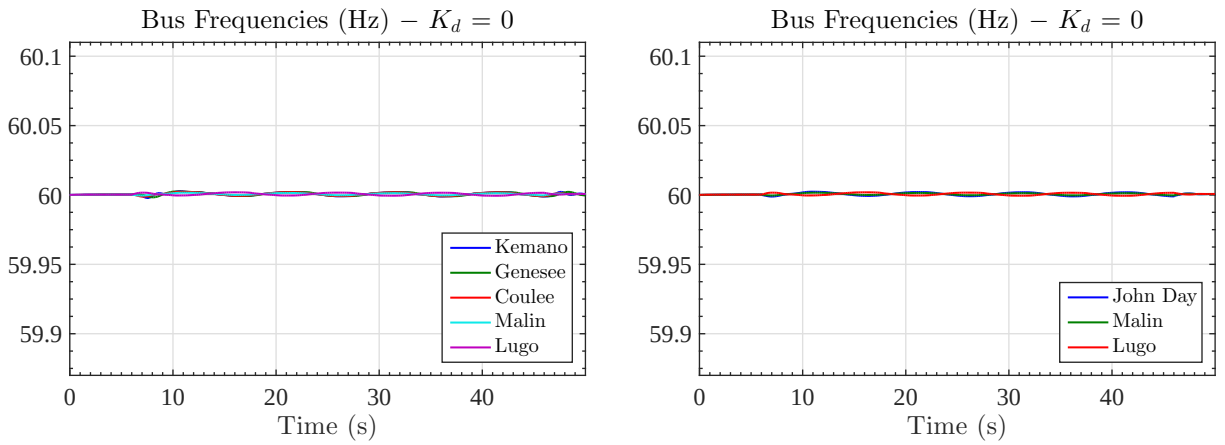


Figure 112. Bus frequencies. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

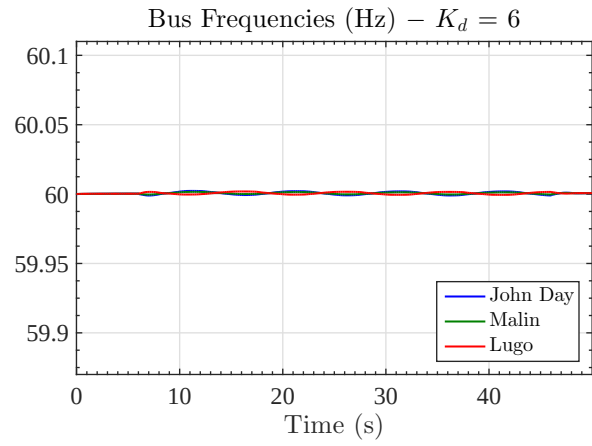
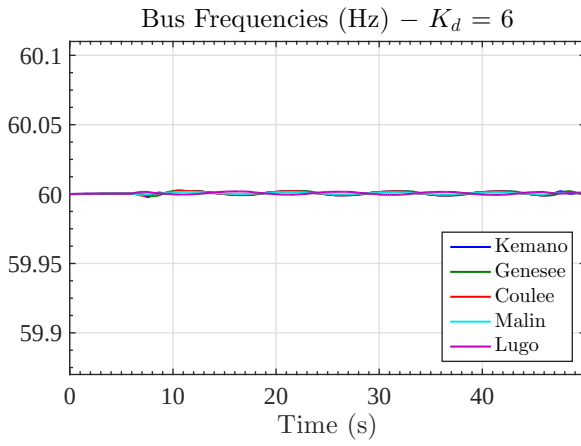


Figure 113. Bus frequencies. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

3. CASE STUDY: HEAVY SUMMER 2016

3.1. Open Loop Testing

3.1.1. *Test System: Heavy Summer 2016. Controller Open Loop Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe*

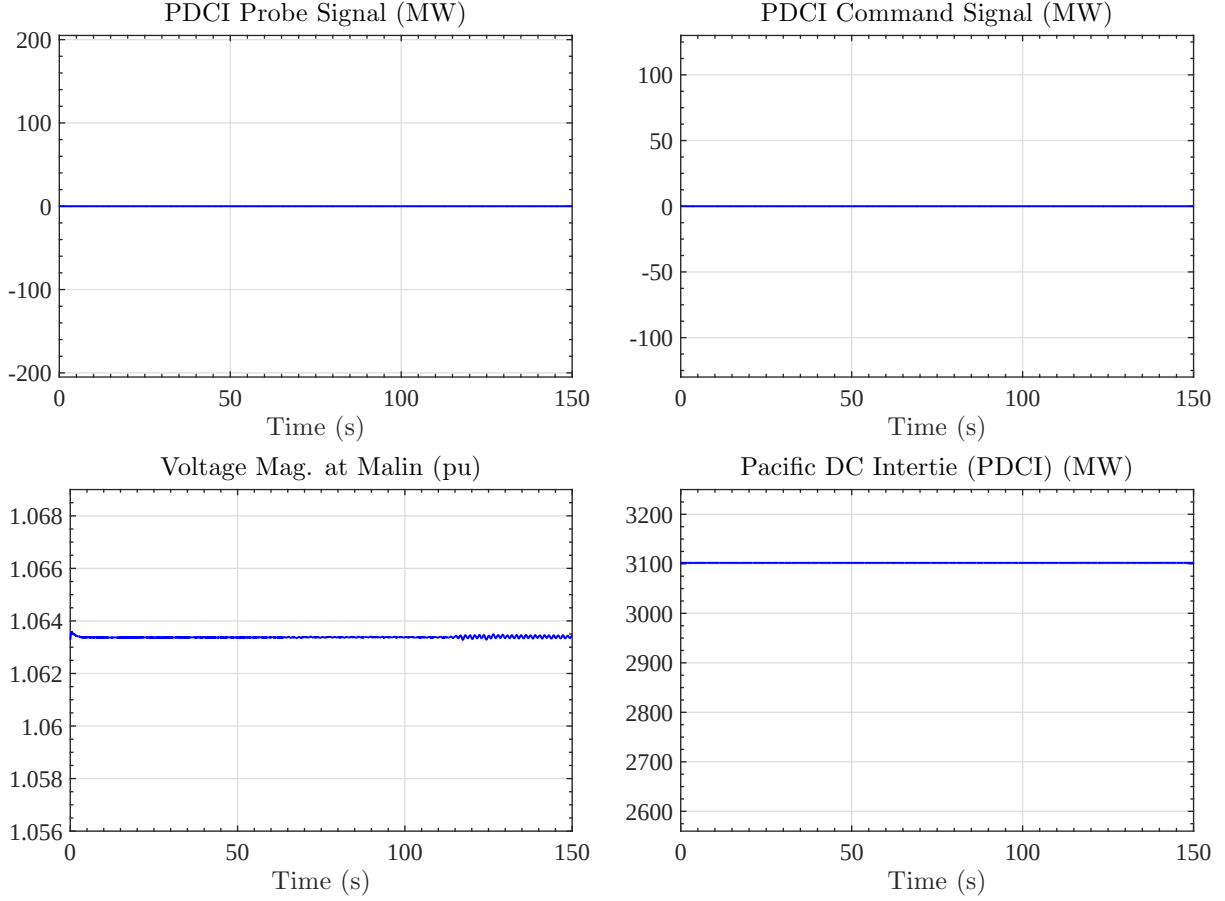


Figure 114. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

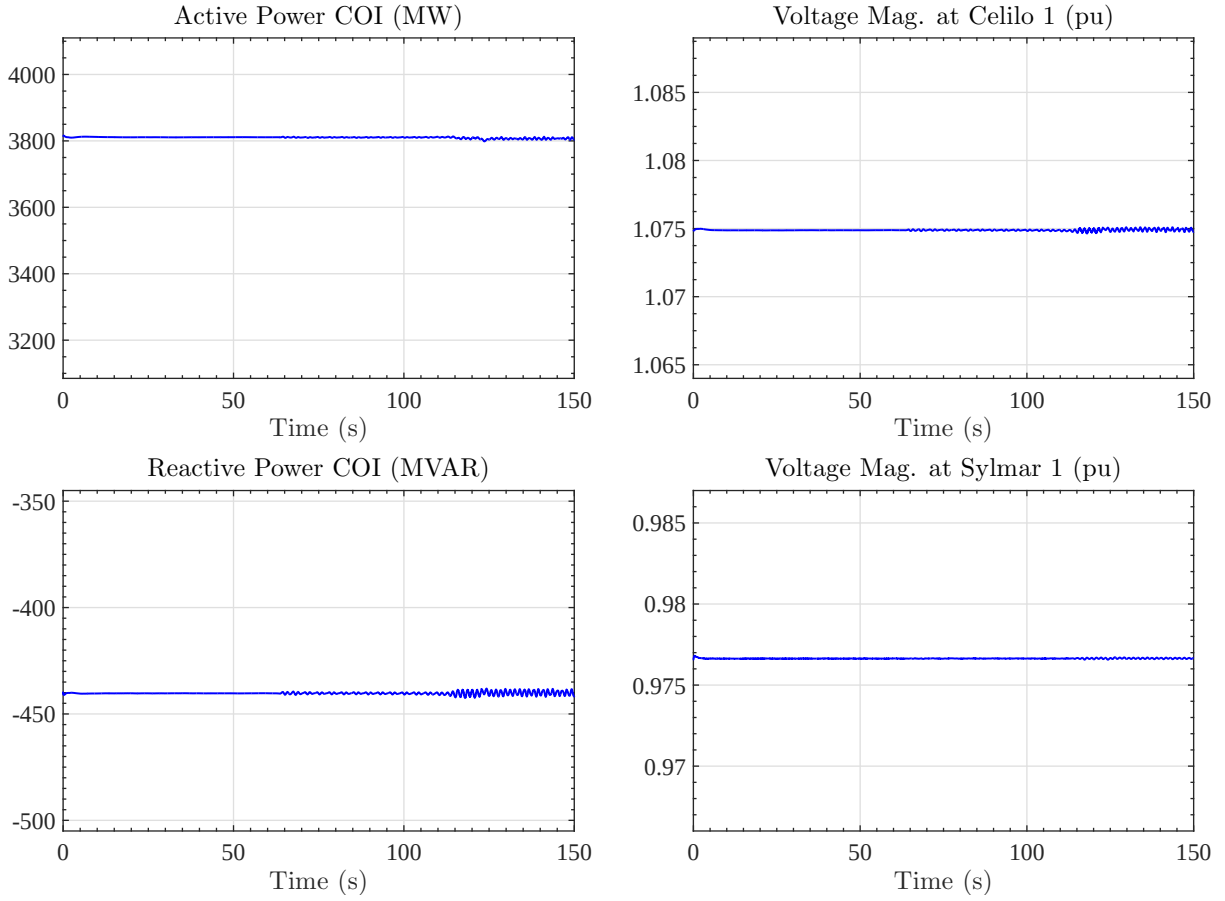


Figure 115. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

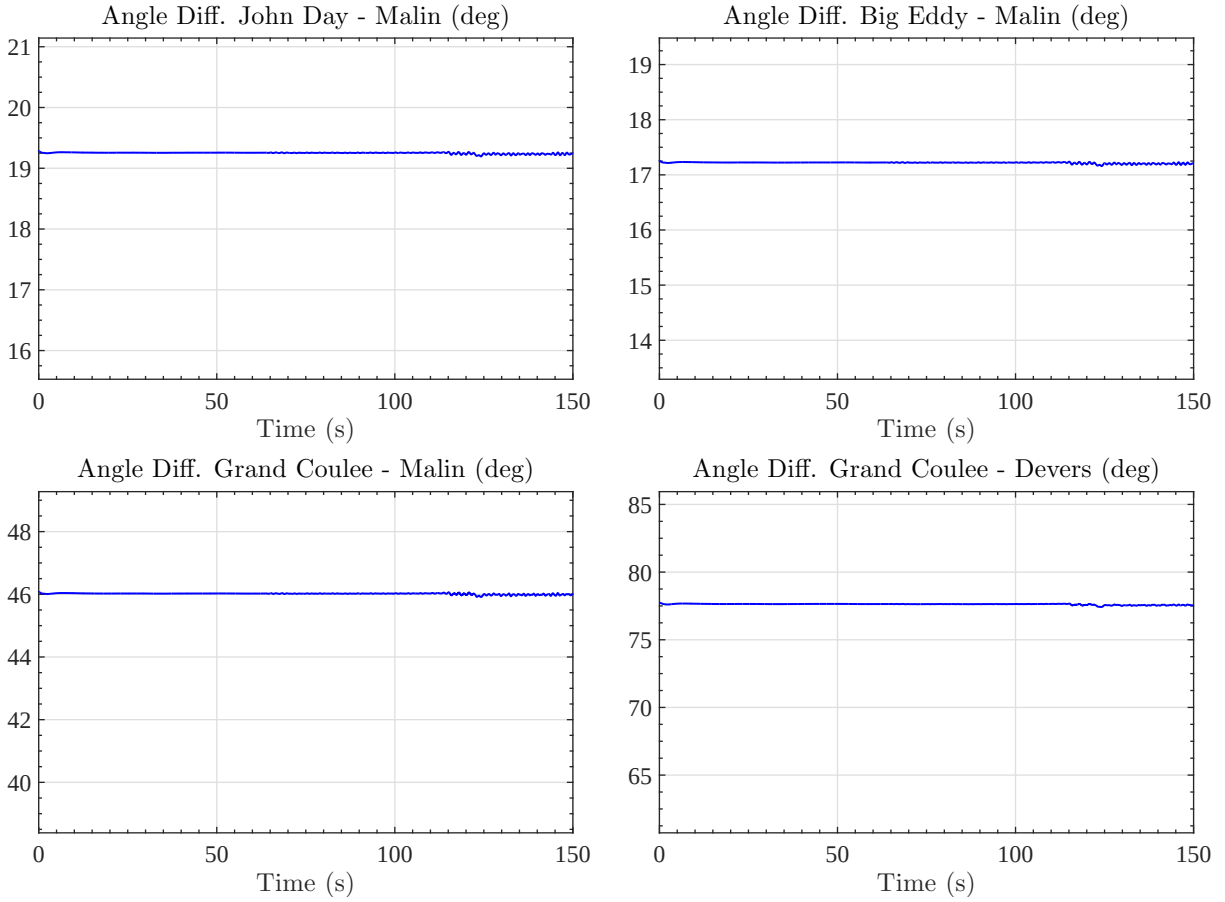


Figure 116. Angle differences. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

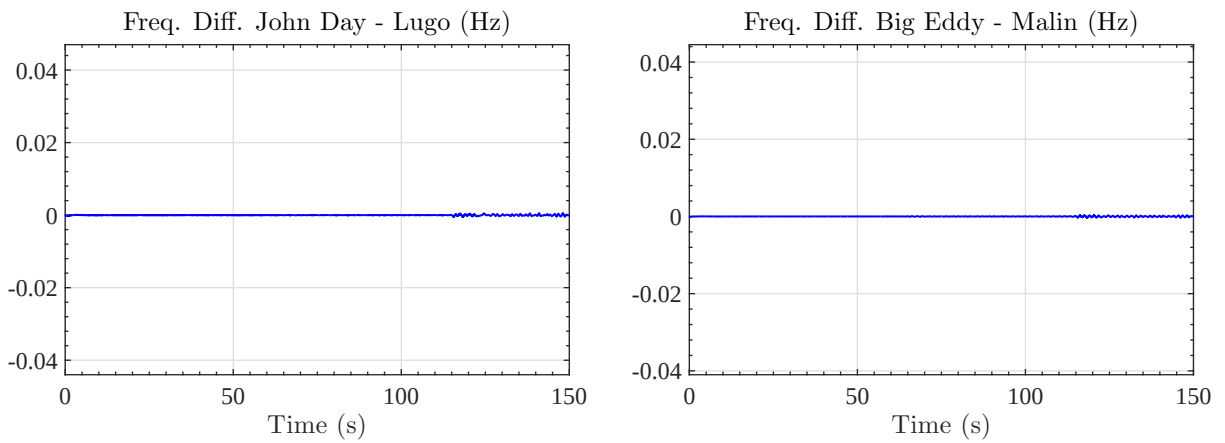


Figure 117. Frequency differences. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

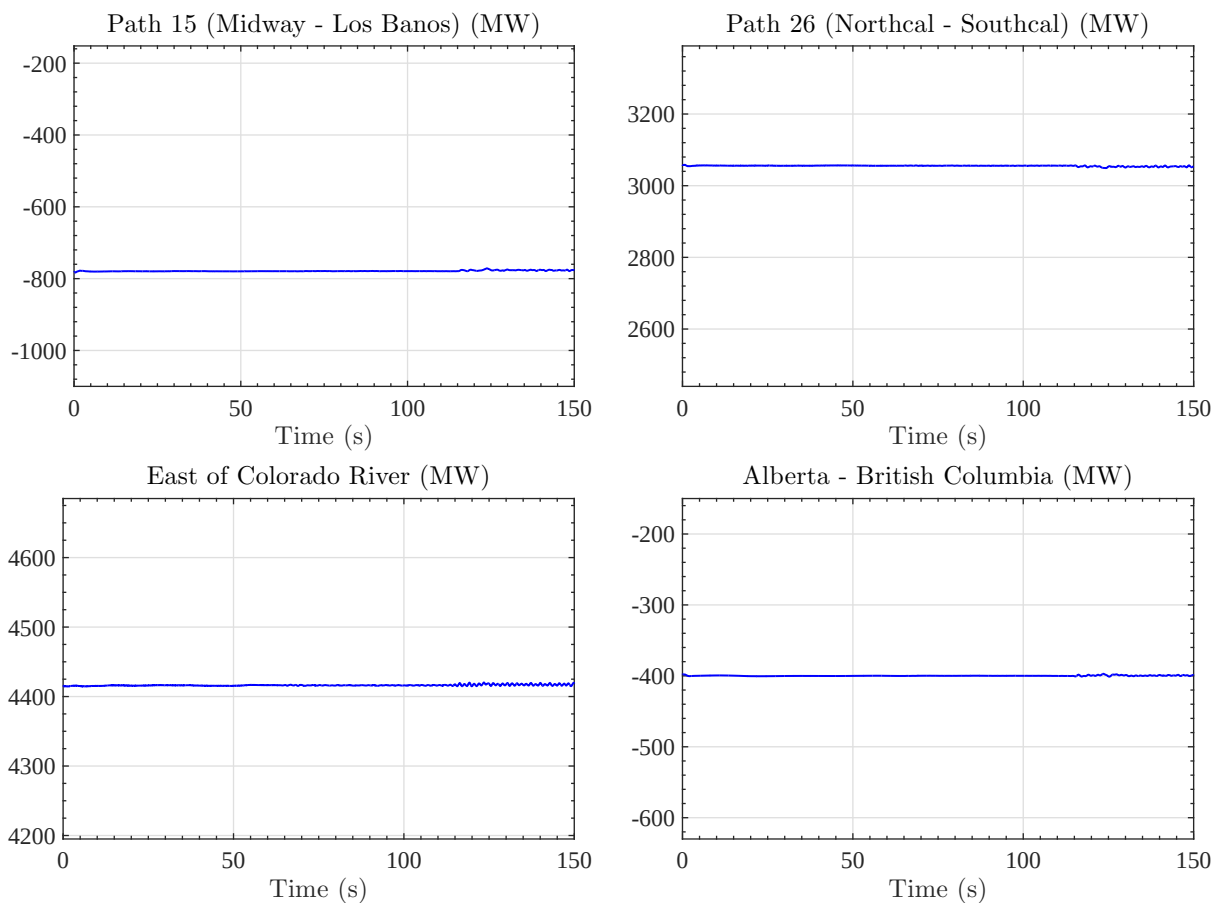


Figure 118. Active power flows. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

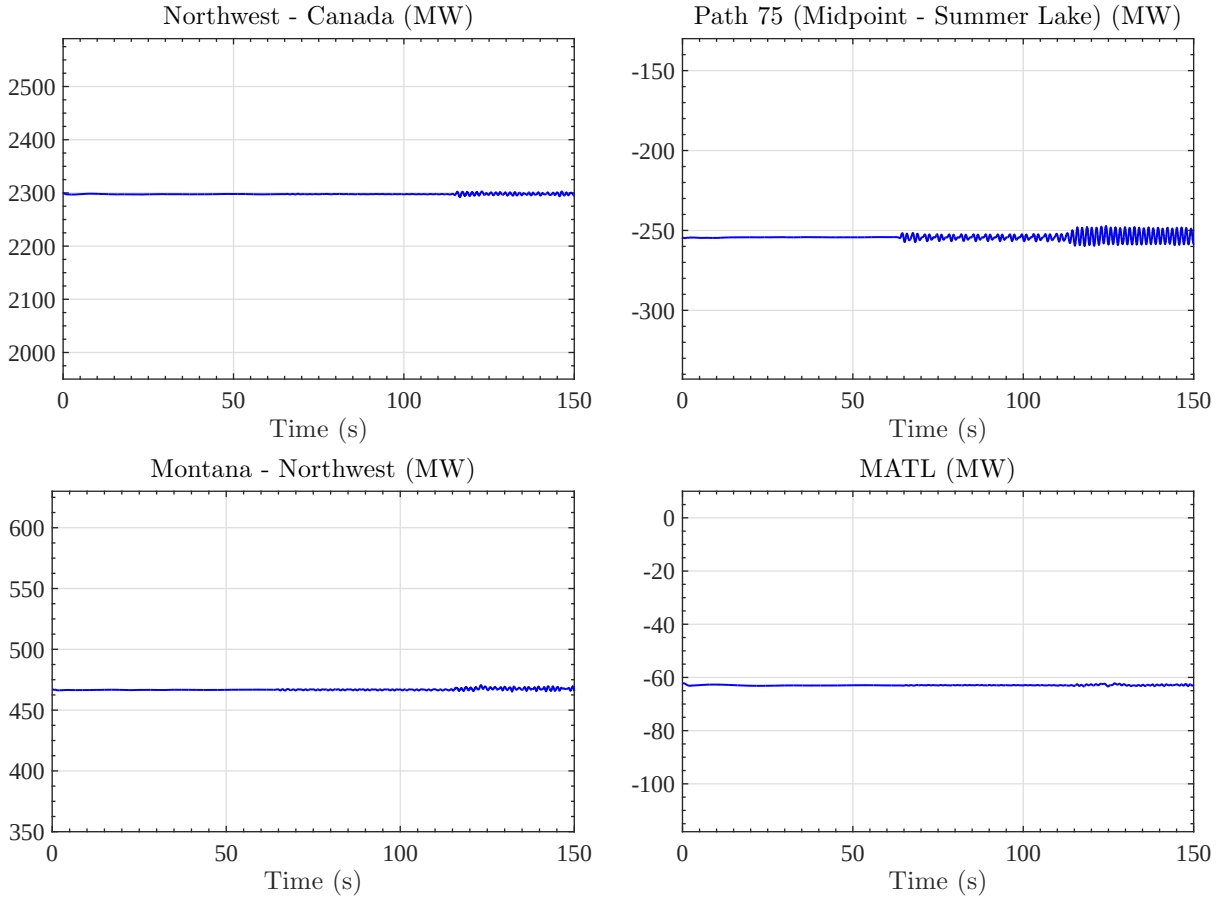


Figure 119. Active power flows. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

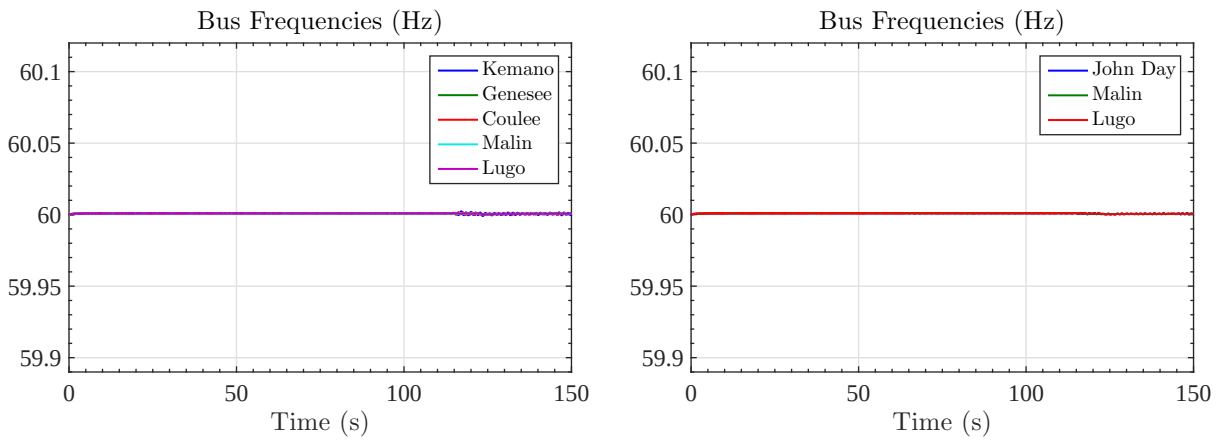


Figure 120. Bus frequencies. Event: WECC Heavy Summer ran for 150 seconds: Base case, no event, no probe.

3.1.2. *Test System: Heavy Summer 2016. Controller Open Loop Event: 200 MW positive and negative pulses*

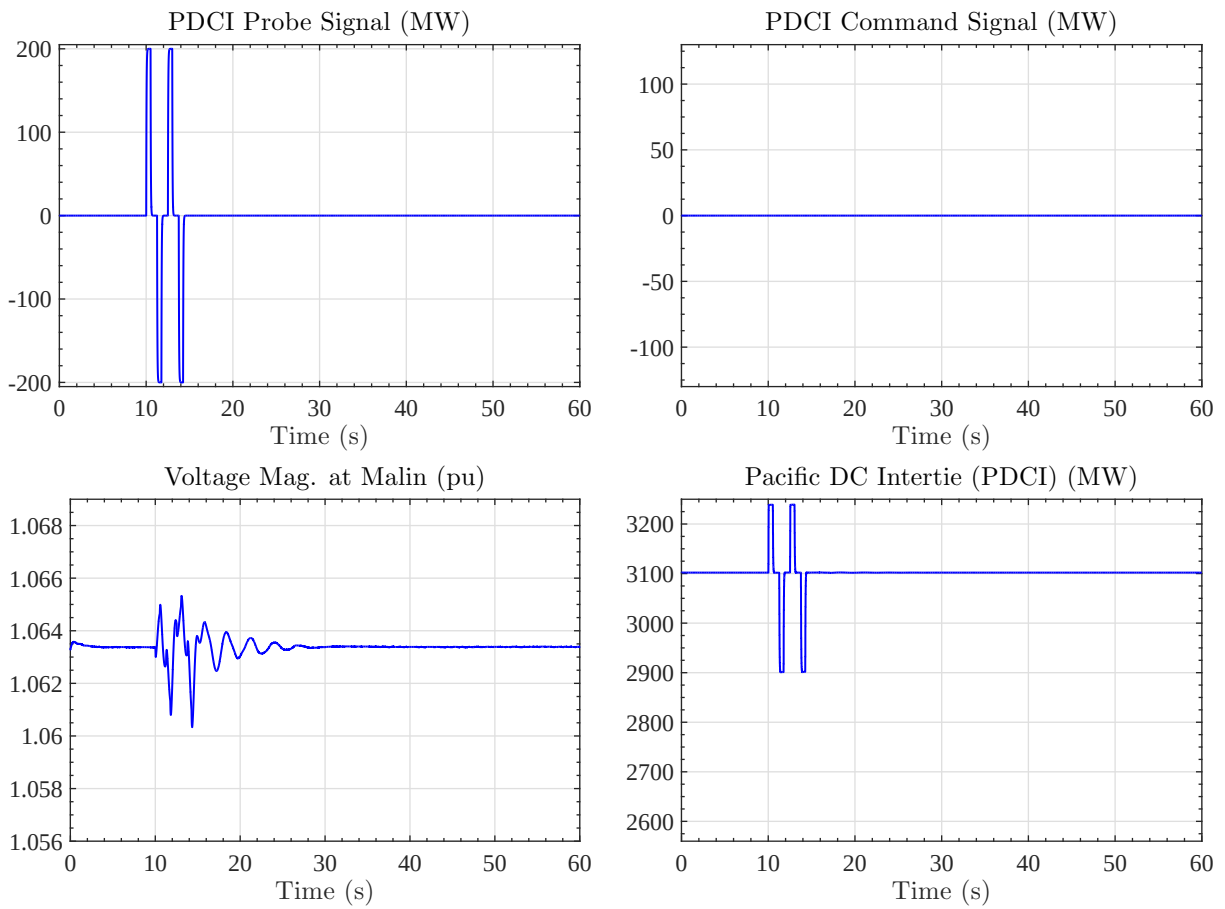


Figure 121. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW positive and negative pulses.

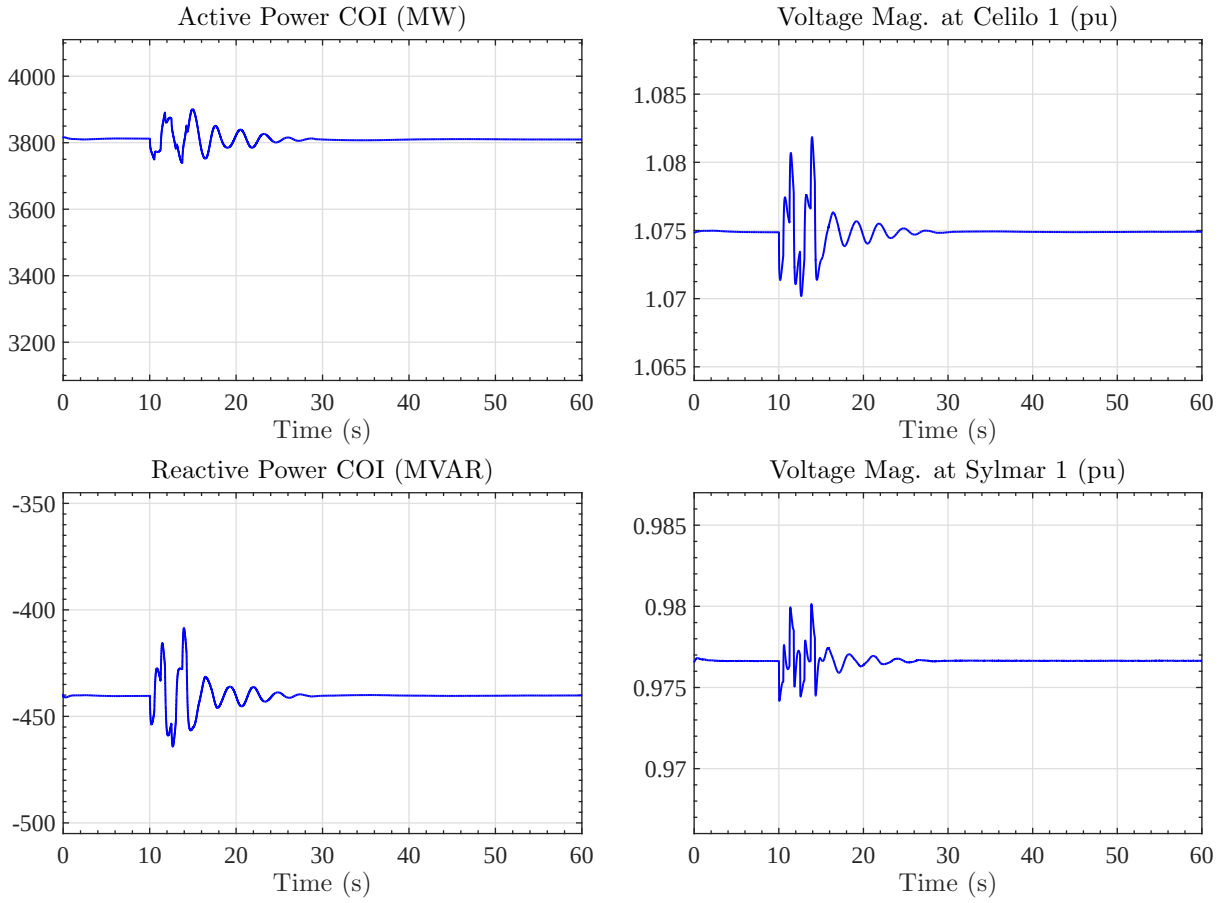


Figure 122. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW positive and negative pulses.

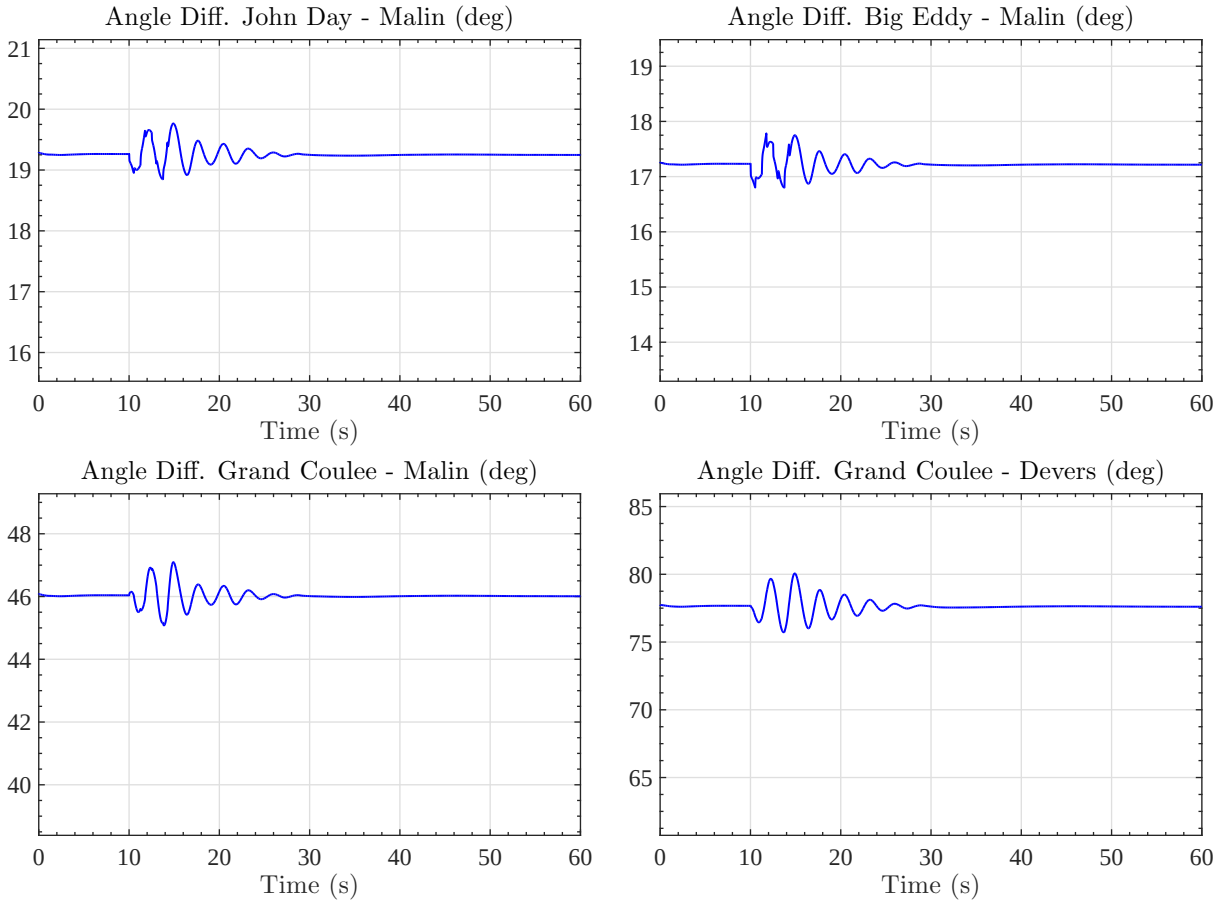


Figure 123. Angle differences. Event: 200 MW positive and negative pulses.

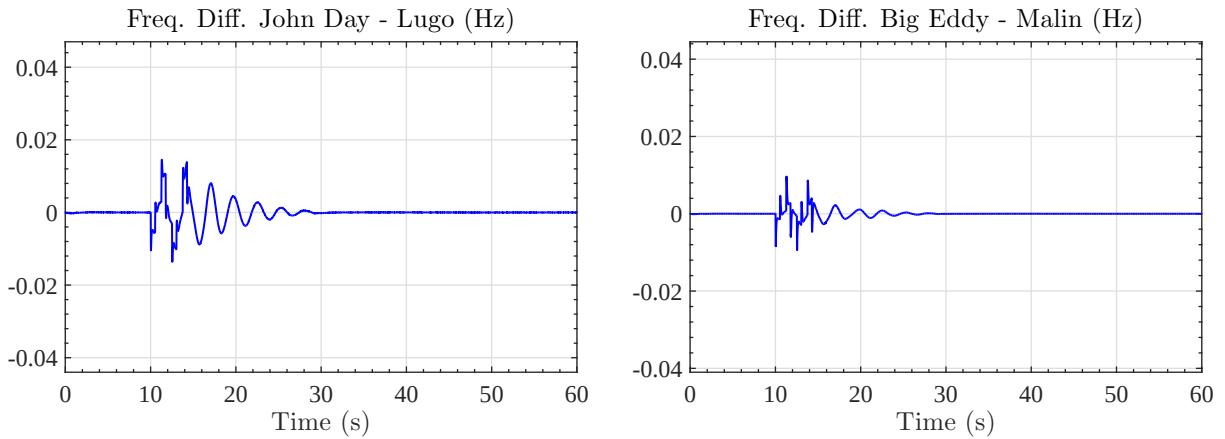


Figure 124. Frequency differences. Event: 200 MW positive and negative pulses.

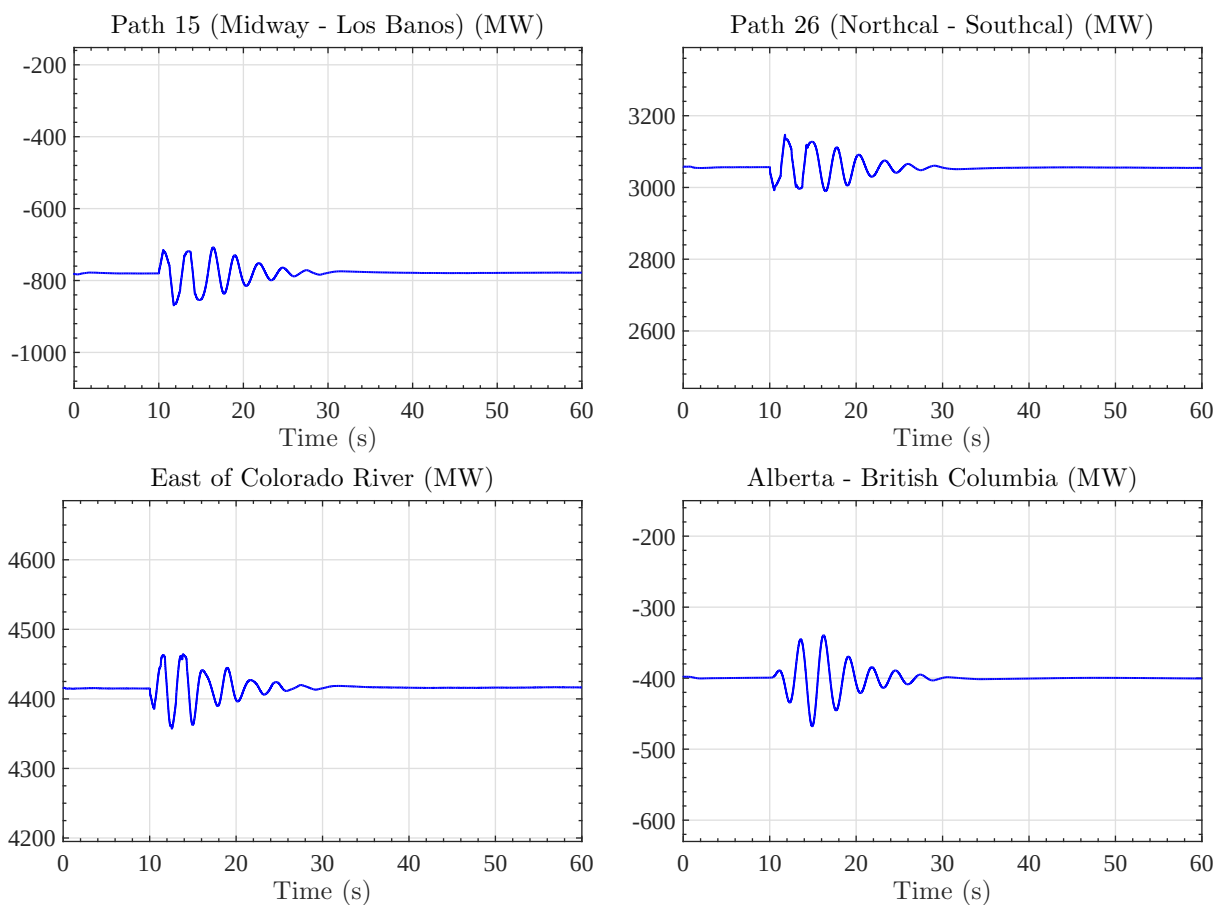


Figure 125. Active power flows. Event: 200 MW positive and negative pulses.

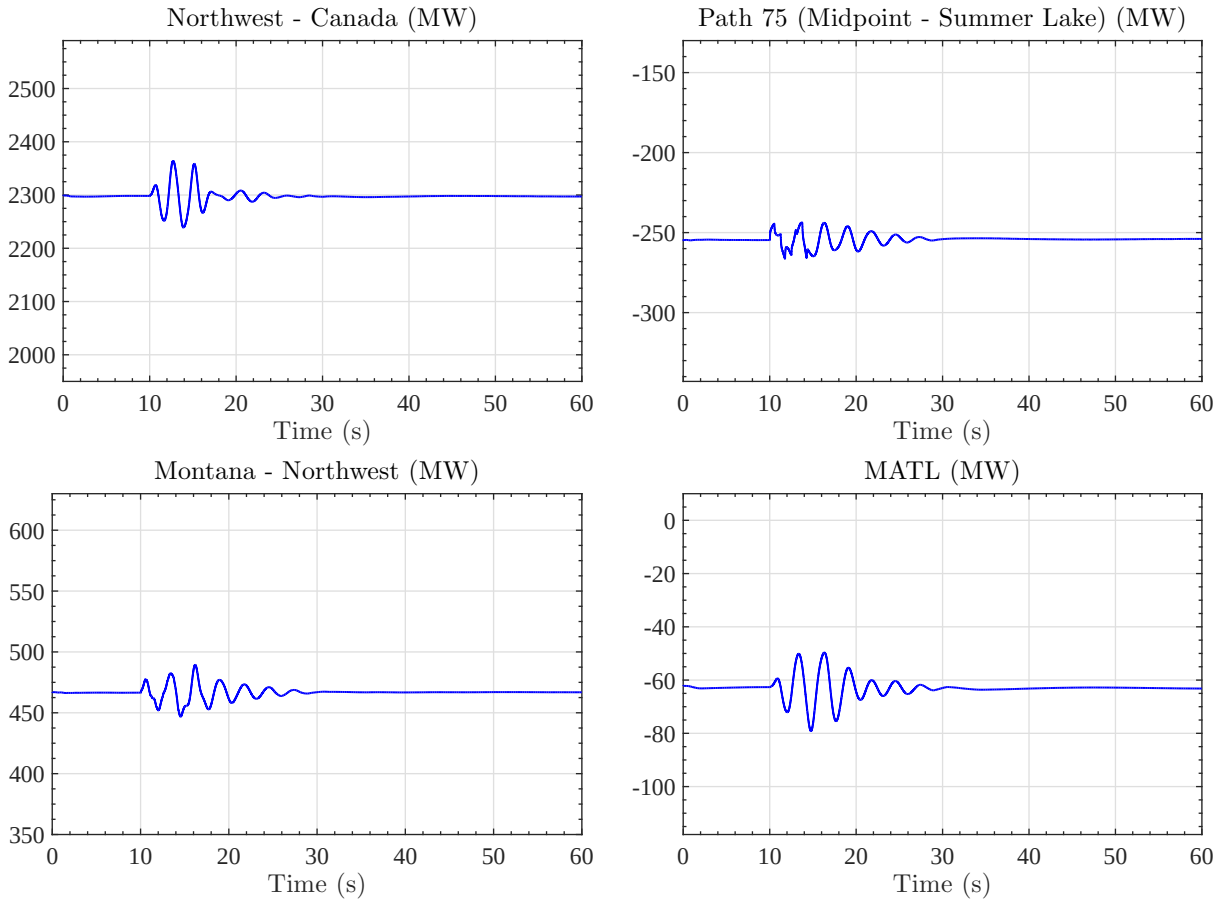


Figure 126. Active power flows. Event: 200 MW positive and negative pulses.

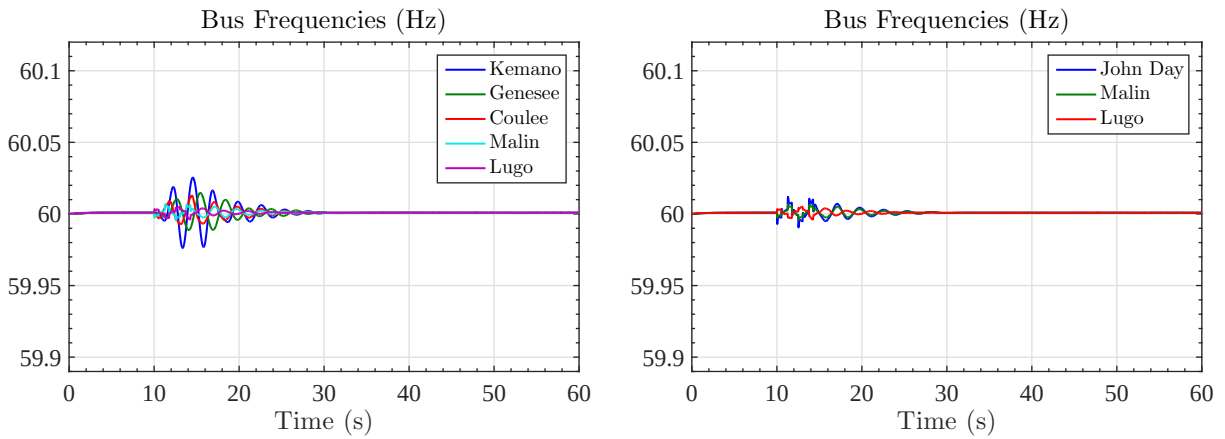


Figure 127. Bus frequencies. Event: 200 MW positive and negative pulses.

3.1.3. *Test System: Heavy Summer 2016. Controller Open Loop Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds*

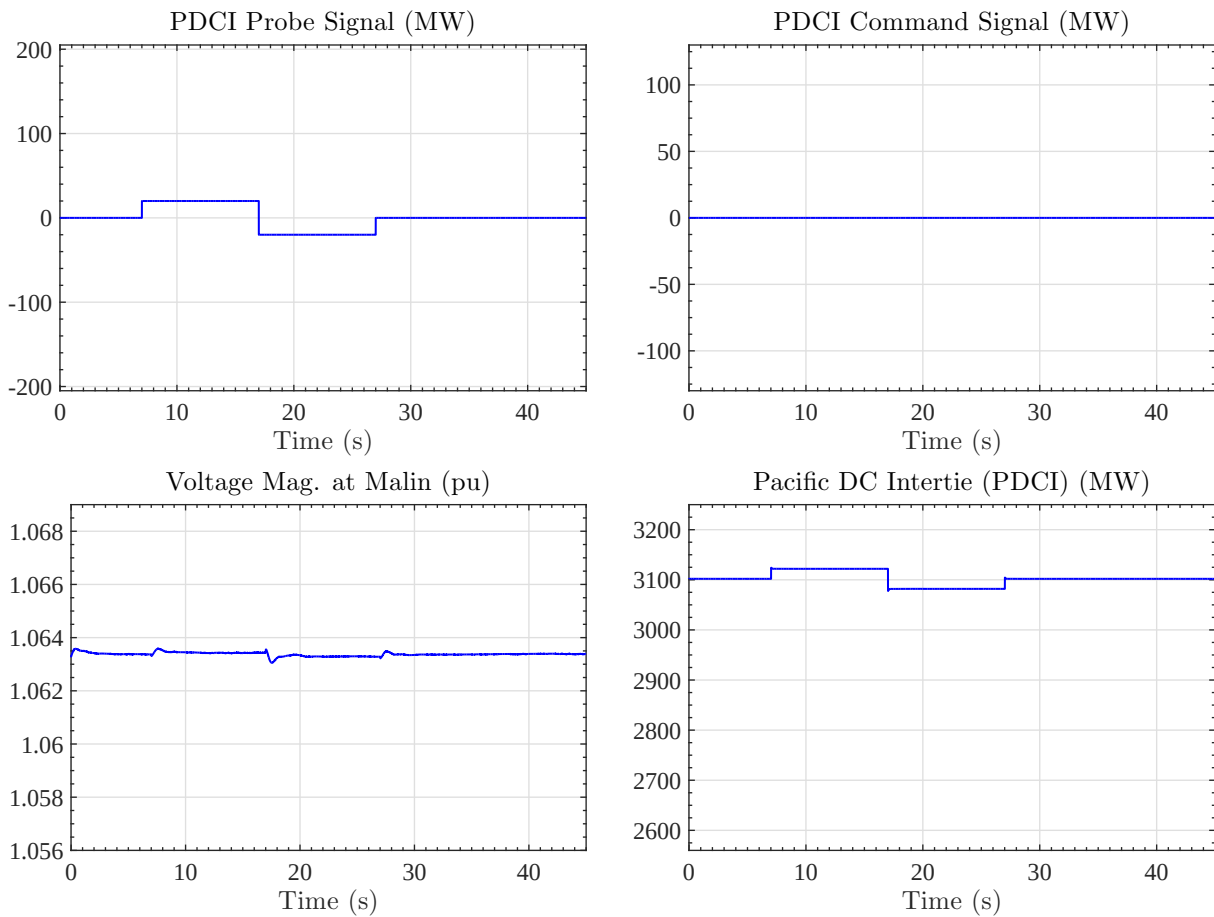


Figure 128. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

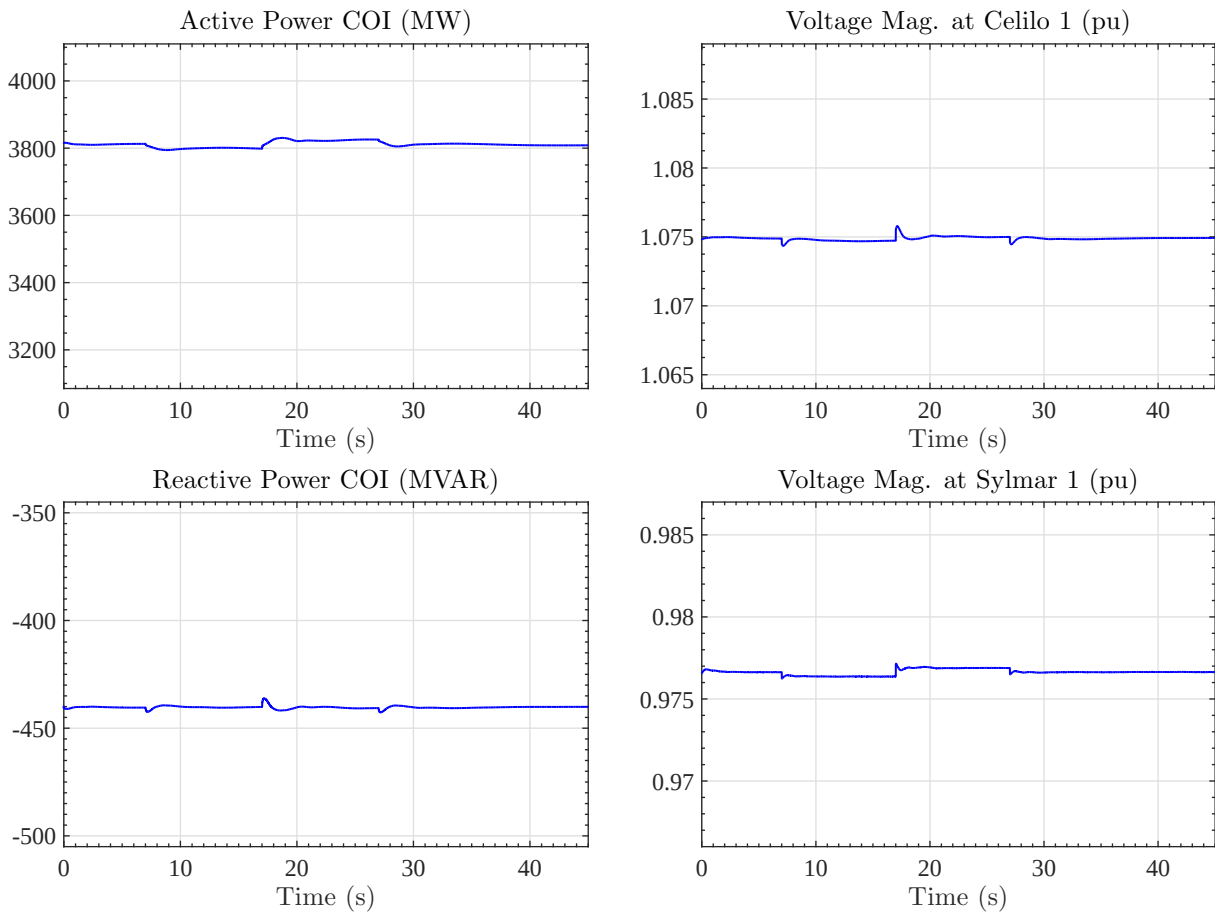


Figure 129. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

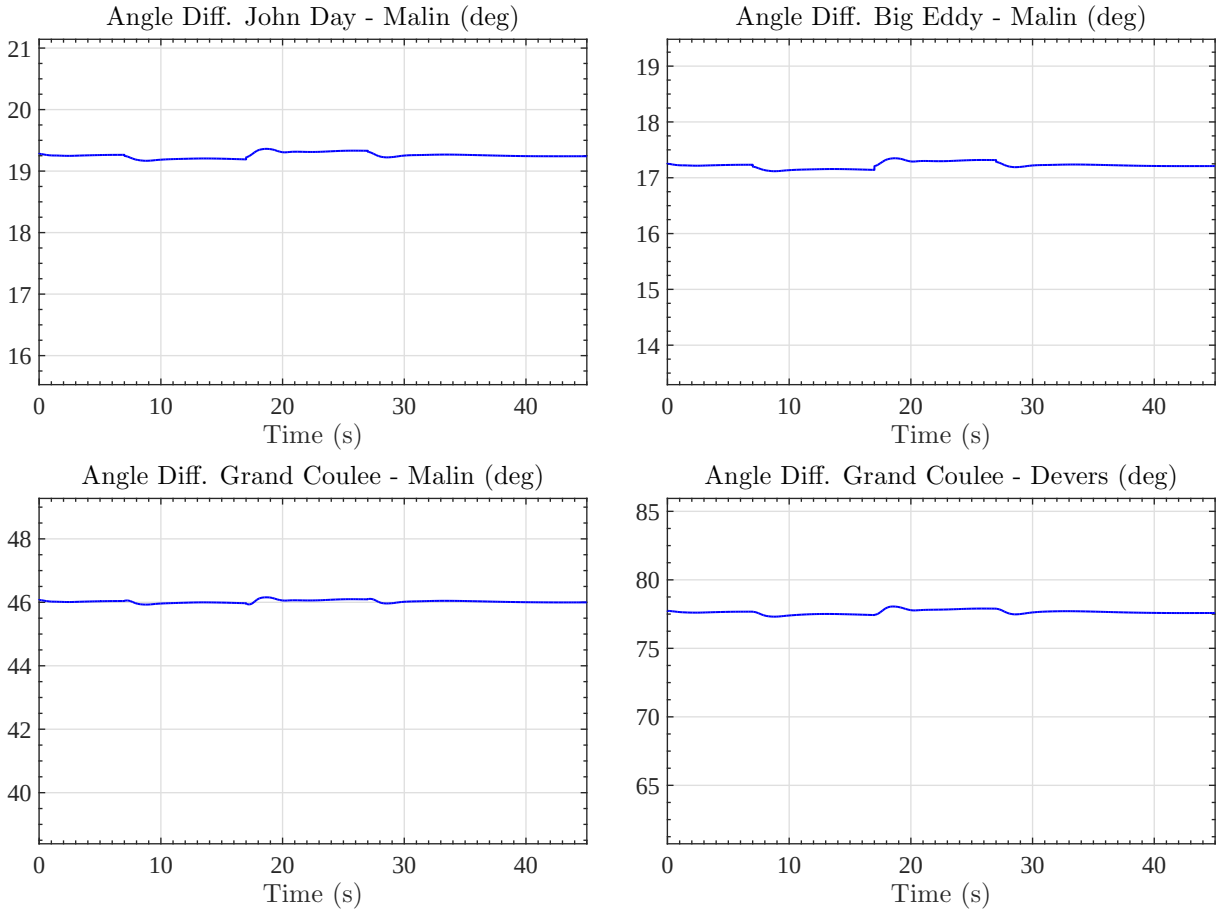


Figure 130. Angle differences. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

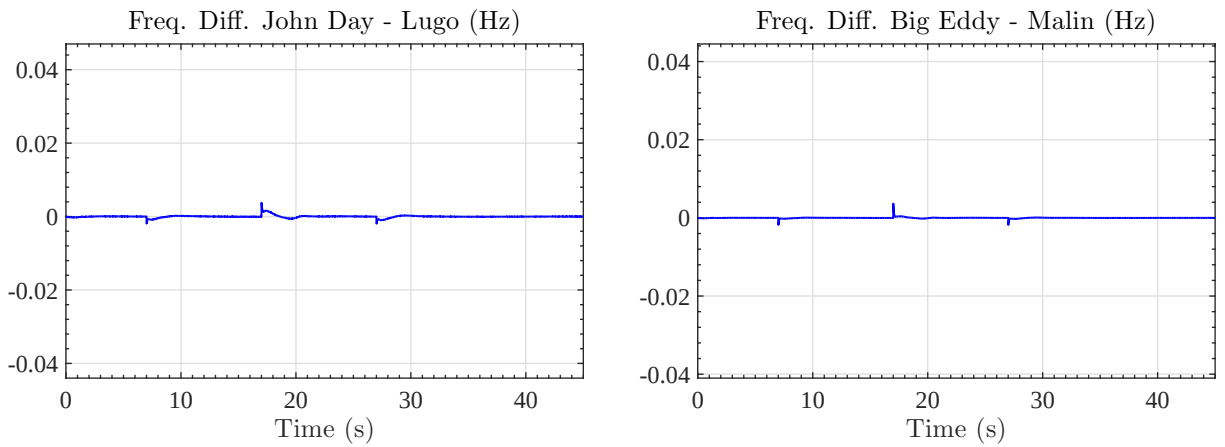


Figure 131. Frequency differences. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

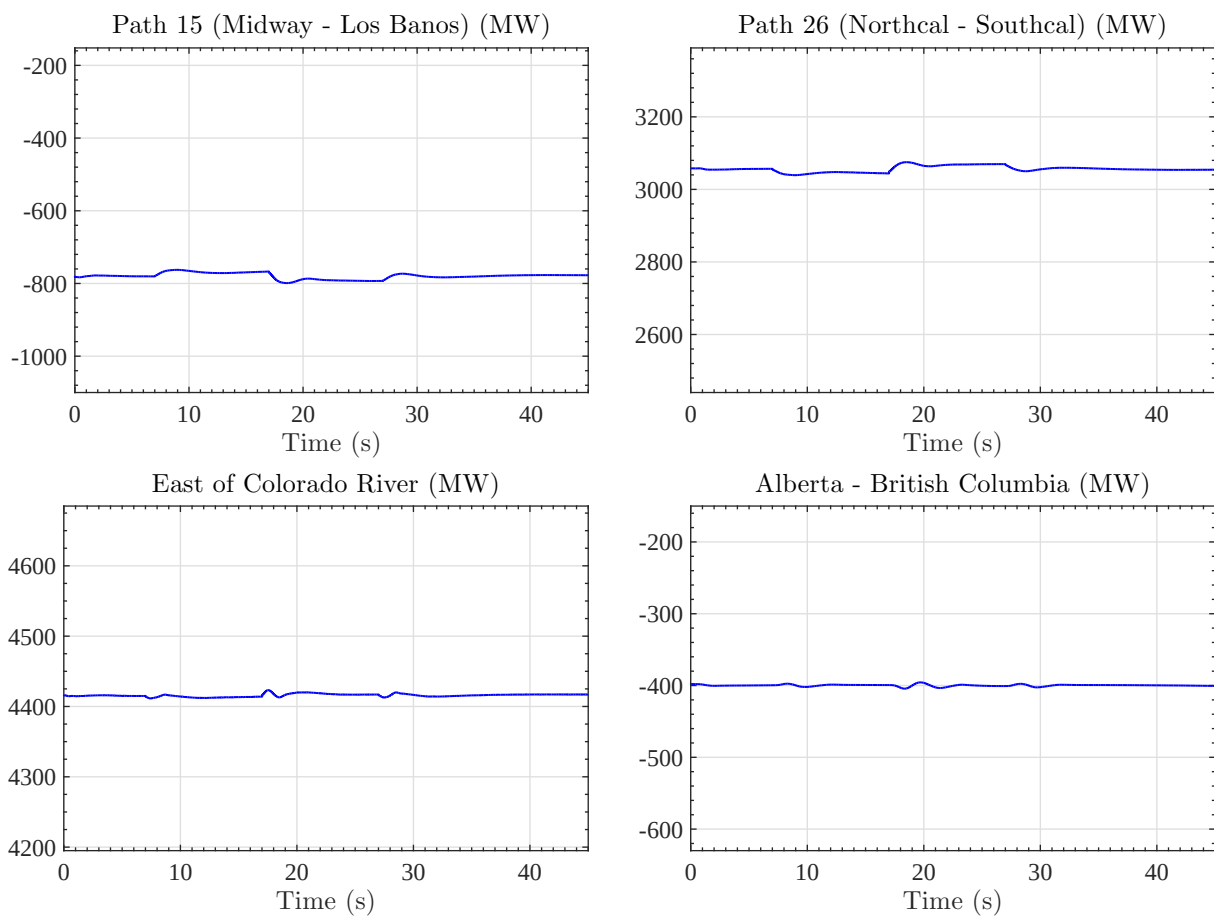


Figure 132. Active power flows. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

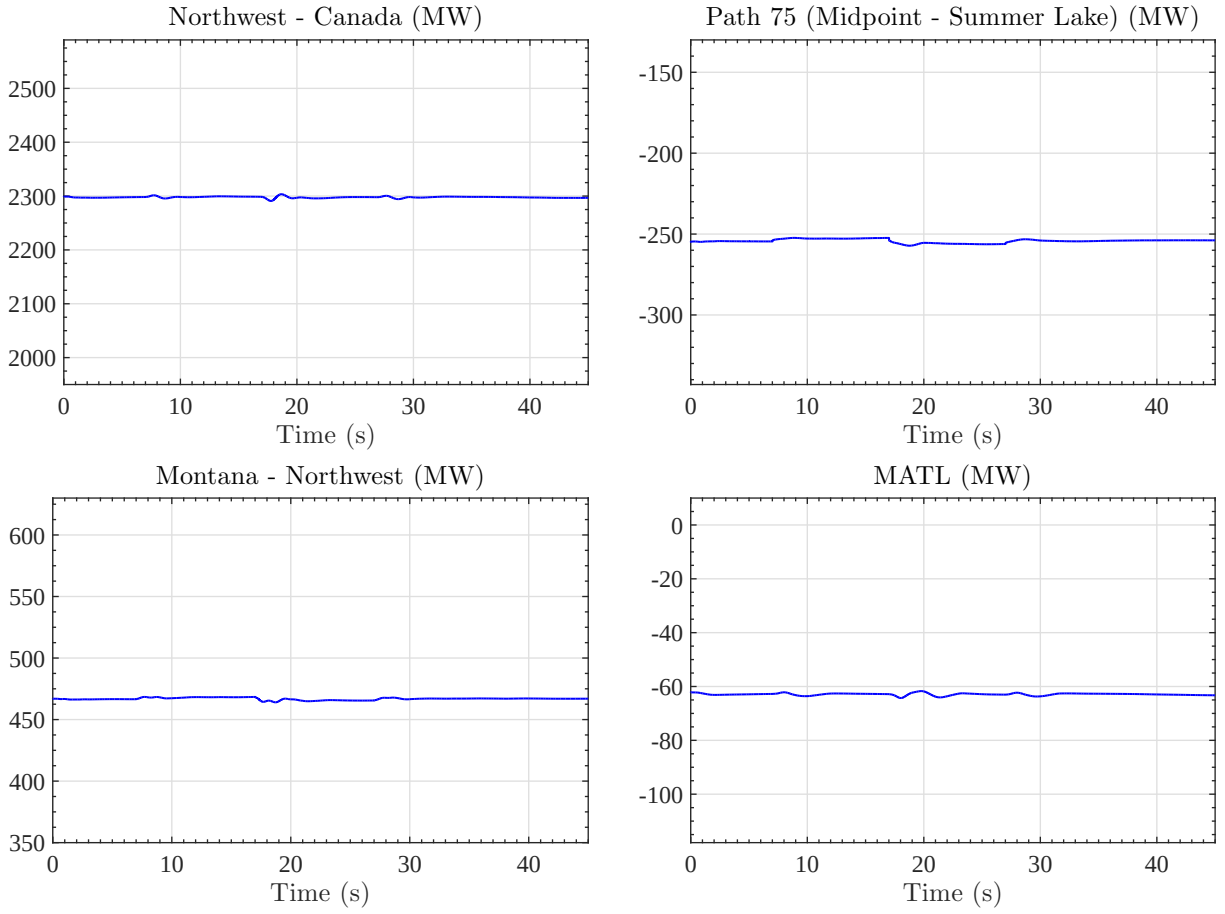


Figure 133. Active power flows. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

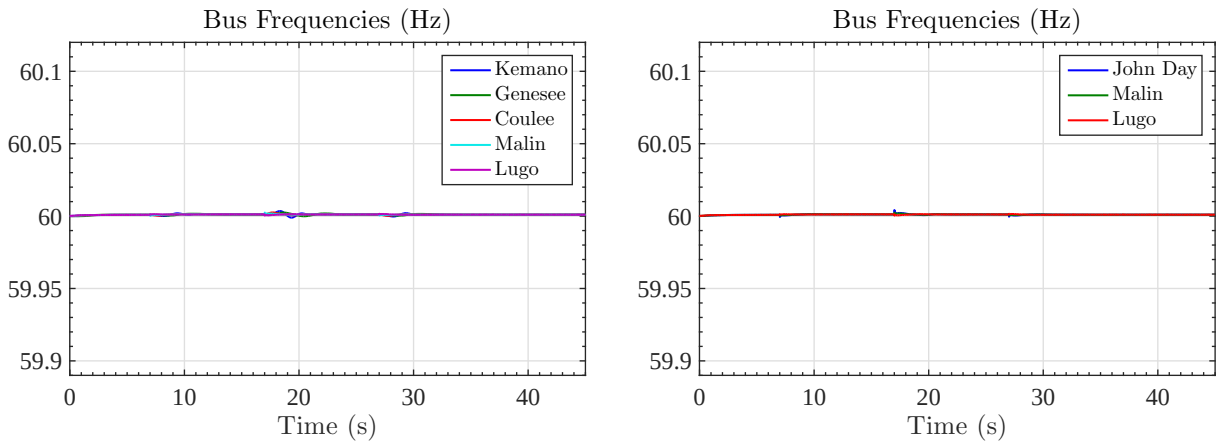


Figure 134. Bus frequencies. Event: Step of +20MW for 10 seconds straight down to -20MW for 10 seconds.

3.1.4. Test System: Heavy Summer 2016. Controller Open Loop Event: MSF 1/30/1/100 with amplitude of 20MW

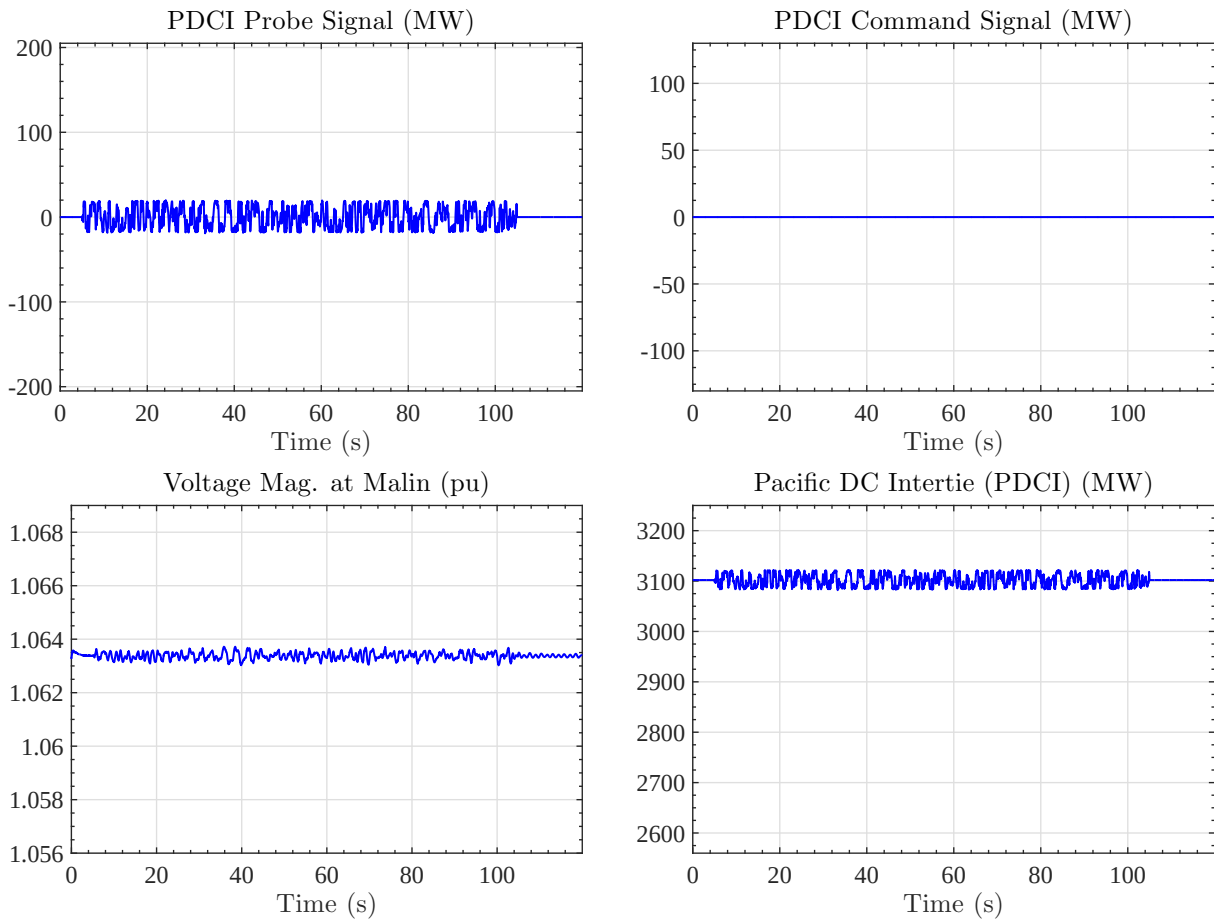


Figure 135. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 1/30/1/100 with amplitude of 20MW.

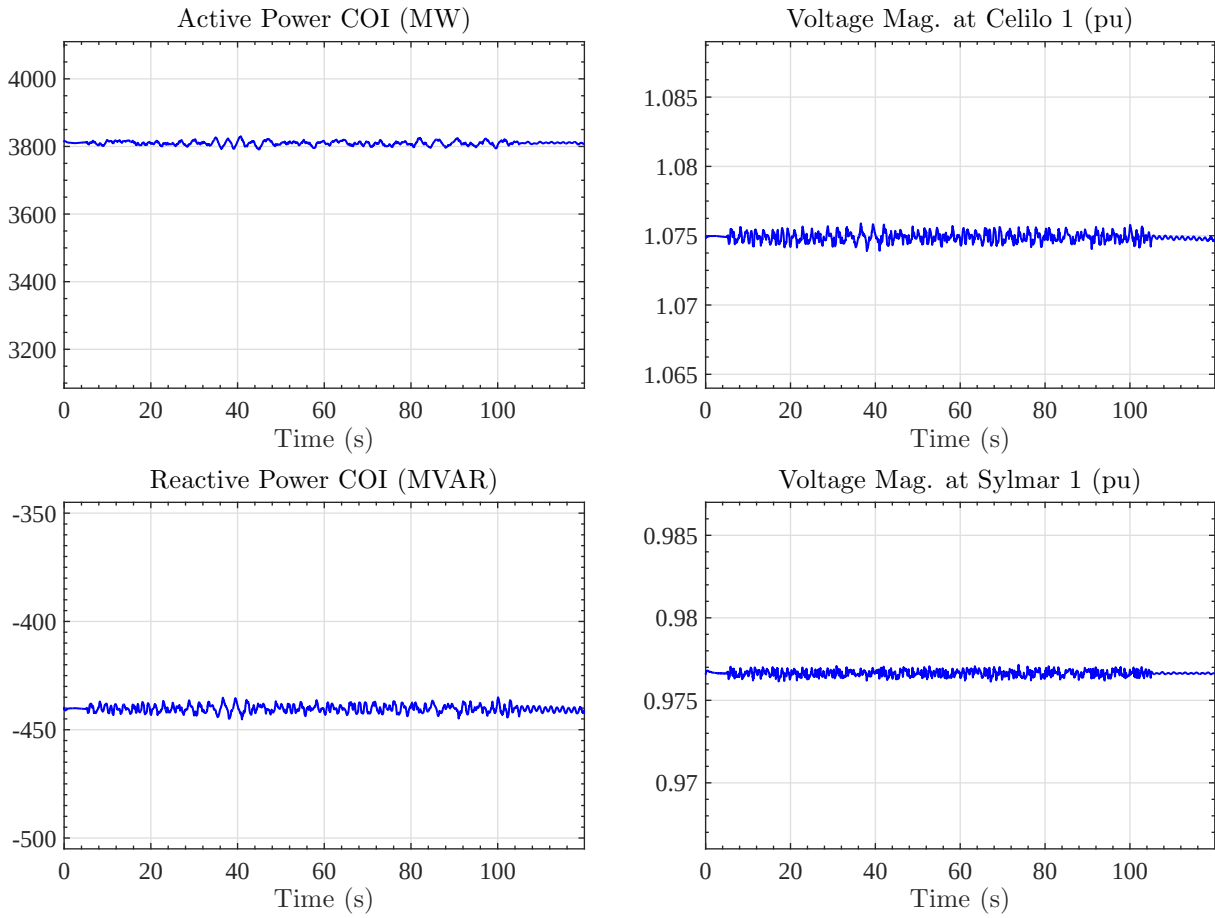


Figure 136. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 1/30/1/100 with amplitude of 20MW.

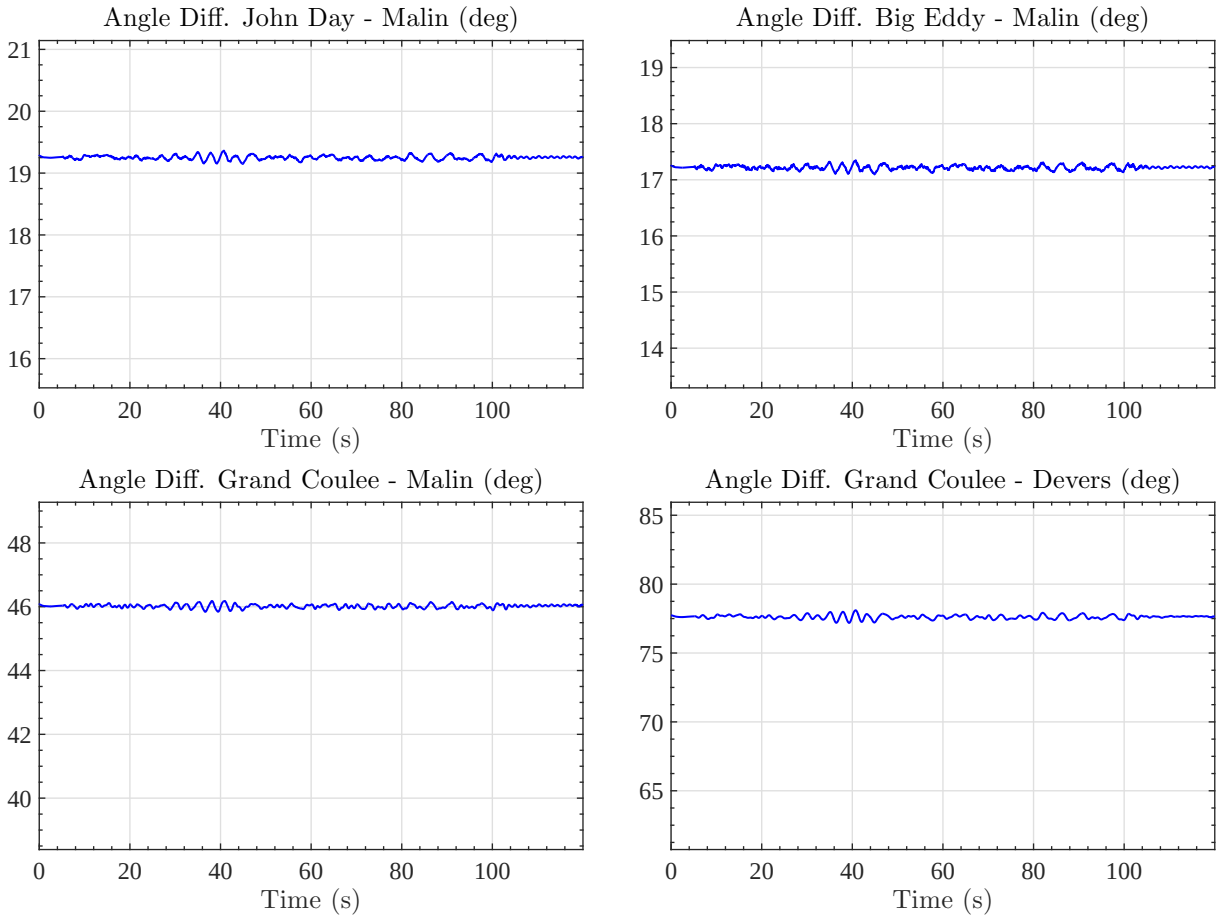


Figure 137. Angle differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

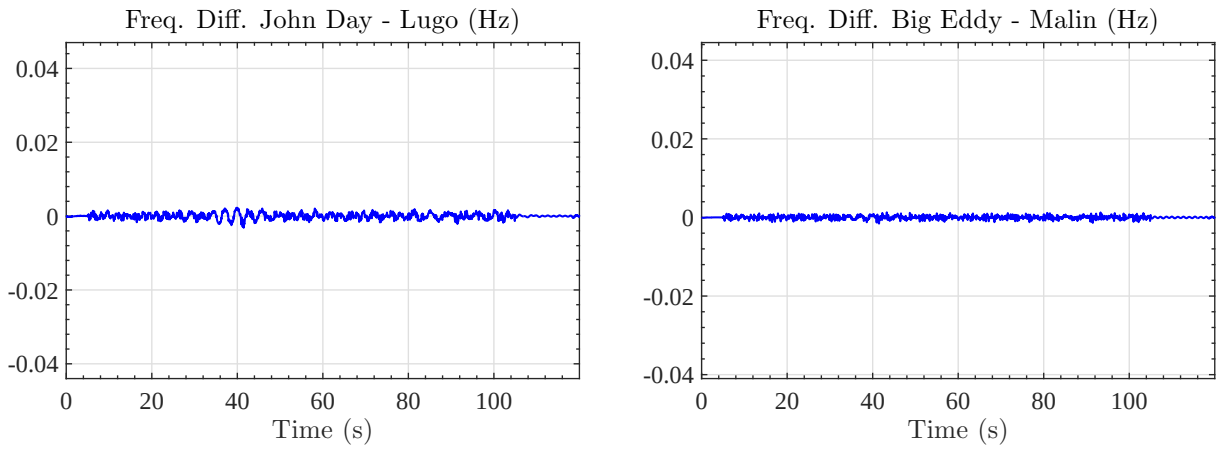


Figure 138. Frequency differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

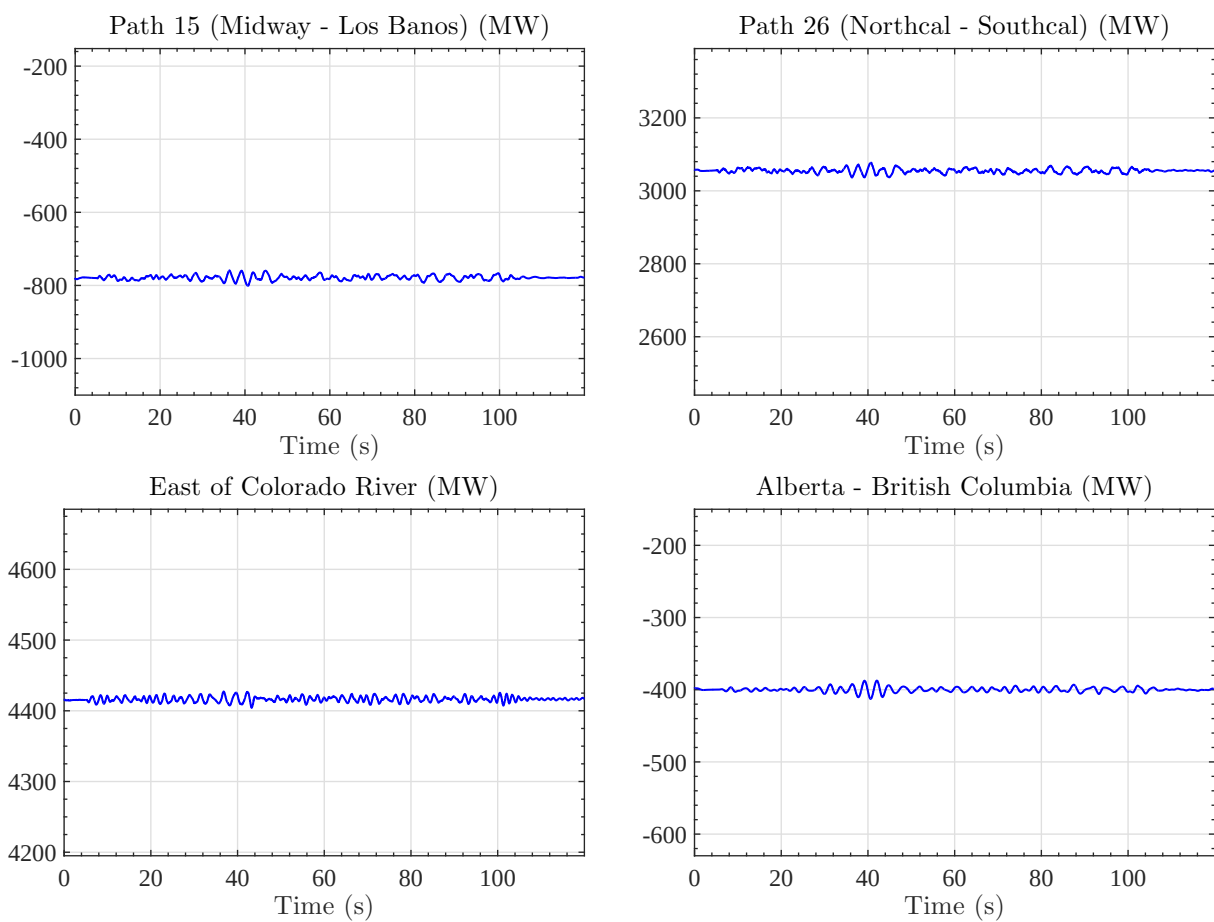


Figure 139. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

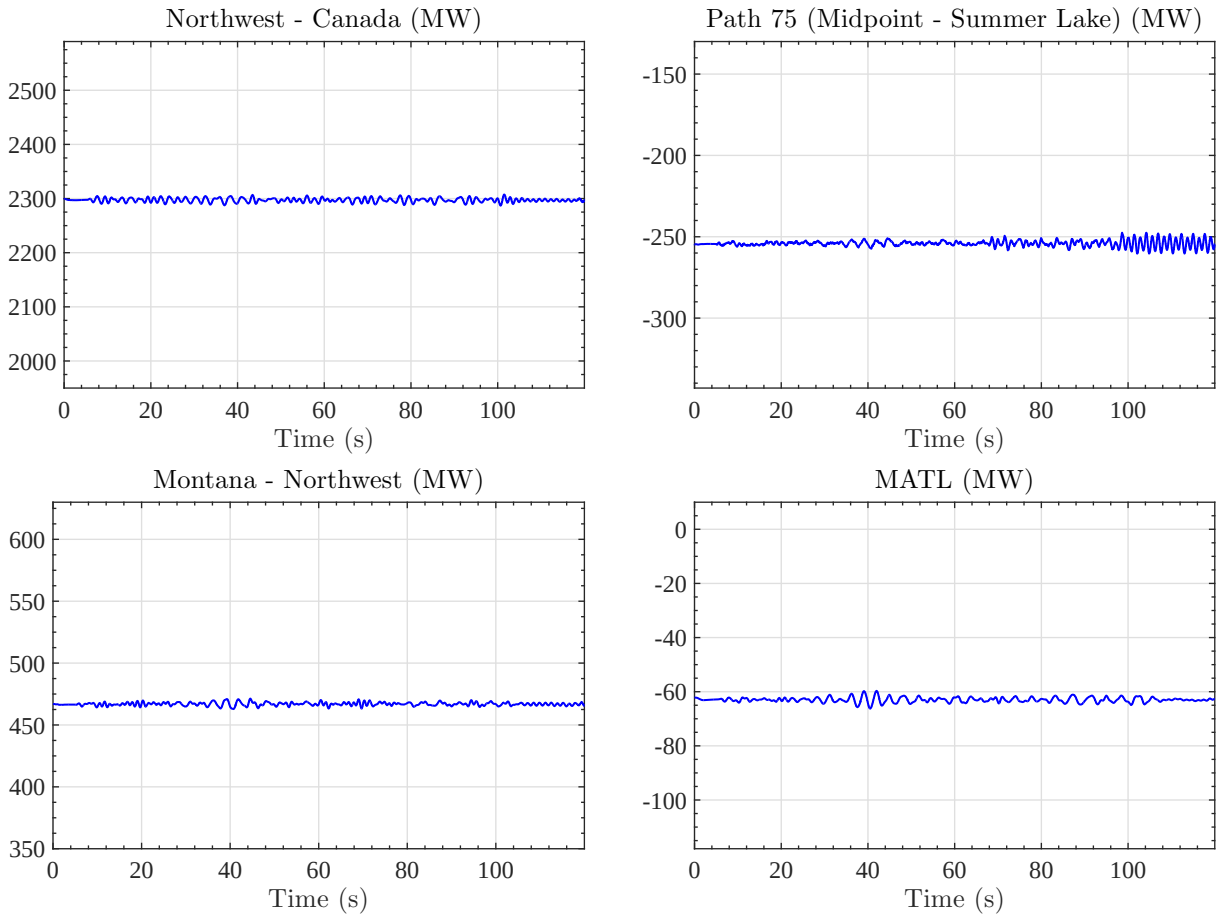


Figure 140. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

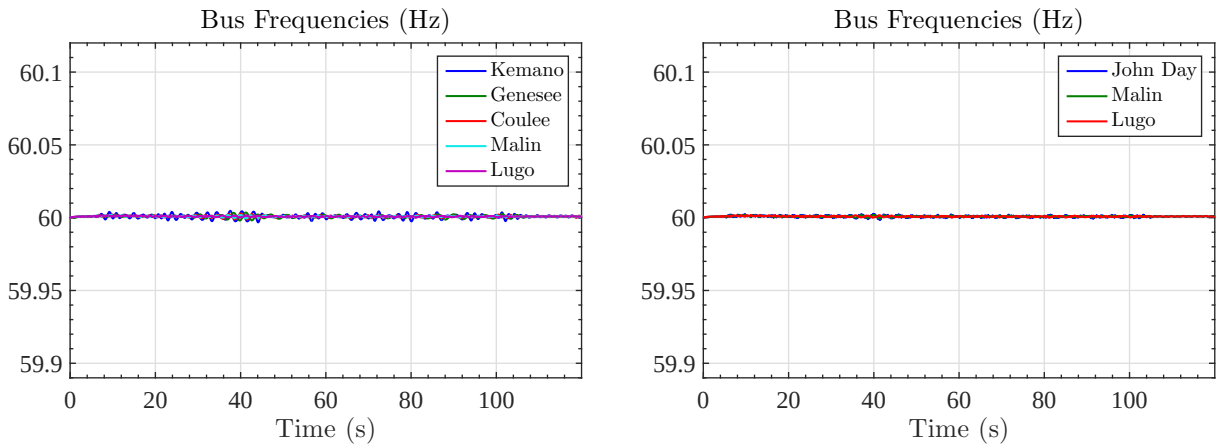


Figure 141. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

3.1.5. *Test System: Heavy Summer 2016. Controller Open Loop Event: SF 0.1/4x with amplitude of 125MW*

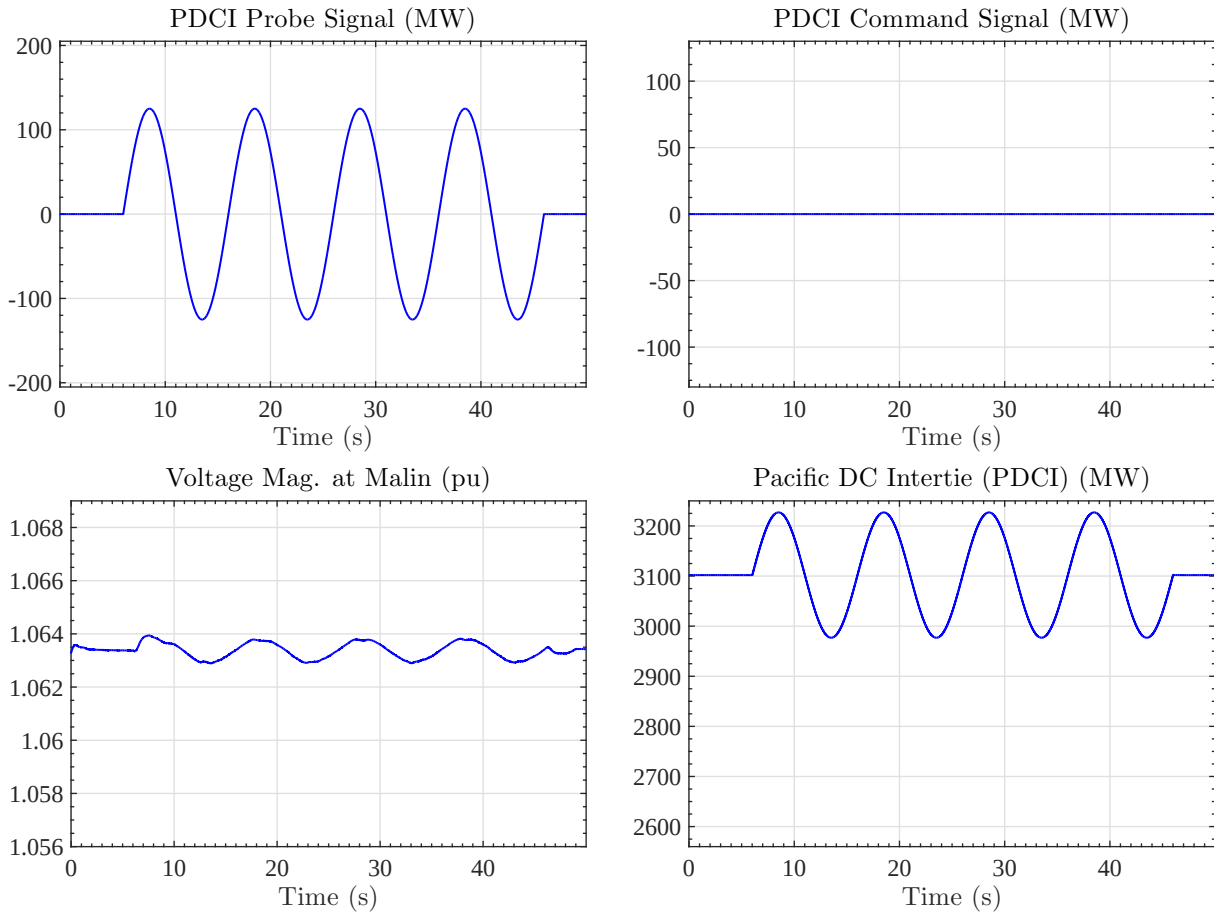


Figure 142. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 0.1/4x with amplitude of 125MW.

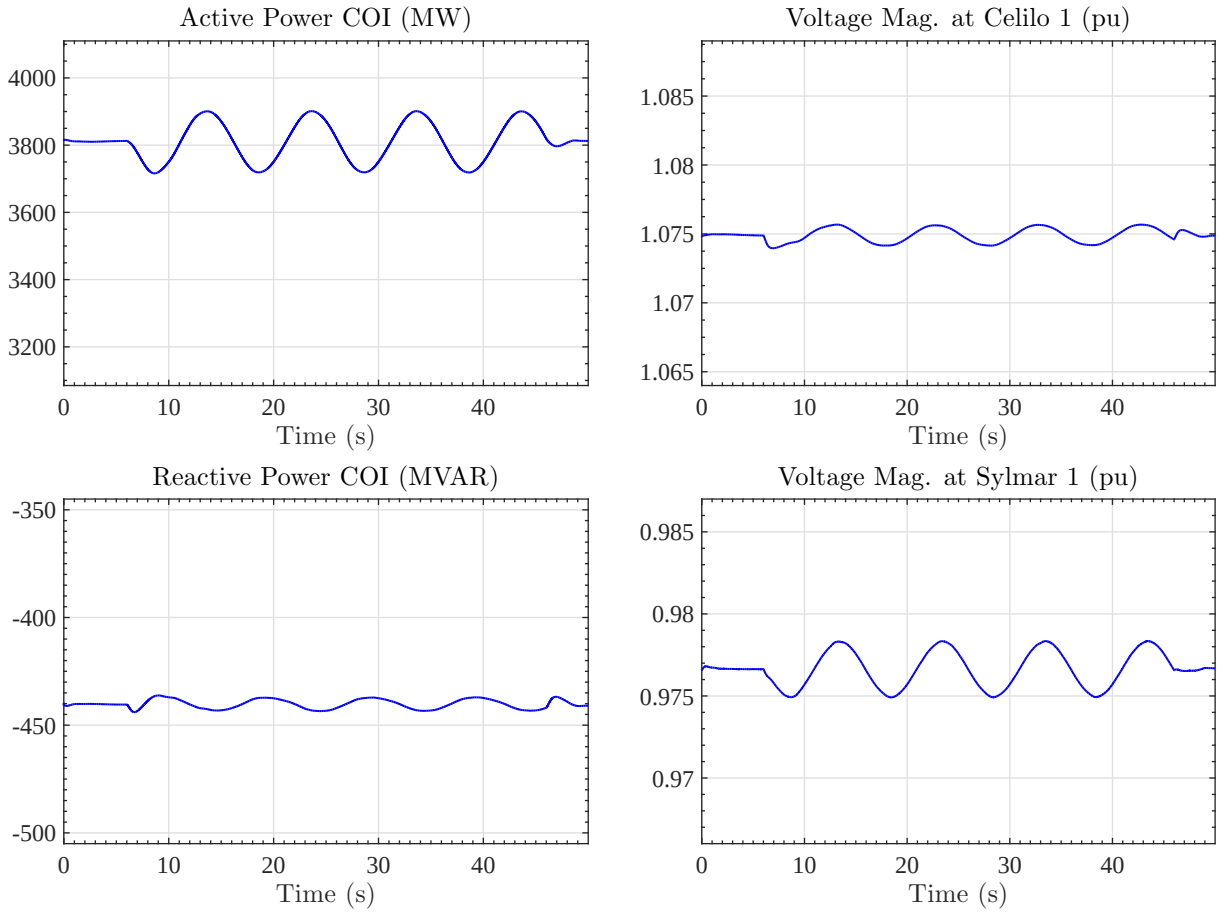


Figure 143. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 0.1/4x with amplitude of 125MW.

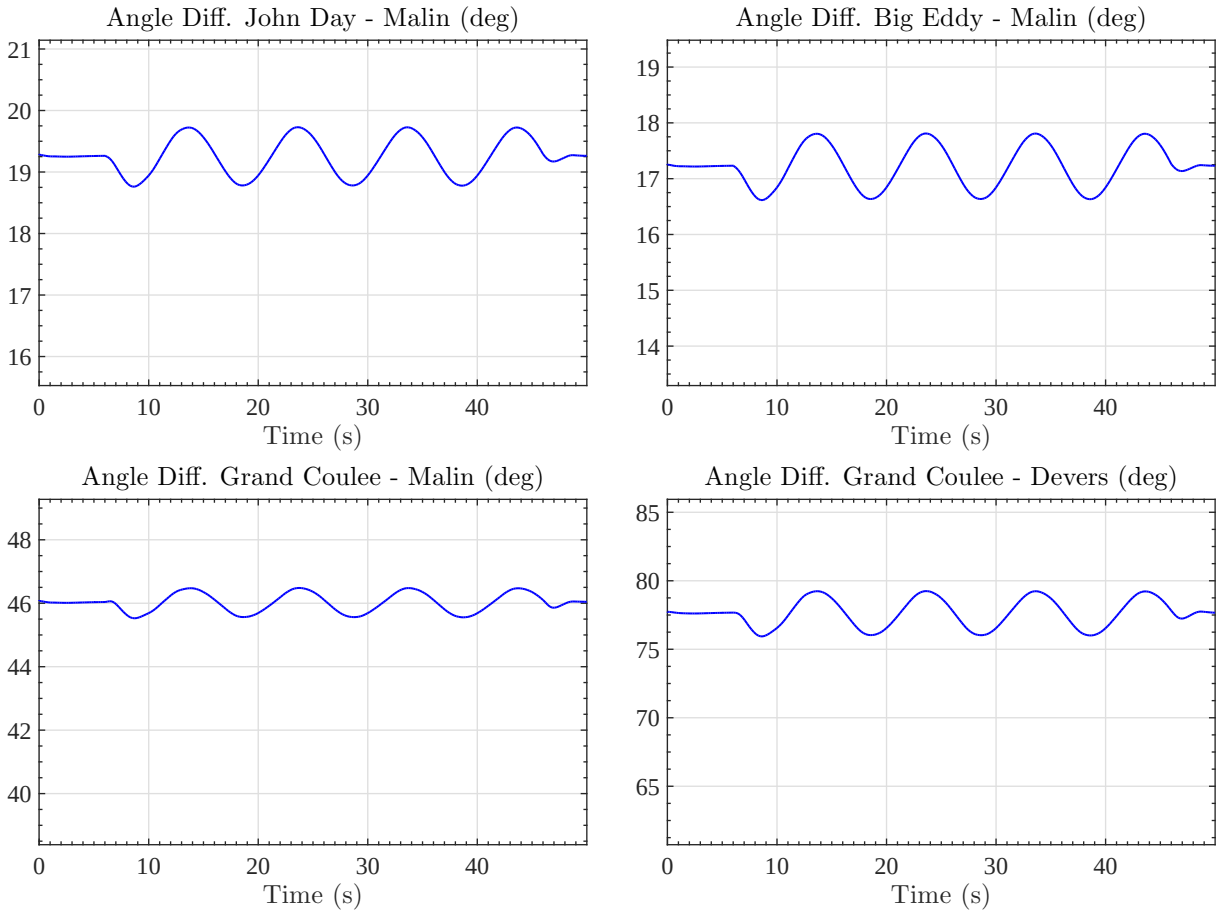


Figure 144. Angle differences. Event: SF 0.1/4x with amplitude of 125MW.

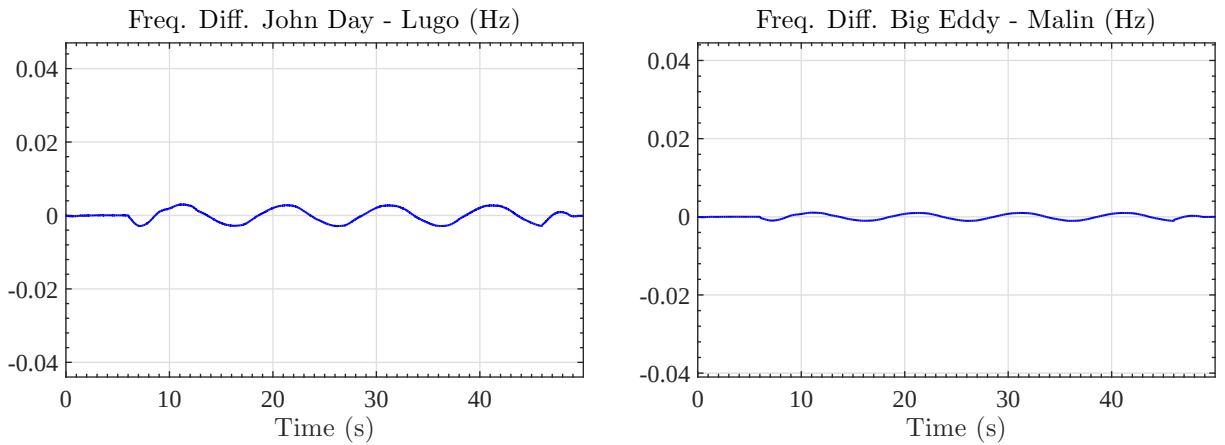


Figure 145. Frequency differences. Event: SF 0.1/4x with amplitude of 125MW.

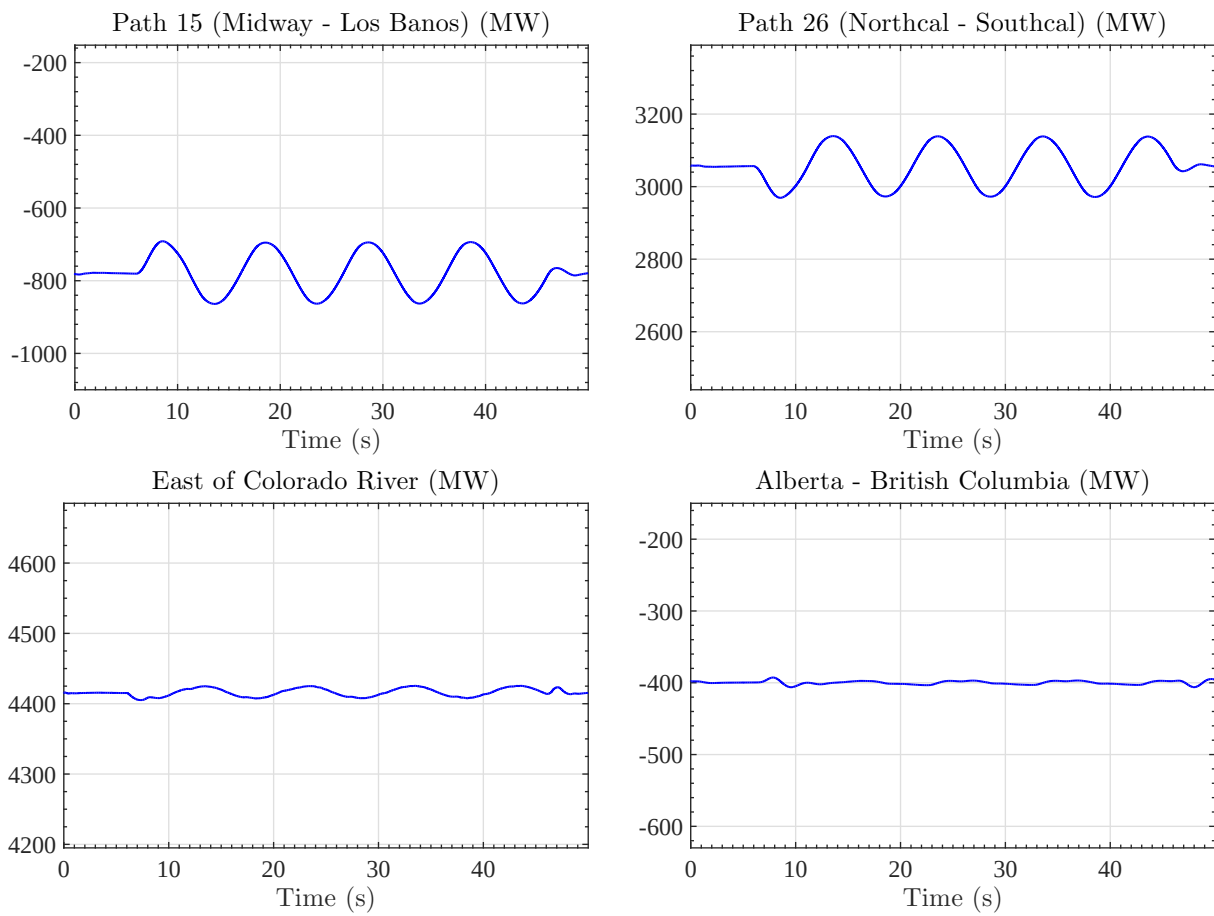


Figure 146. Active power flows. Event: SF 0.1/4x with amplitude of 125MW.

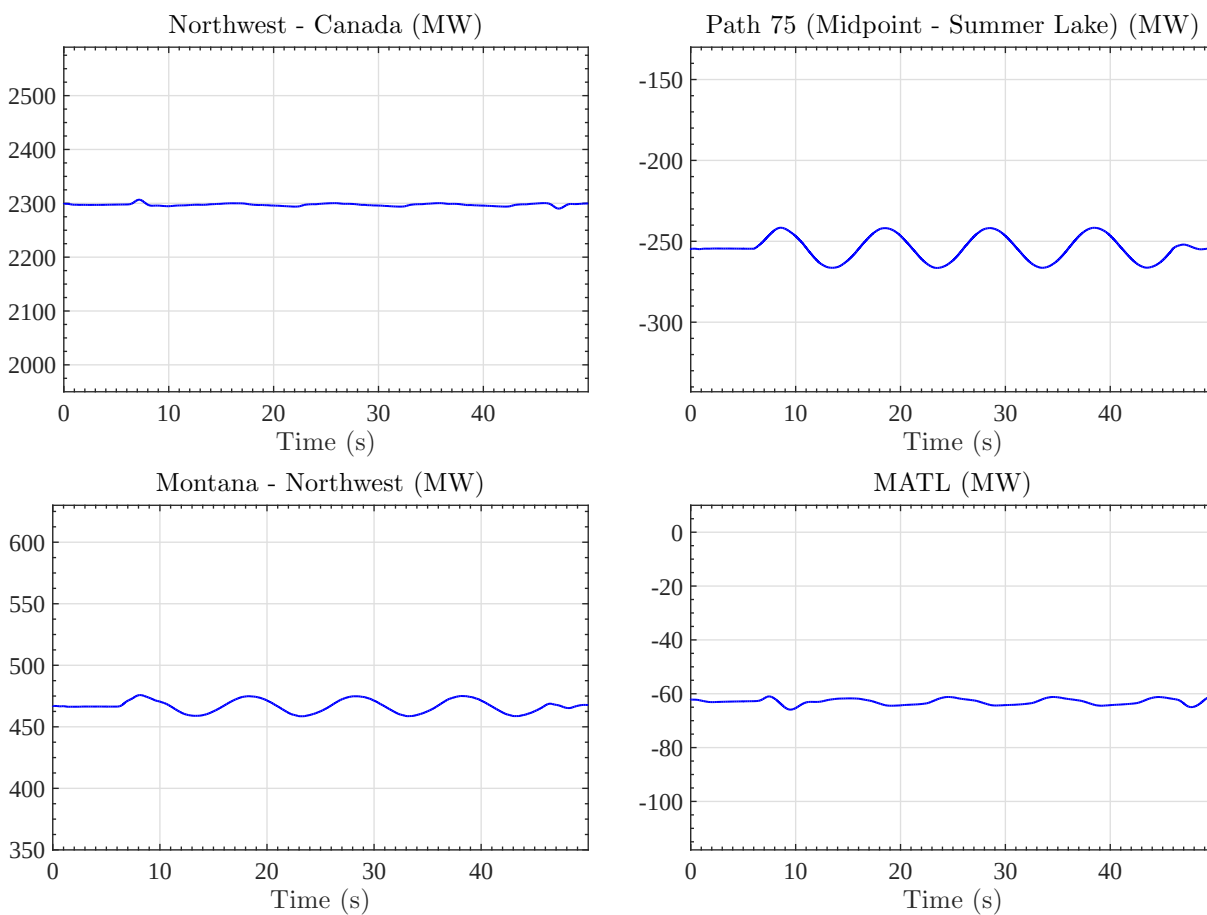


Figure 147. Active power flows. Event: SF 0.1/4x with amplitude of 125MW.

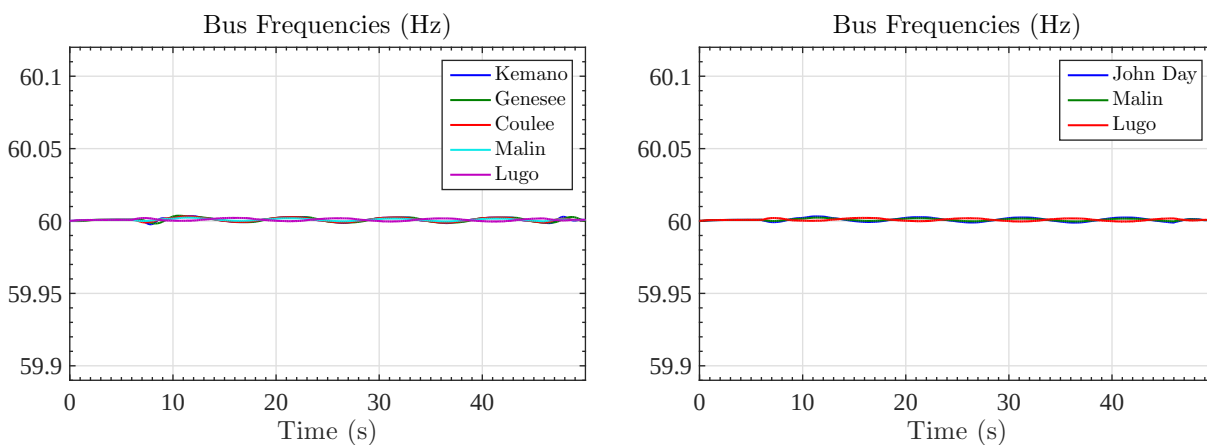


Figure 148. Bus frequencies. Event: SF 0.1/4x with amplitude of 125MW.

3.1.6. Test System: Heavy Summer 2016. Controller Open Loop Event: SF 0.3/4x with amplitude of 125MW

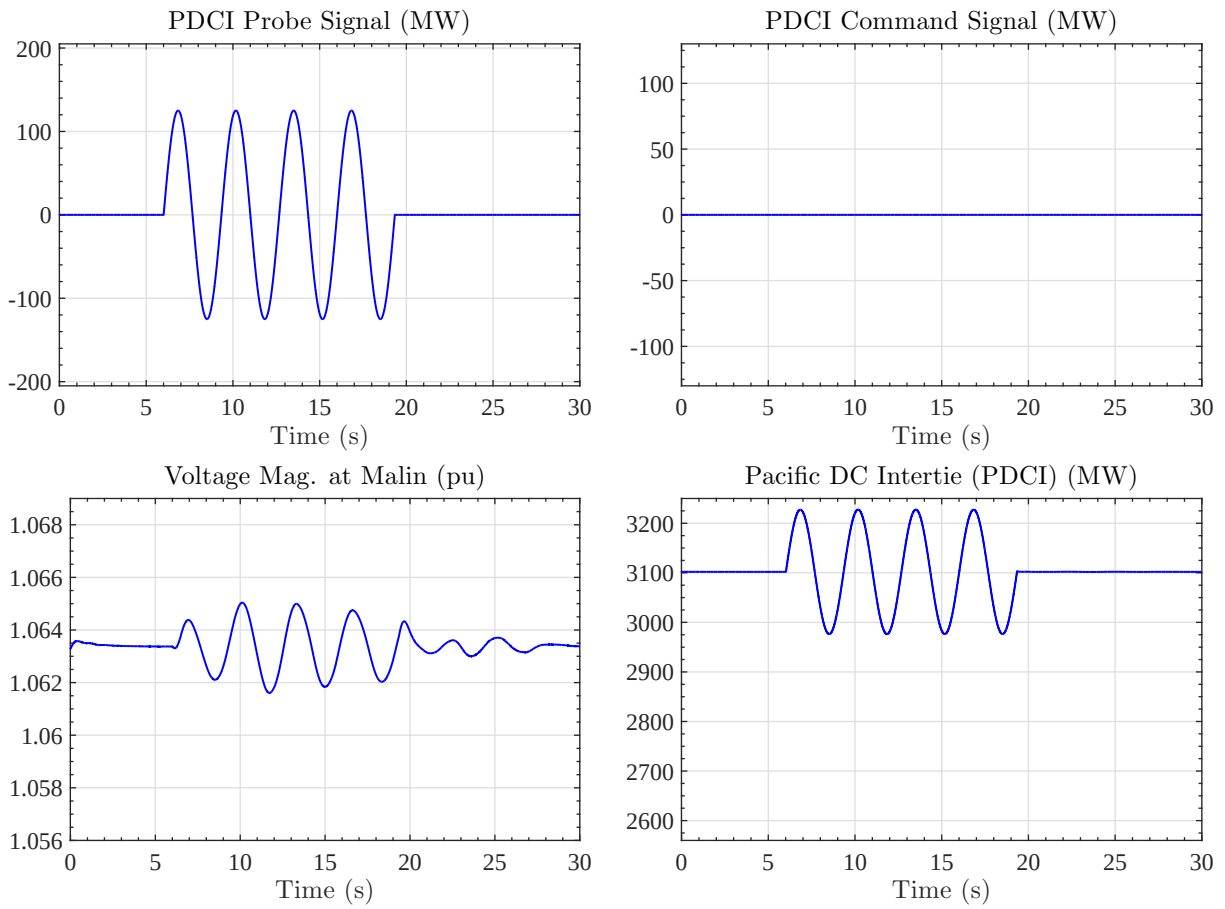


Figure 149. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 0.3/4x with amplitude of 125MW.

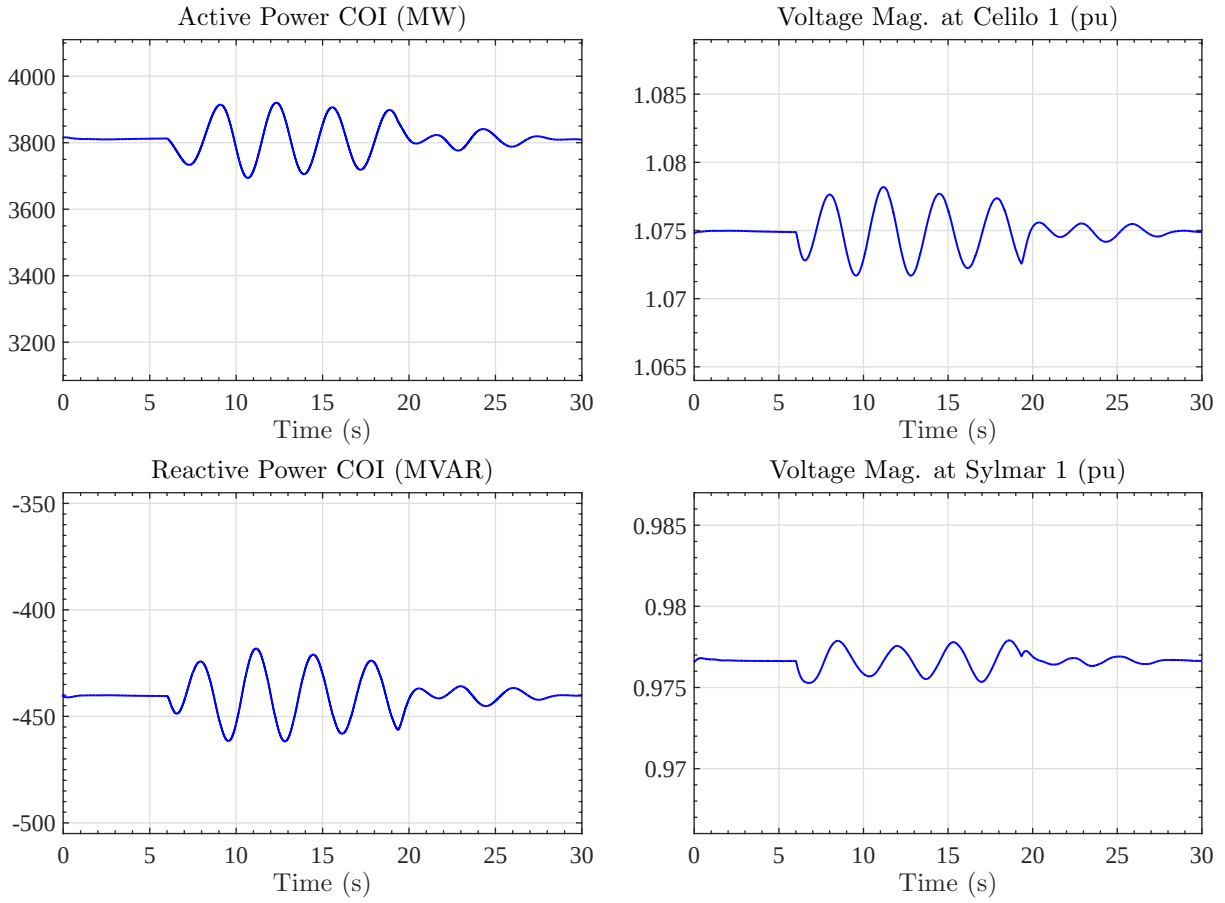


Figure 150. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 0.3/4x with amplitude of 125MW.

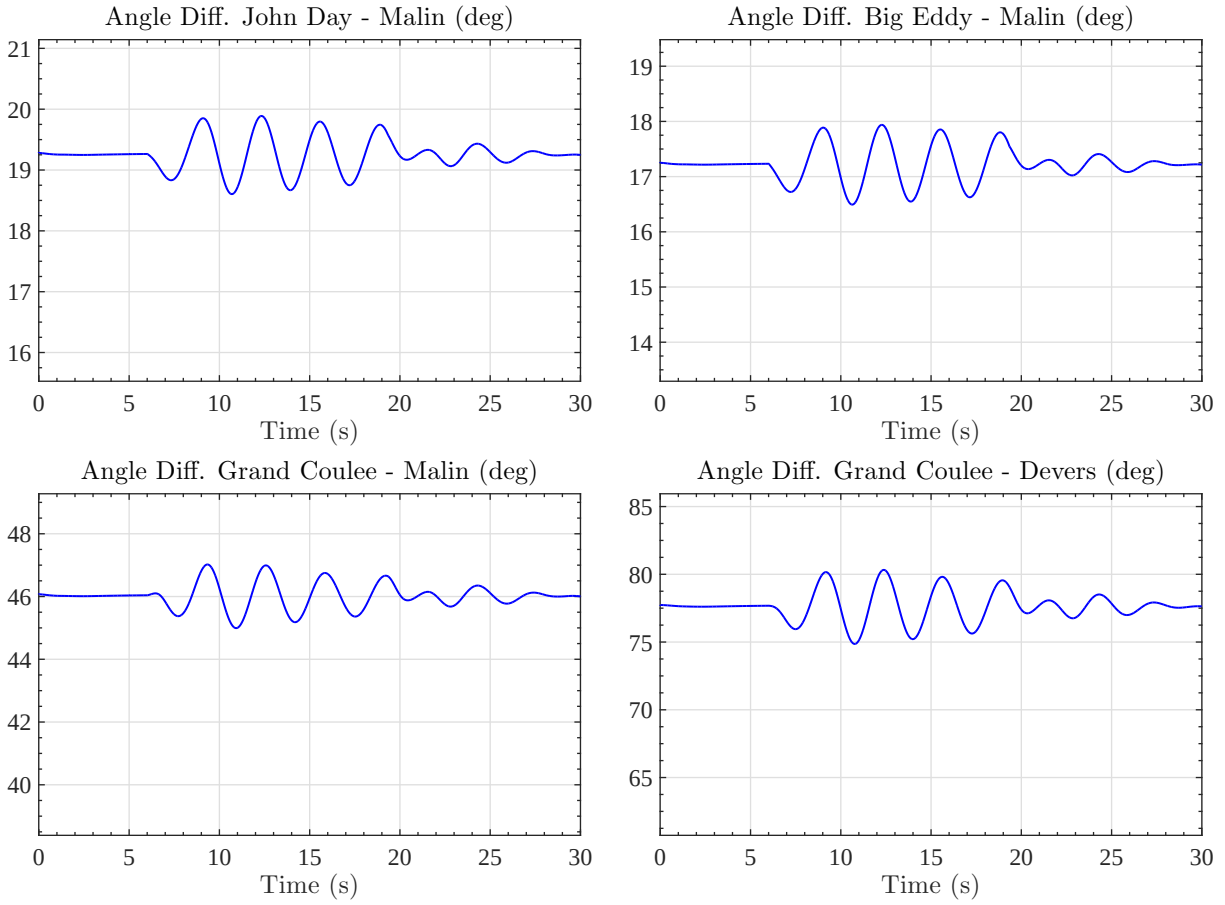


Figure 151. Angle differences. Event: SF 0.3/4x with amplitude of 125MW.

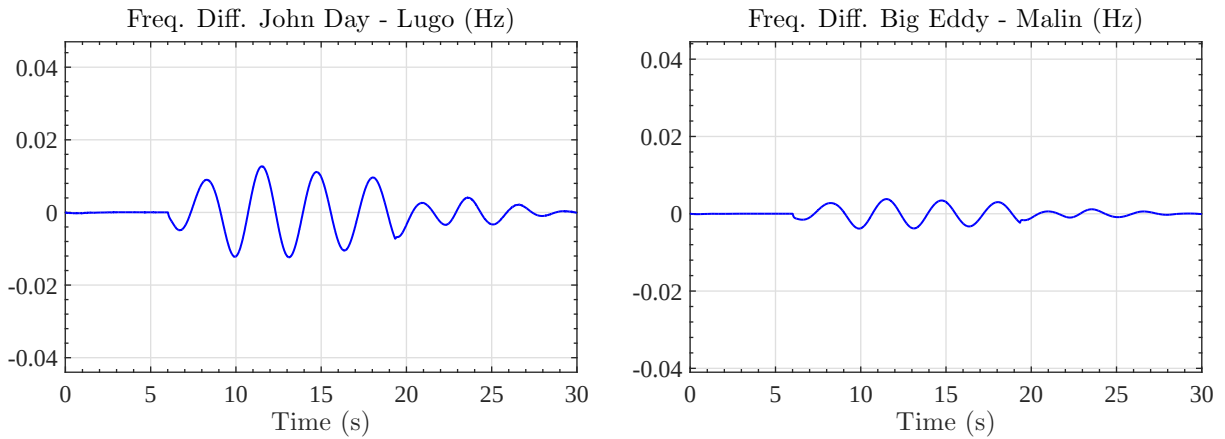


Figure 152. Frequency differences. Event: SF 0.3/4x with amplitude of 125MW.

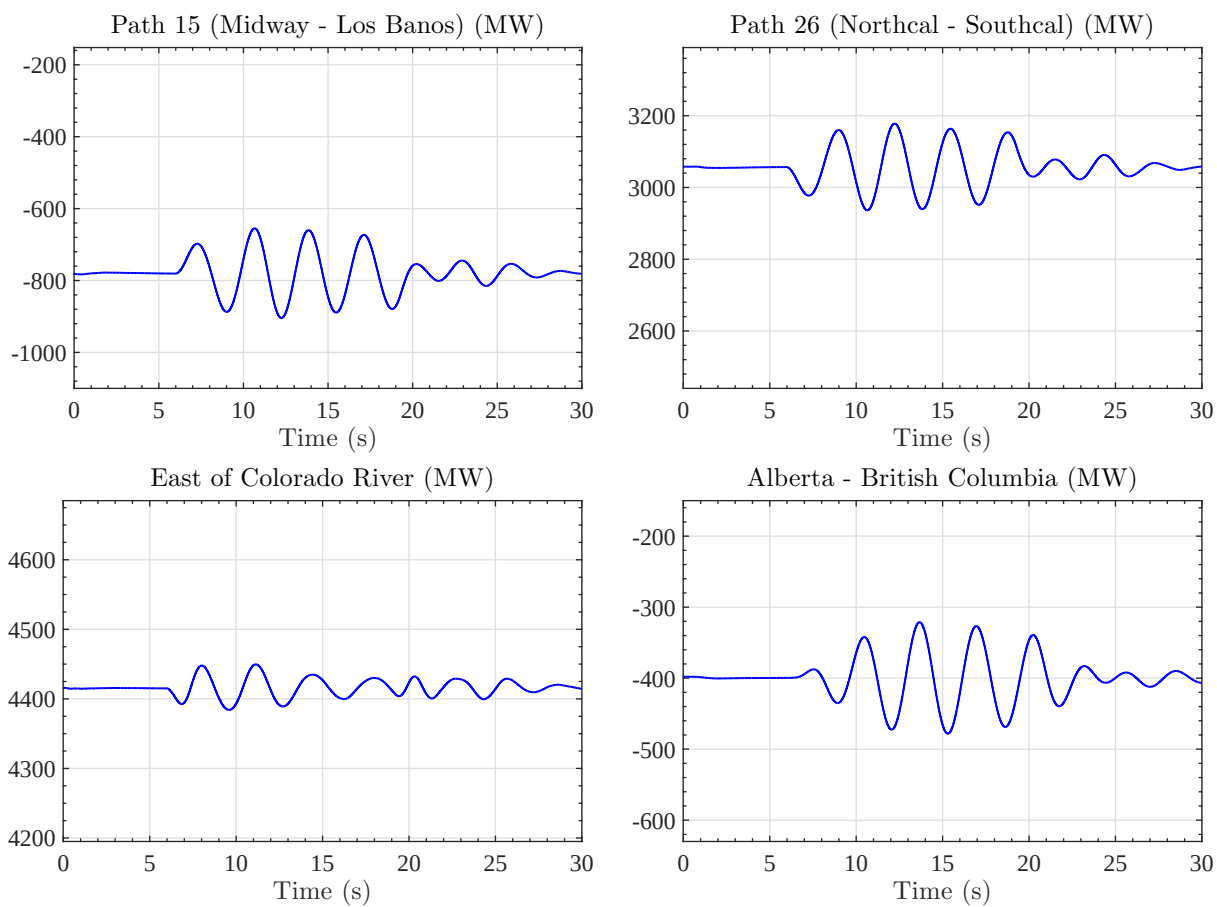


Figure 153. Active power flows. Event: SF 0.3/4x with amplitude of 125MW.

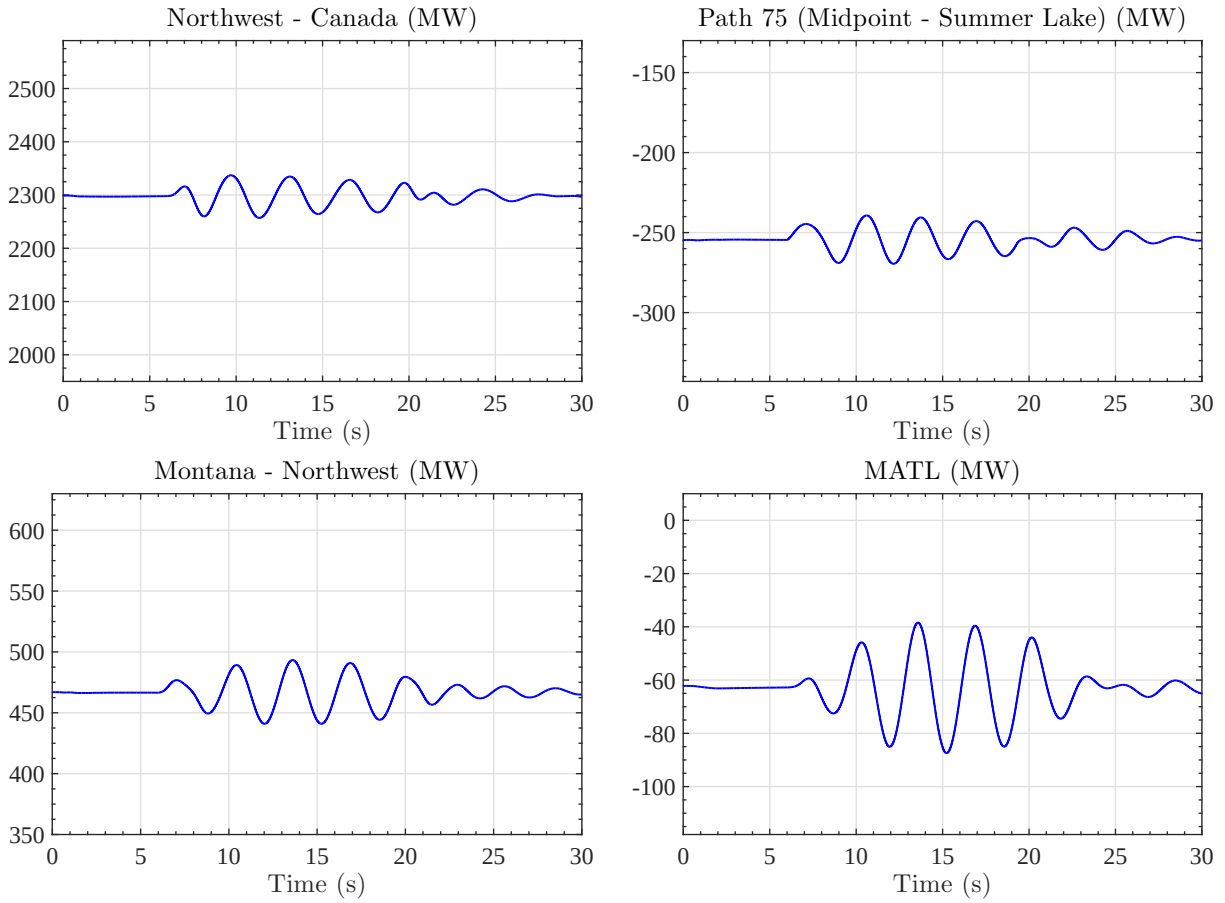


Figure 154. Active power flows. Event: SF 0.3/4x with amplitude of 125MW.

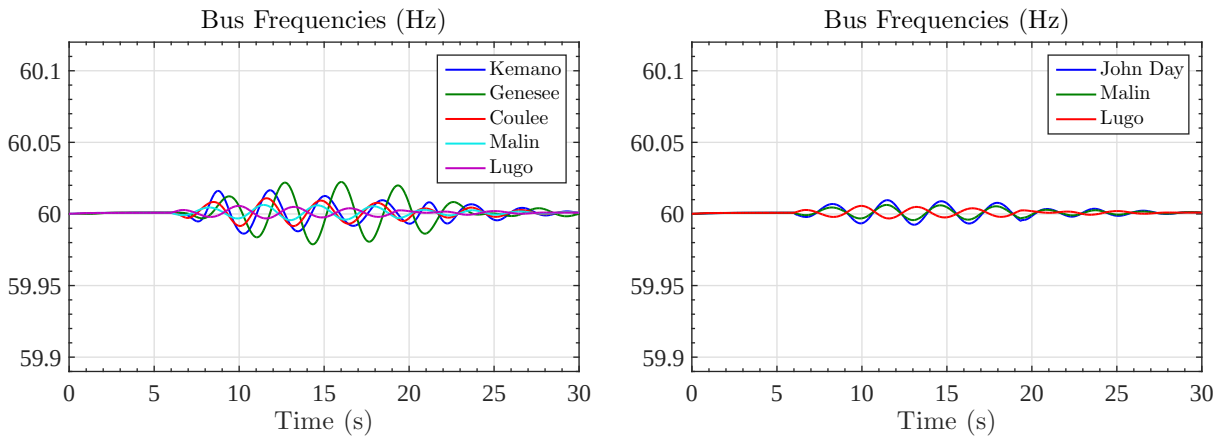


Figure 155. Bus frequencies. Event: SF 0.3/4x with amplitude of 125MW.

3.1.7. *Test System: Heavy Summer 2016. Controller Open Loop Event: SF 1.0/4x with amplitude of 125MW*

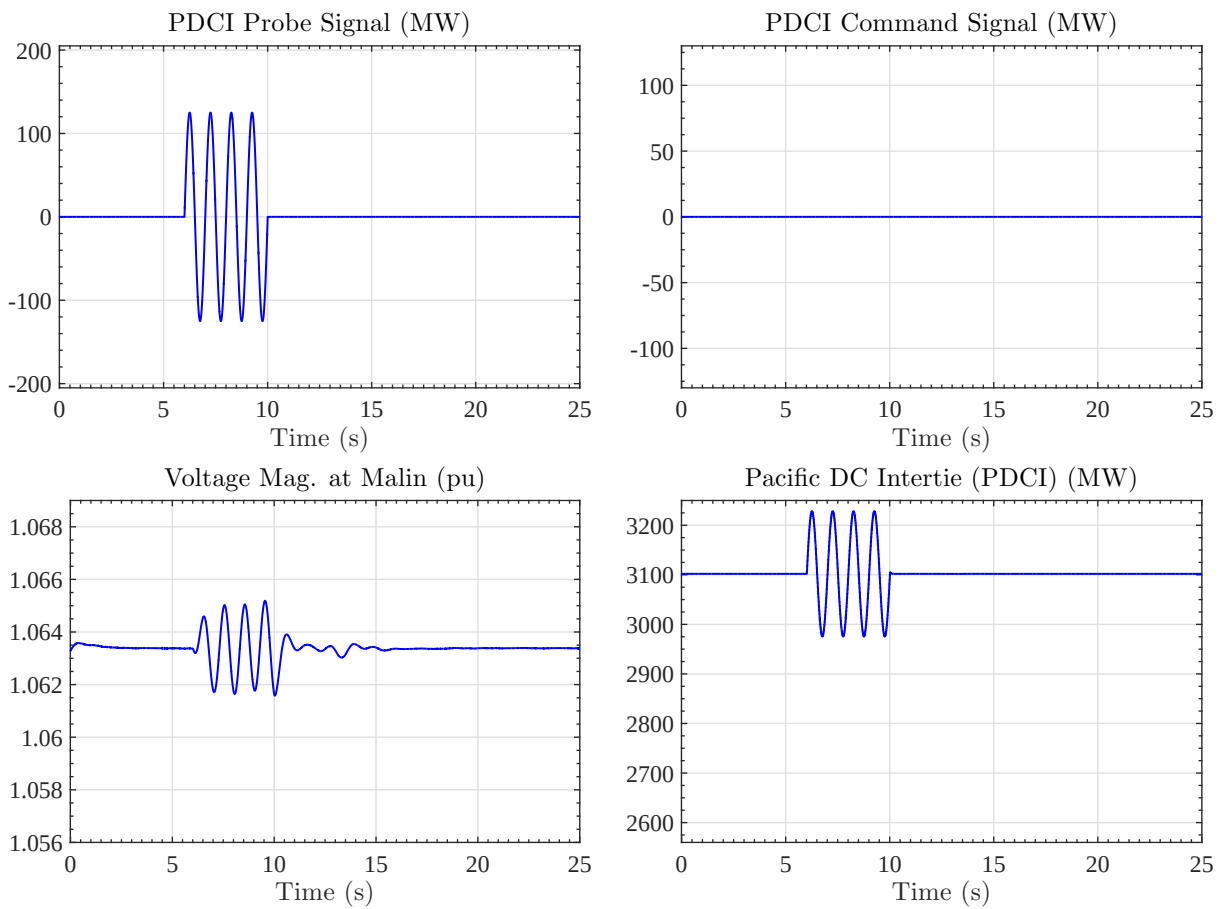


Figure 156. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 1.0/4x with amplitude of 125MW.

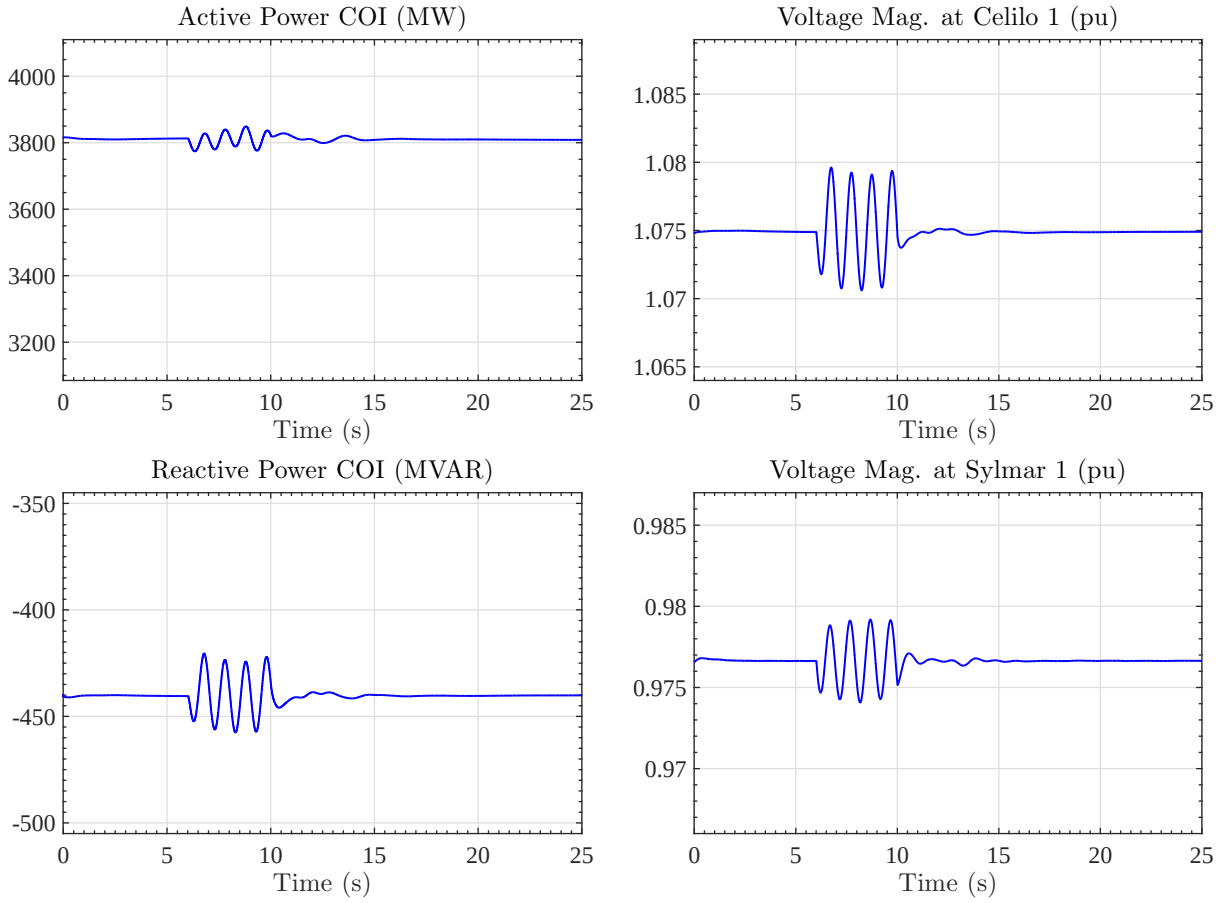


Figure 157. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 1.0/4x with amplitude of 125MW.

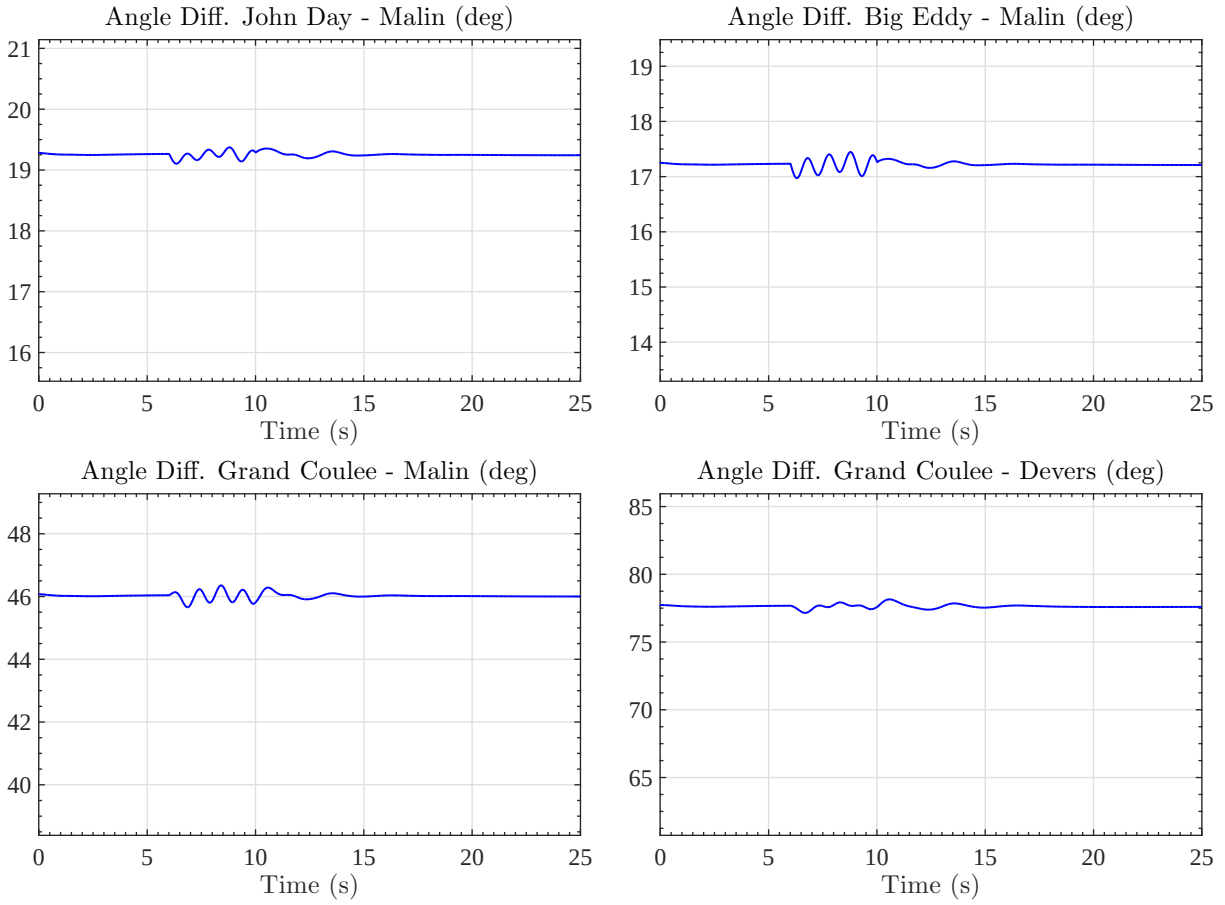


Figure 158. Angle differences. Event: SF 1.0/4x with amplitude of 125MW.

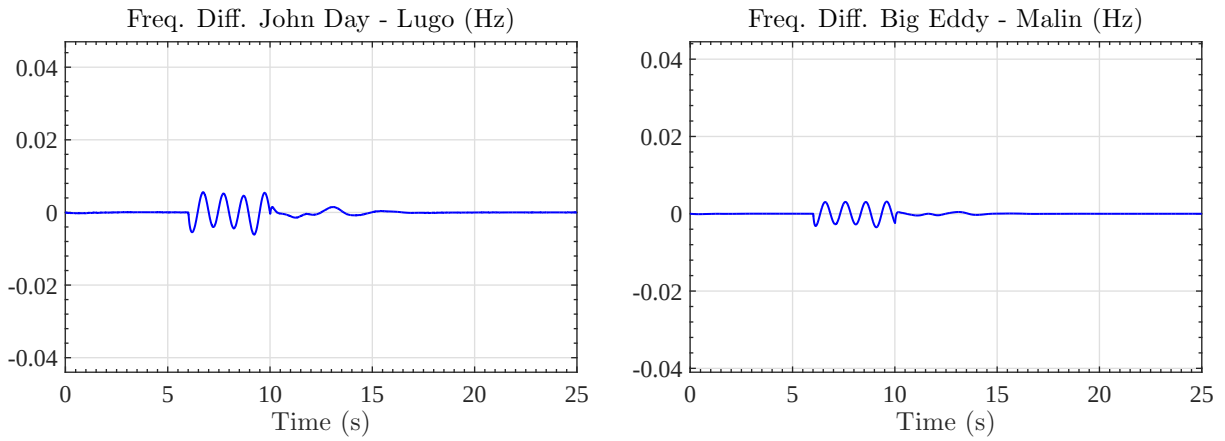


Figure 159. Frequency differences. Event: SF 1.0/4x with amplitude of 125MW.

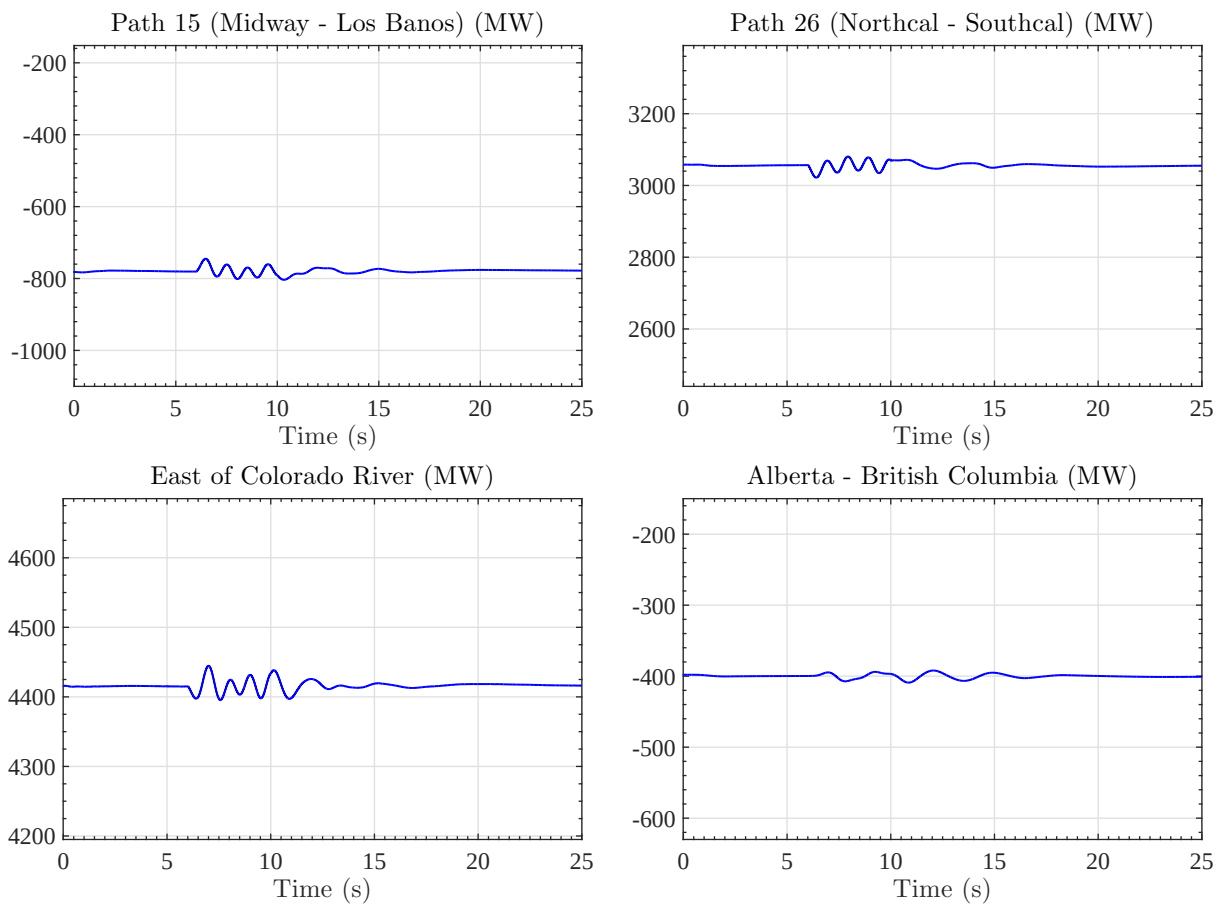


Figure 160. Active power flows. Event: SF 1.0/4x with amplitude of 125MW.

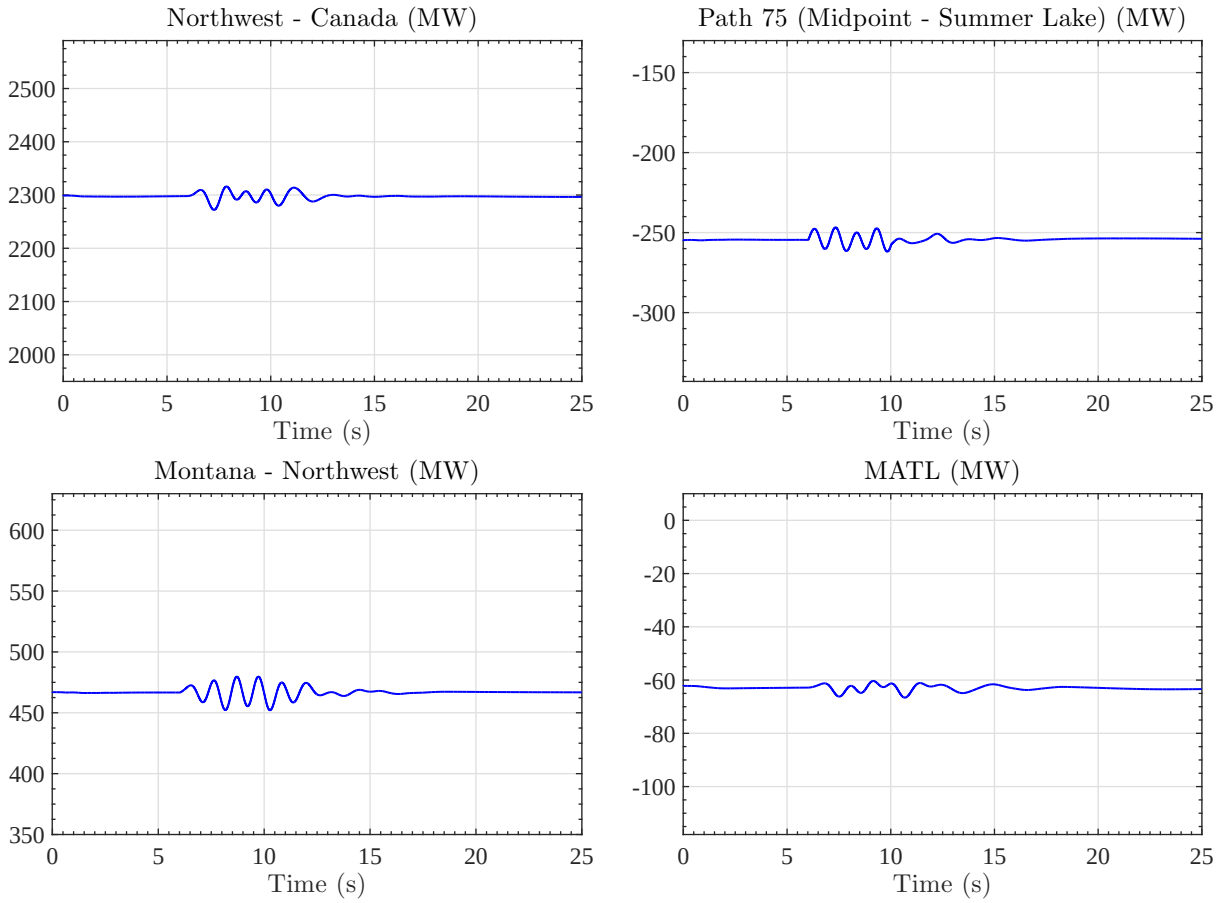


Figure 161. Active power flows. Event: SF 1.0/4x with amplitude of 125MW.

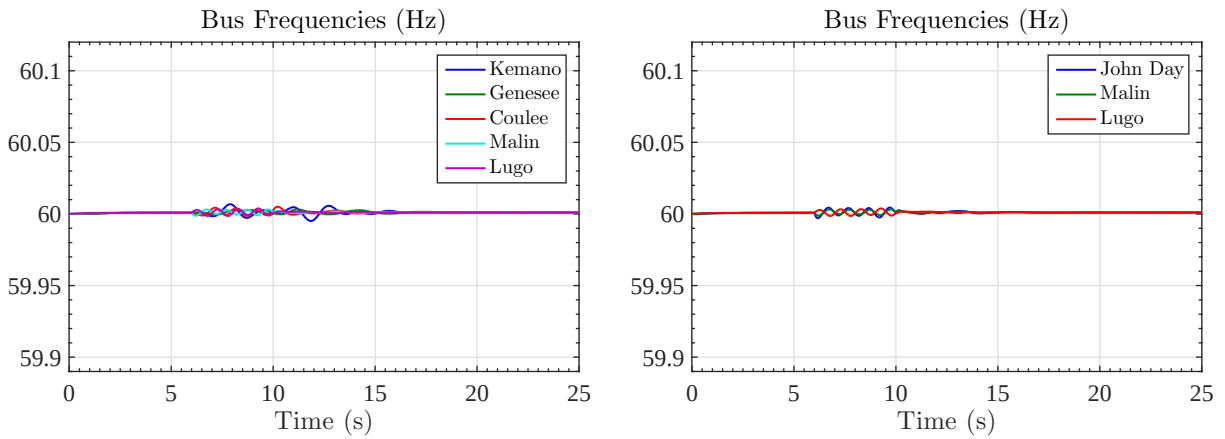


Figure 162. Bus frequencies. Event: SF 1.0/4x with amplitude of 125MW.

3.2. Closed Loop Testing

3.2.1. Test System: Heavy Summer 2016. Event: Chief Joe Brake

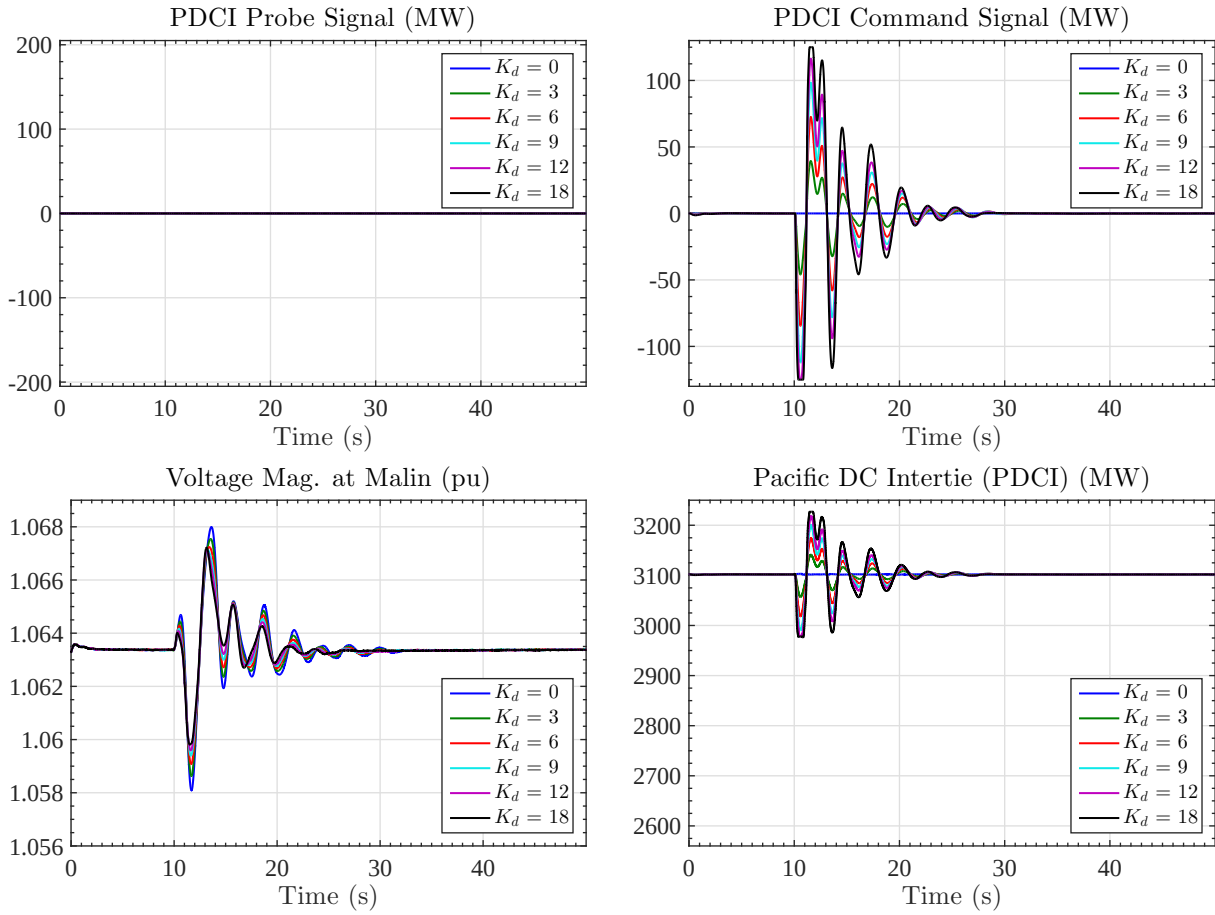


Figure 163. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake.

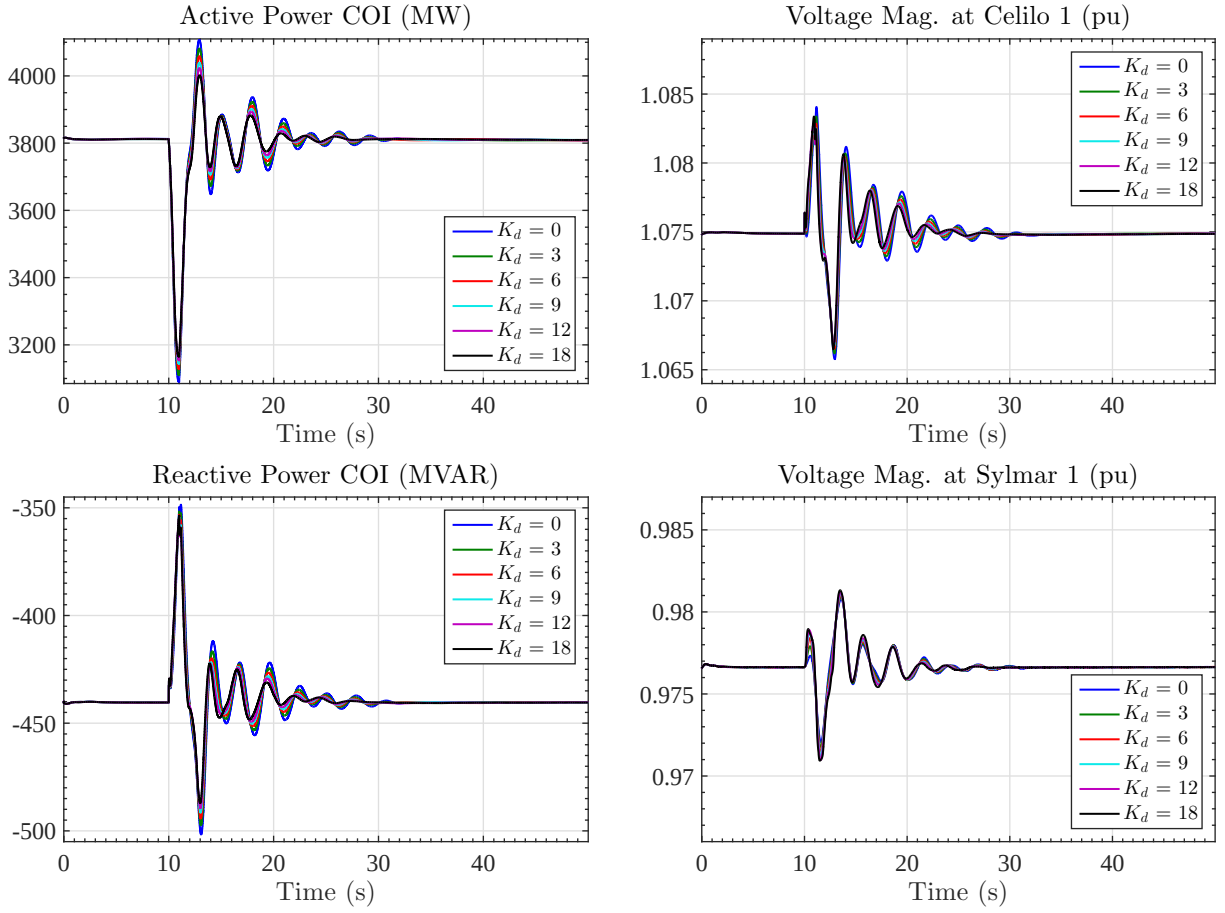


Figure 164. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake.

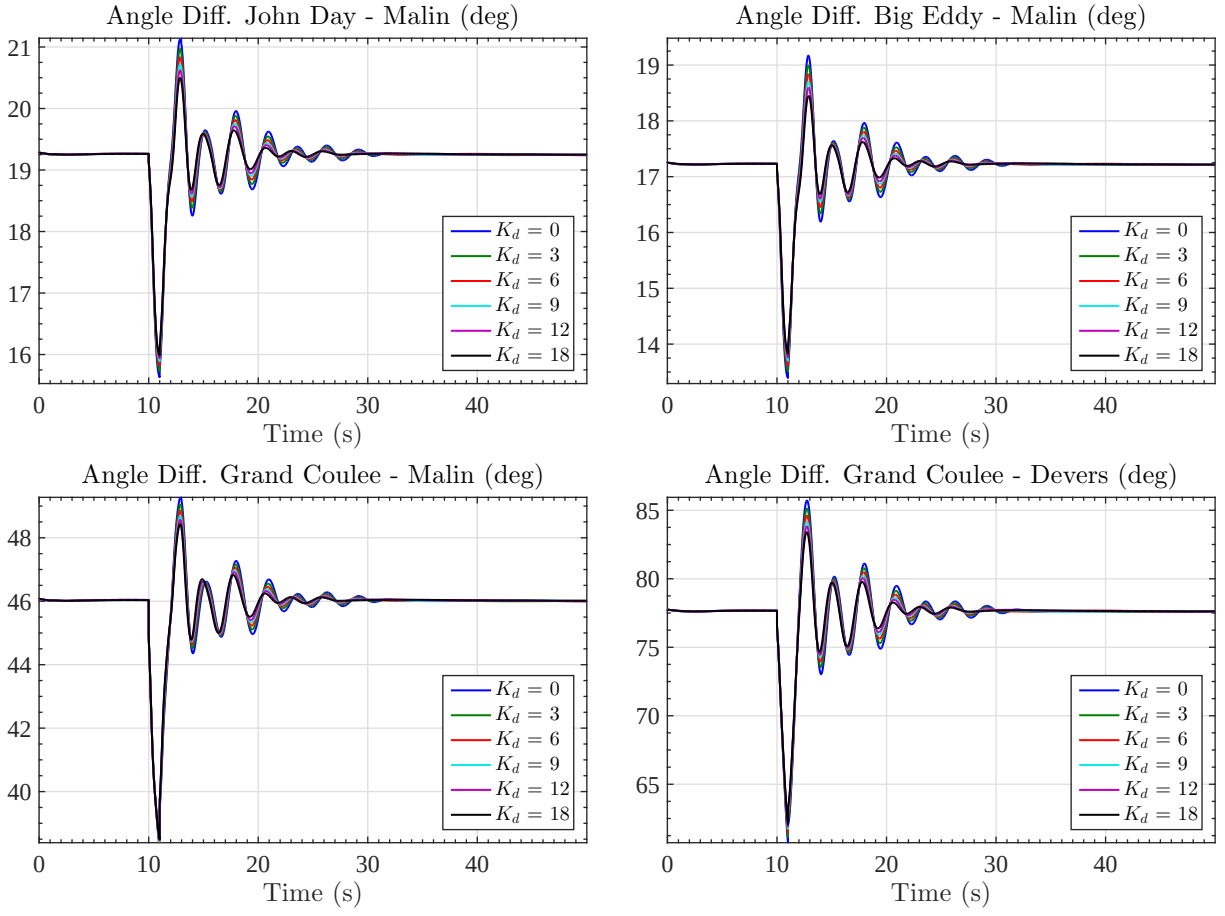


Figure 165. Angle differences. Event: Chief Joe Brake.

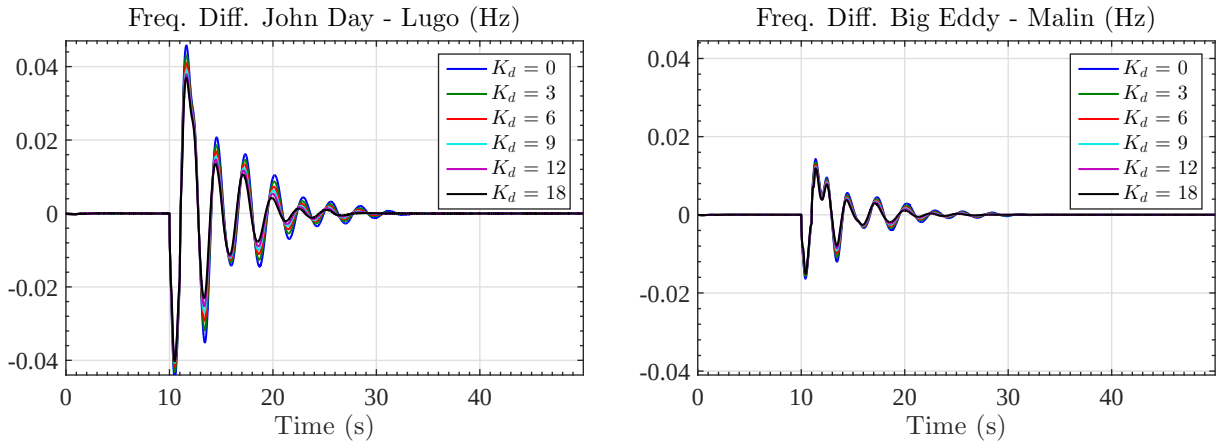


Figure 166. Frequency differences. Event: Chief Joe Brake.

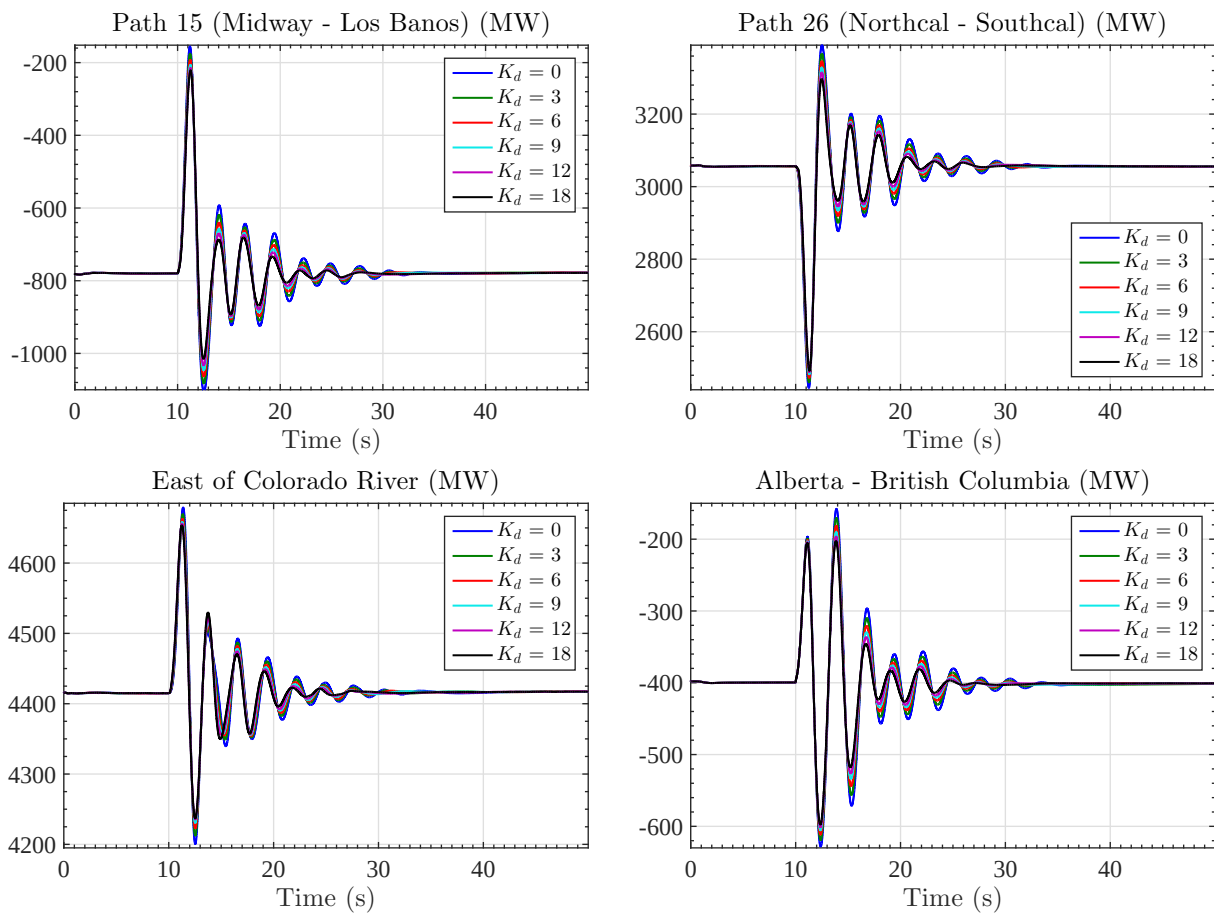


Figure 167. Active power flows. Event: Chief Joe Brake.

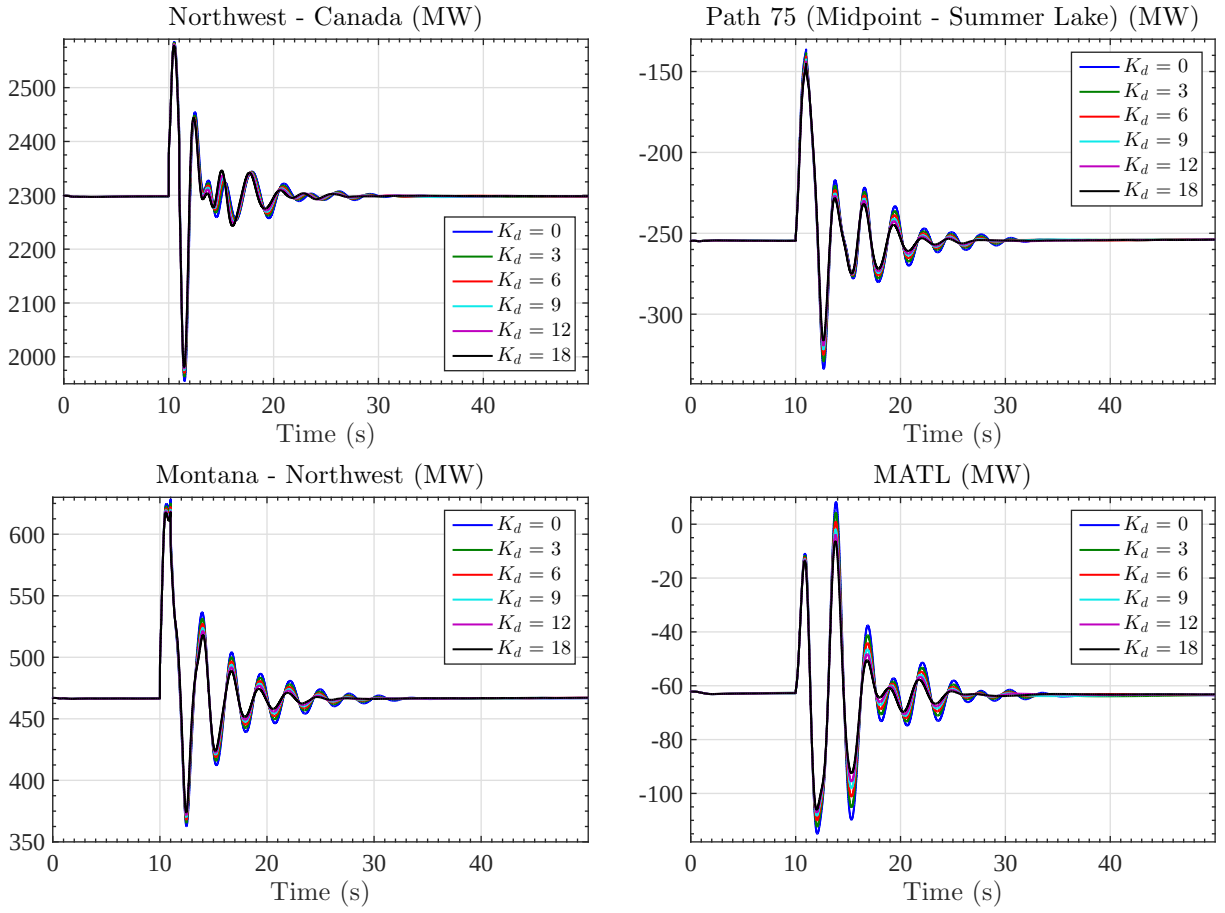


Figure 168. Active power flows. Event: Chief Joe Brake.

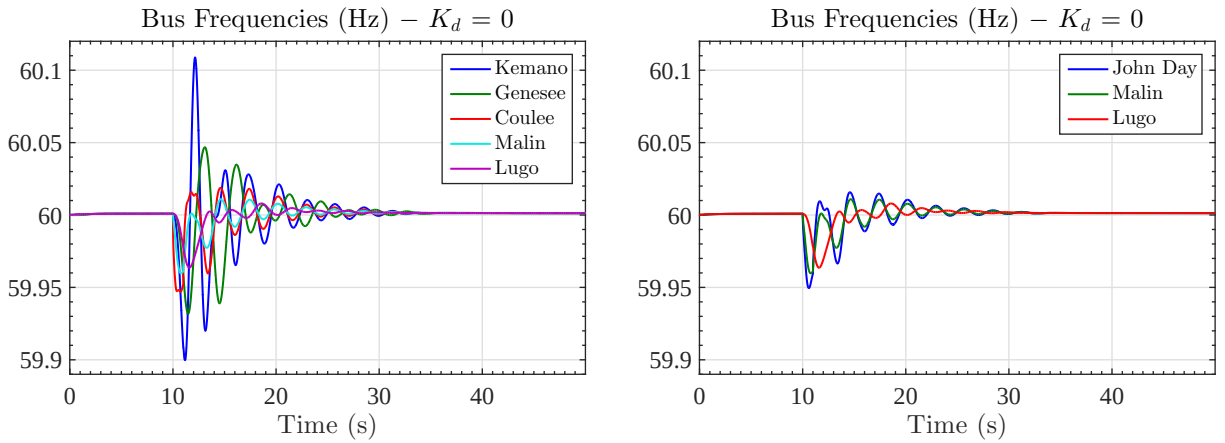


Figure 169. Bus frequencies. Event: Chief Joe Brake.

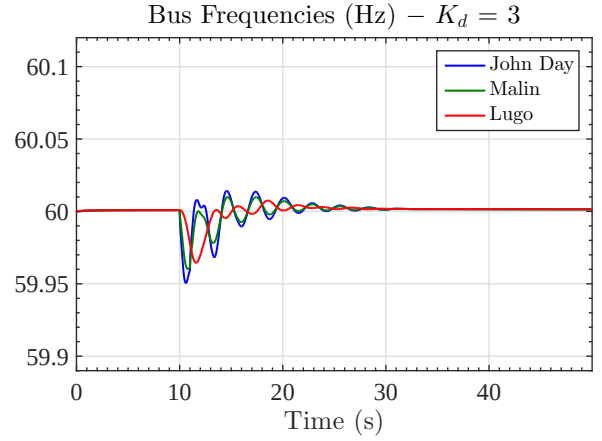
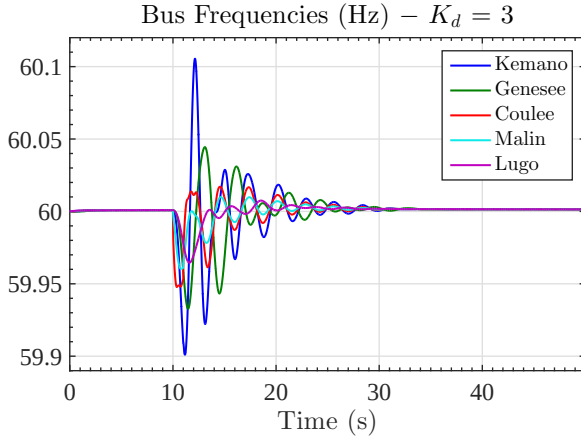


Figure 170. Bus frequencies. Event: Chief Joe Brake.

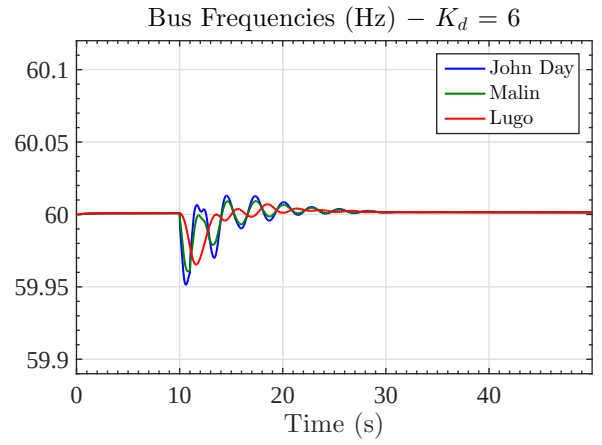
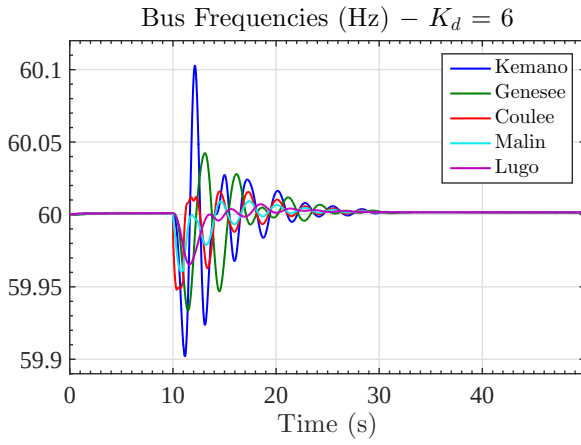


Figure 171. Bus frequencies. Event: Chief Joe Brake.

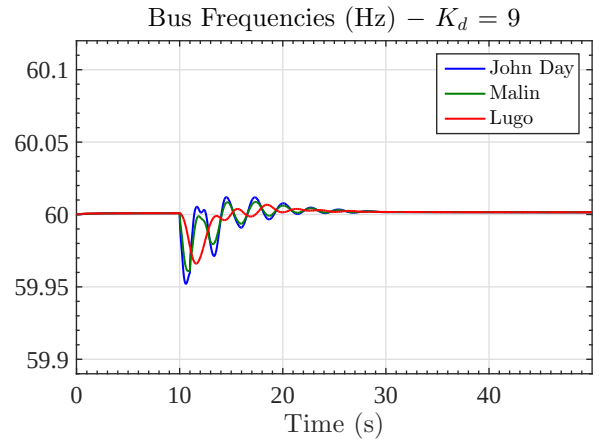
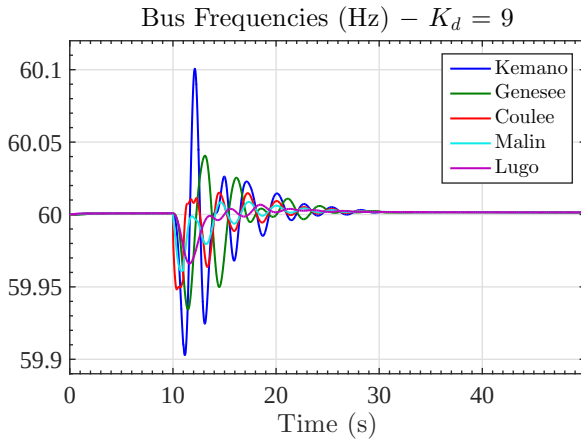


Figure 172. Bus frequencies. Event: Chief Joe Brake.

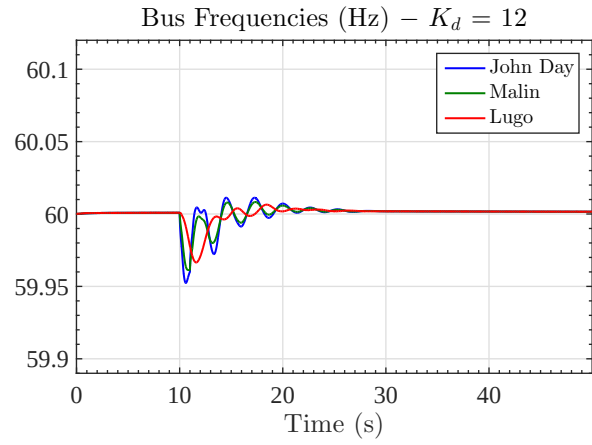
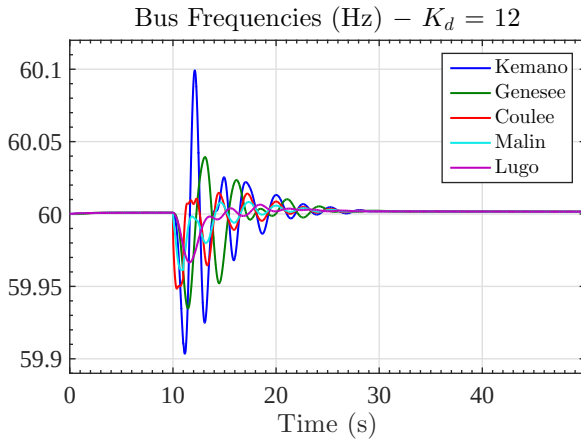


Figure 173. Bus frequencies. Event: Chief Joe Brake.

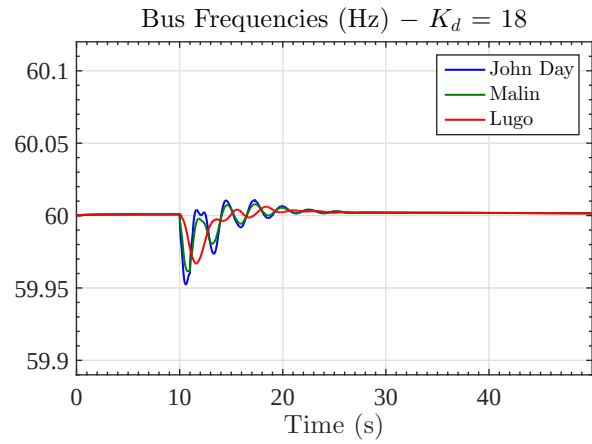
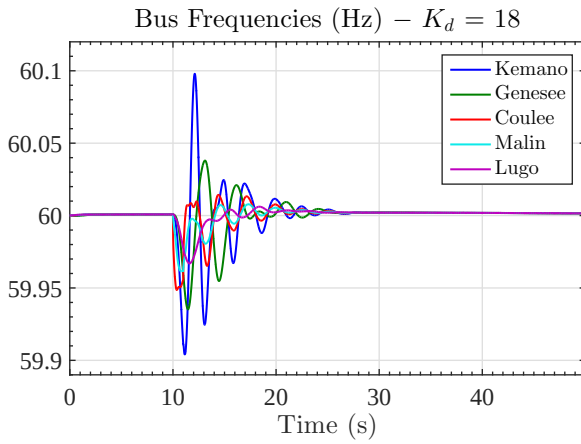


Figure 174. Bus frequencies. Event: Chief Joe Brake.

3.2.2. Test System: Heavy Summer 2016. Event: 200 MW pulses

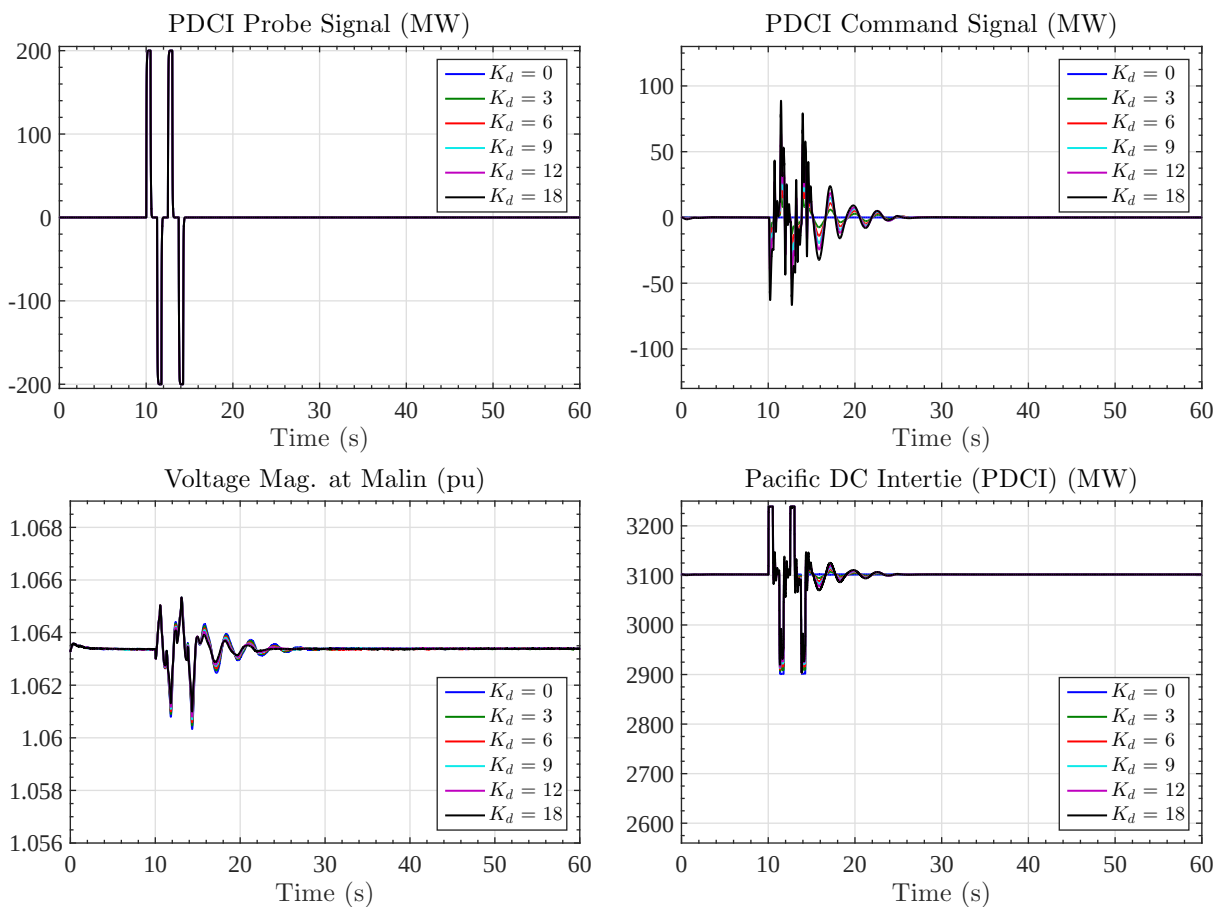


Figure 175. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses.

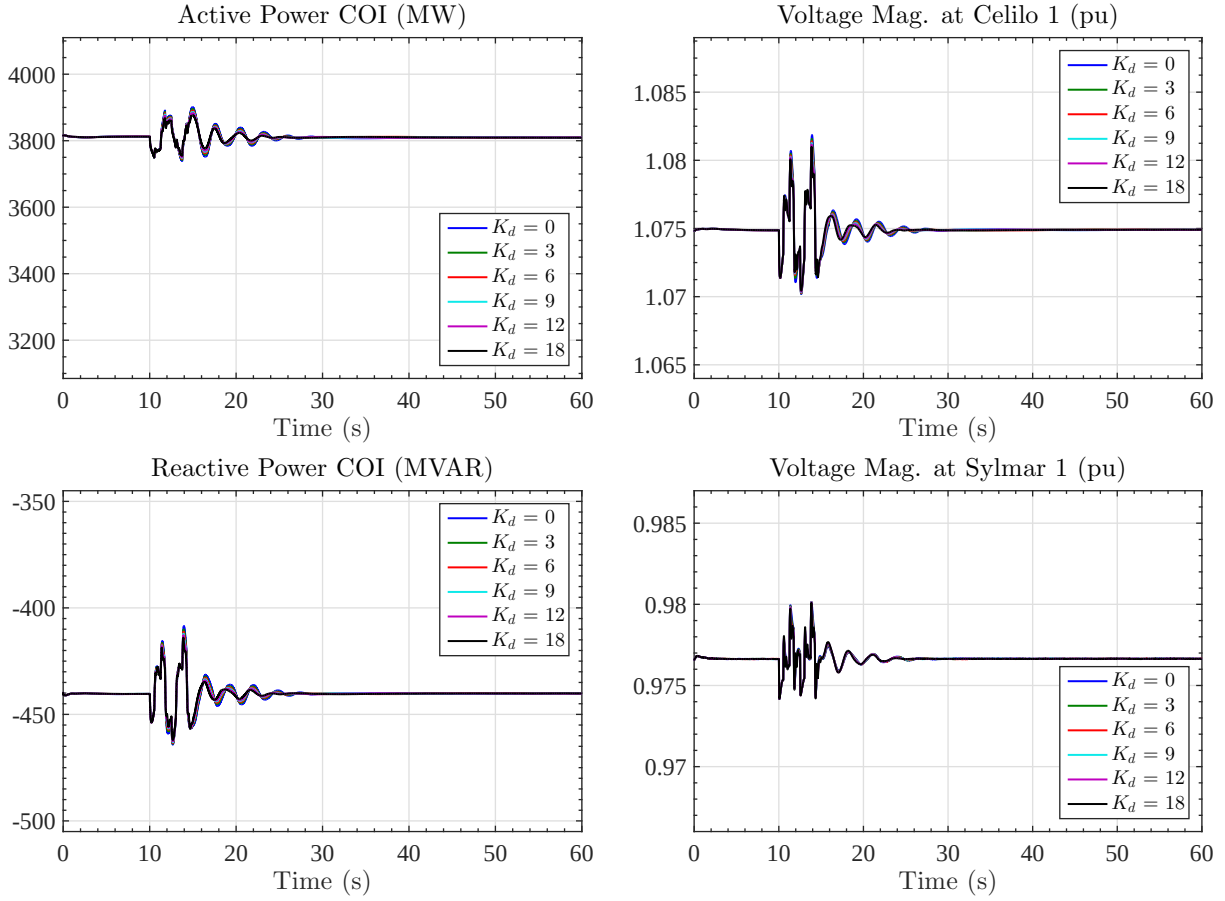


Figure 176. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses.

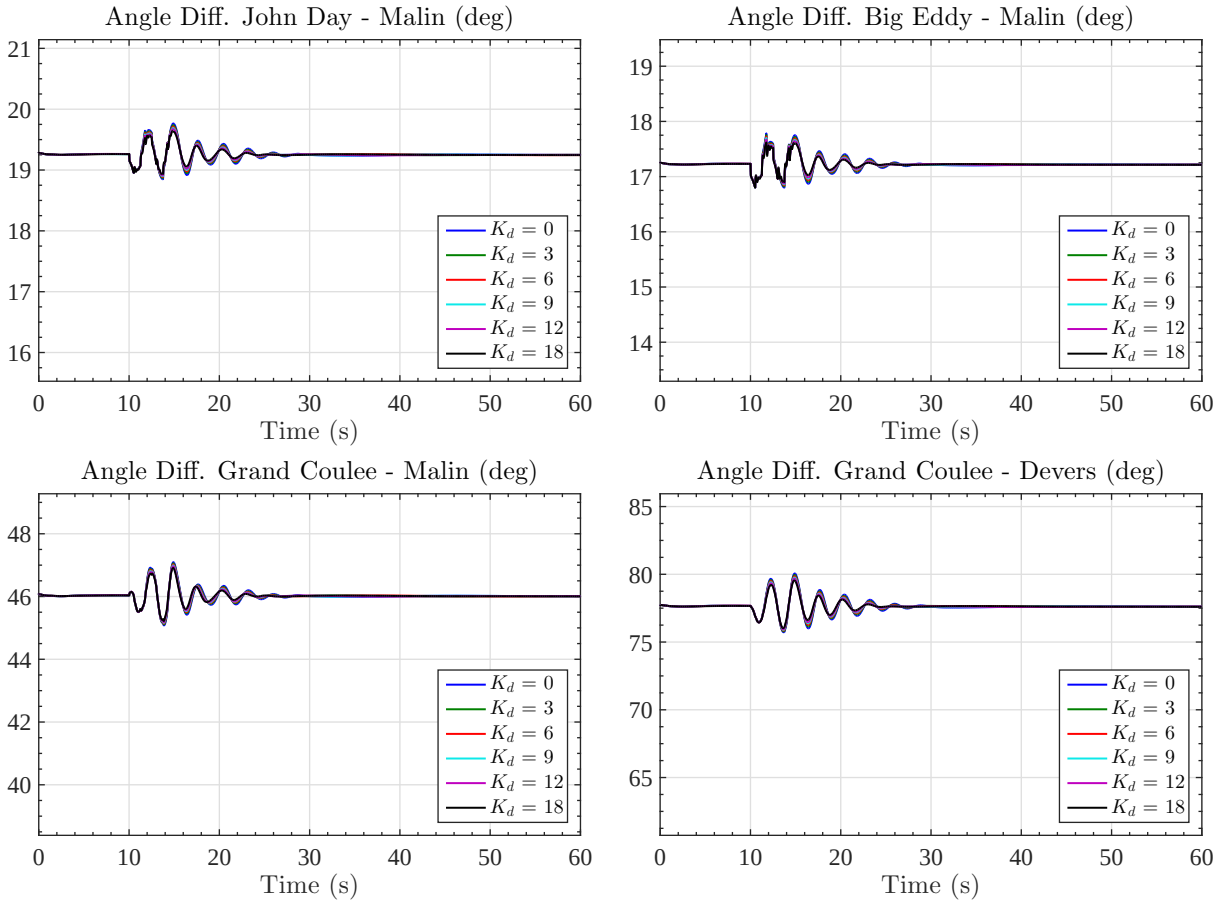


Figure 177. Angle differences. Event: 200 MW pulses.

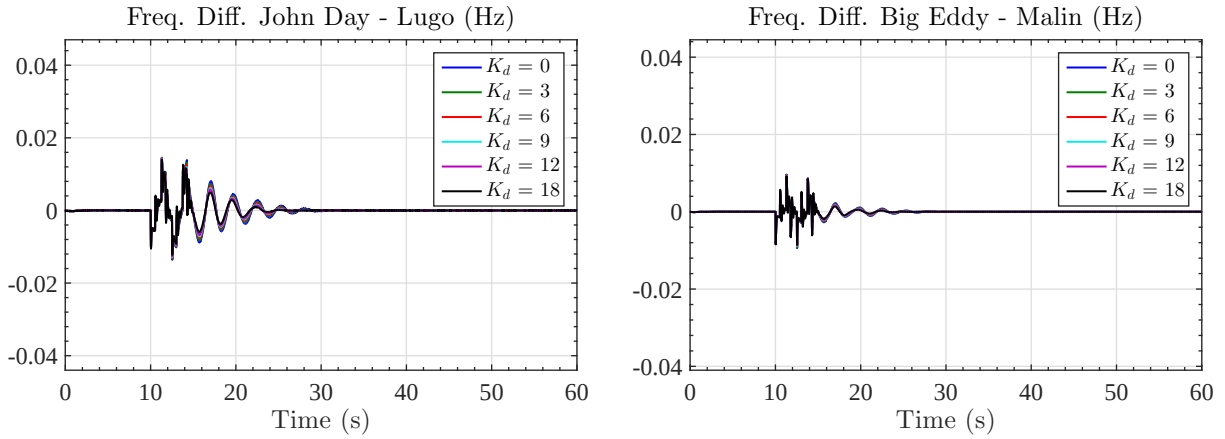


Figure 178. Frequency differences. Event: 200 MW pulses.

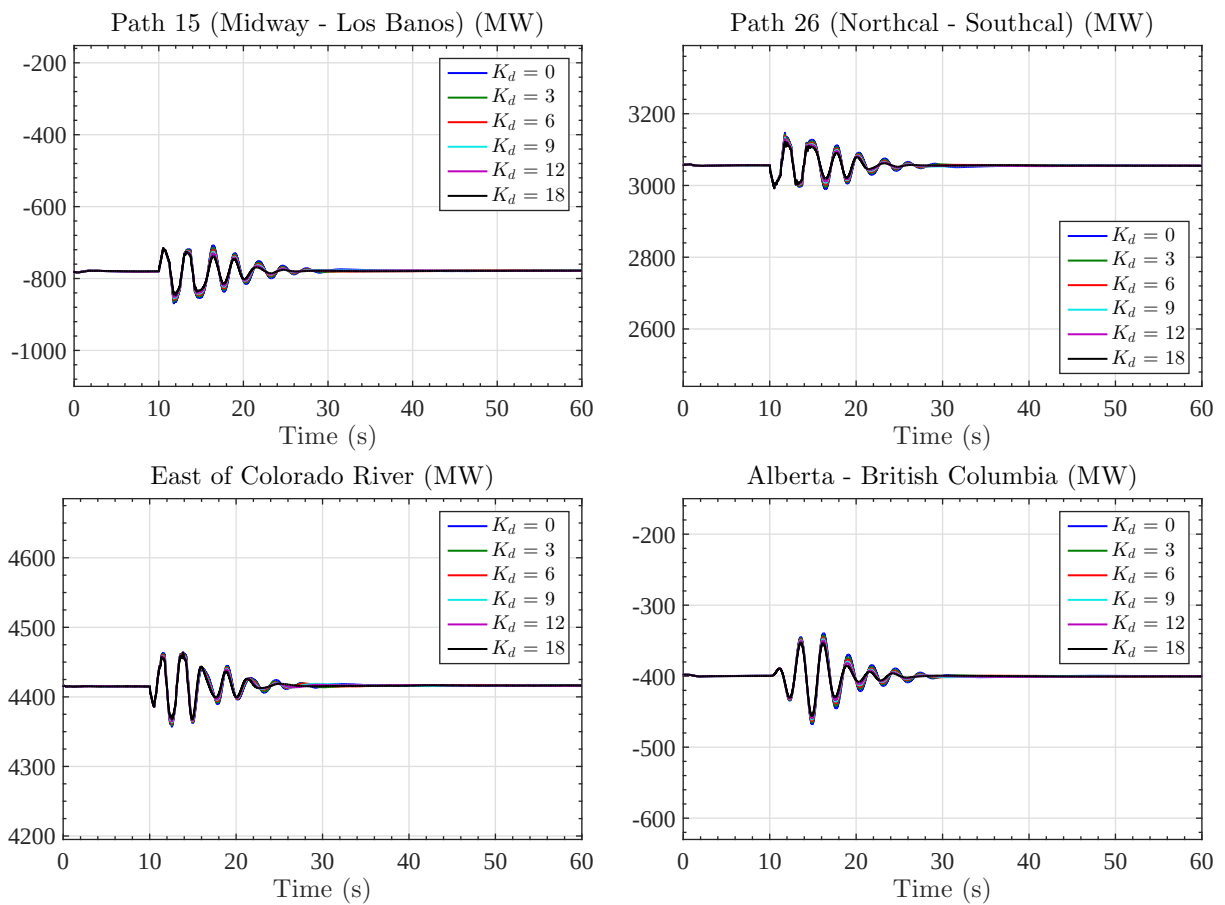


Figure 179. Active power flows. Event: 200 MW pulses.

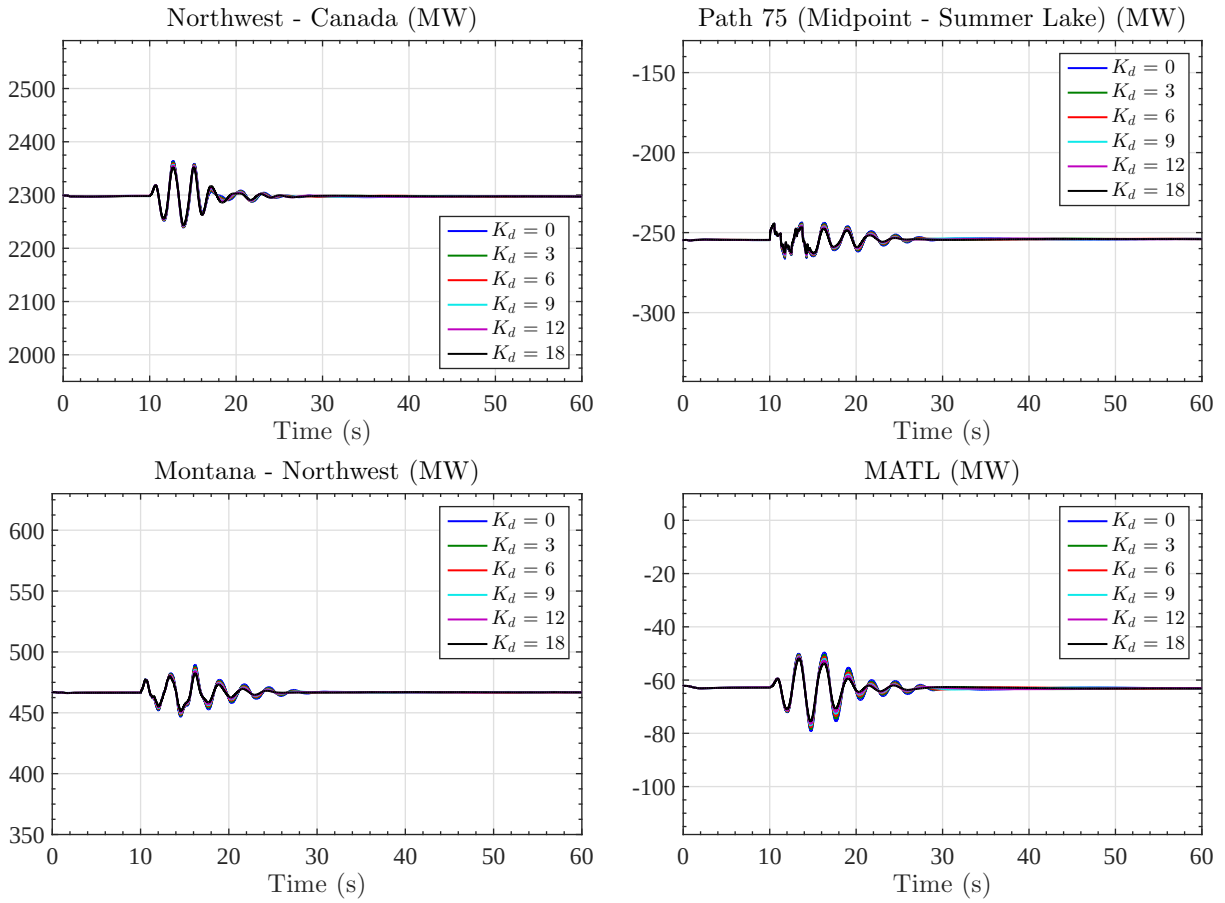


Figure 180. Active power flows. Event: 200 MW pulses.

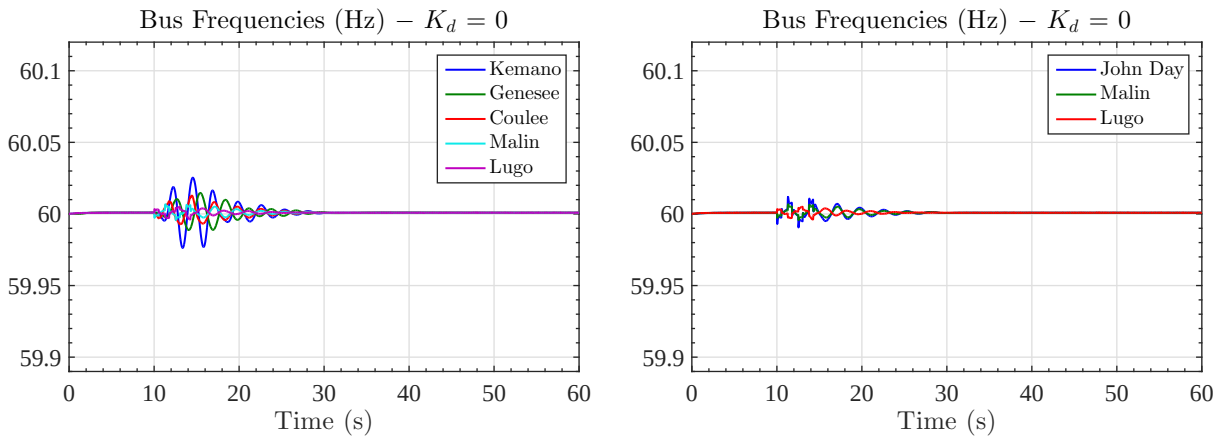


Figure 181. Bus frequencies. Event: 200 MW pulses.

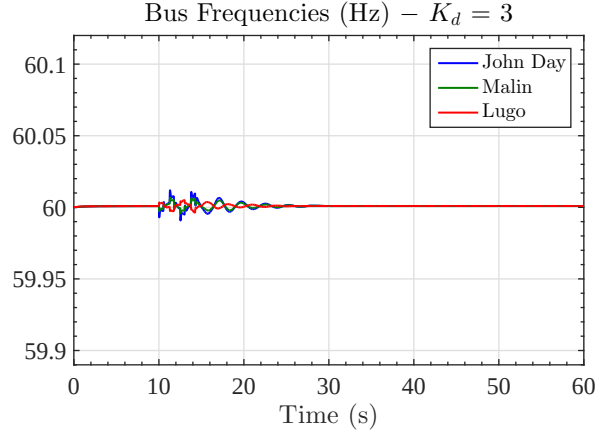
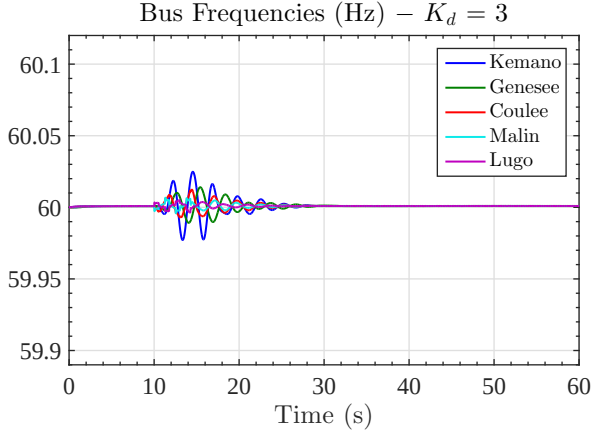


Figure 182. Bus frequencies. Event: 200 MW pulses.

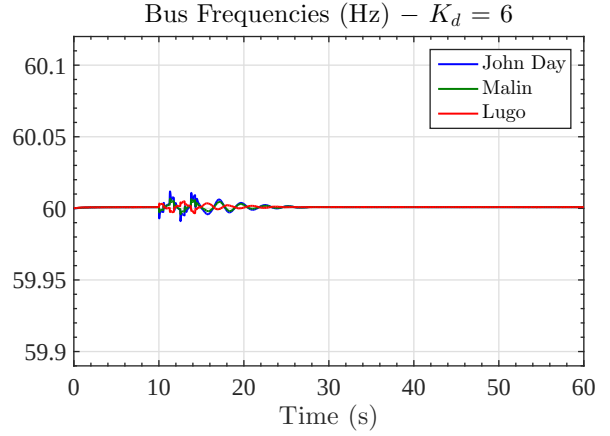
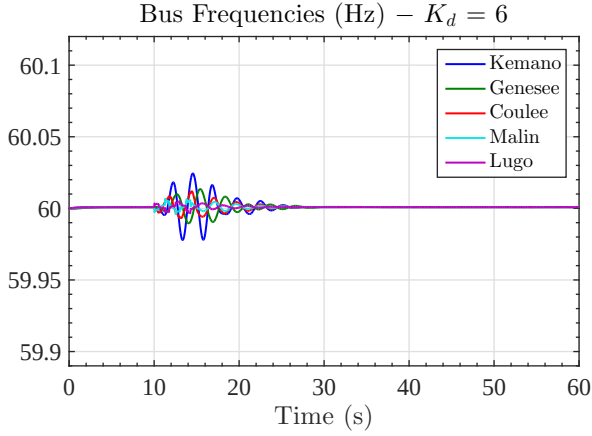


Figure 183. Bus frequencies. Event: 200 MW pulses.

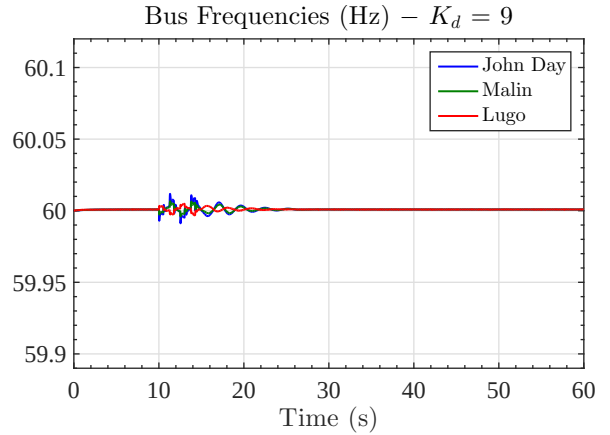
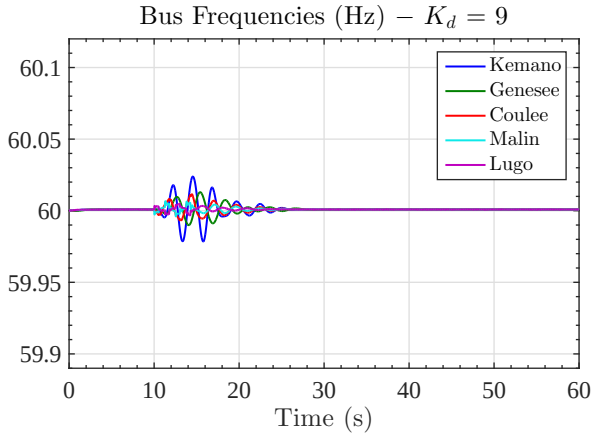


Figure 184. Bus frequencies. Event: 200 MW pulses.

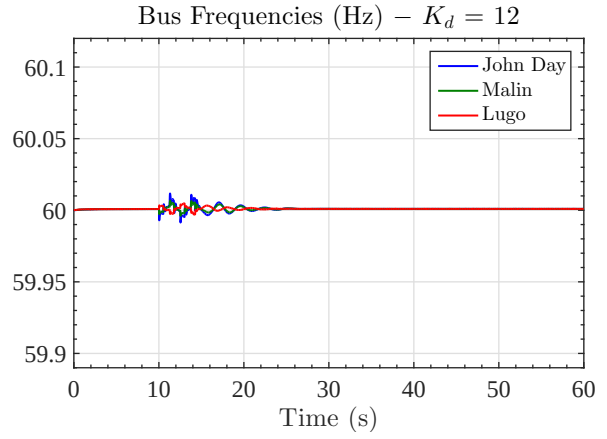
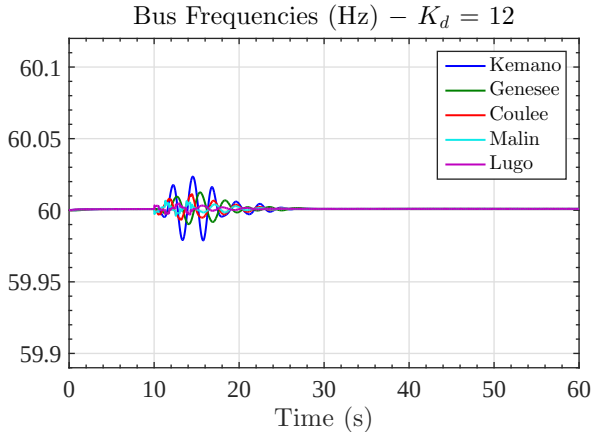


Figure 185. Bus frequencies. Event: 200 MW pulses.

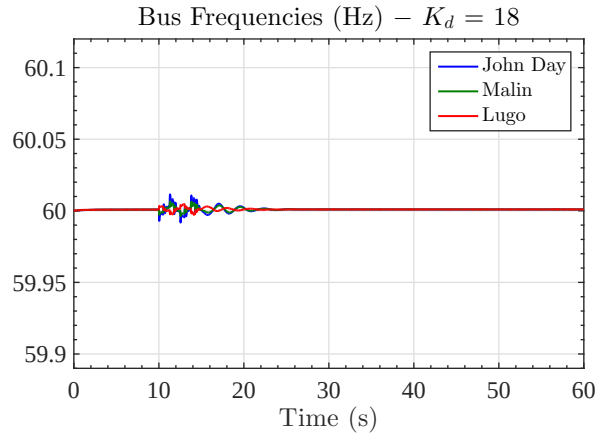
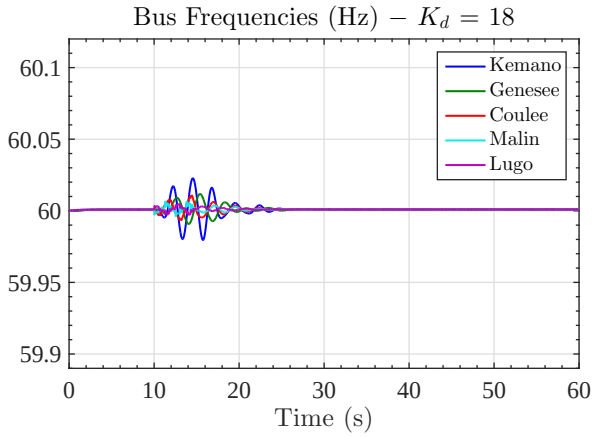


Figure 186. Bus frequencies. Event: 200 MW pulses.

3.2.3. Test System: Heavy Summer 2016. Event: 200 MW pulses with control limit of 50 MW

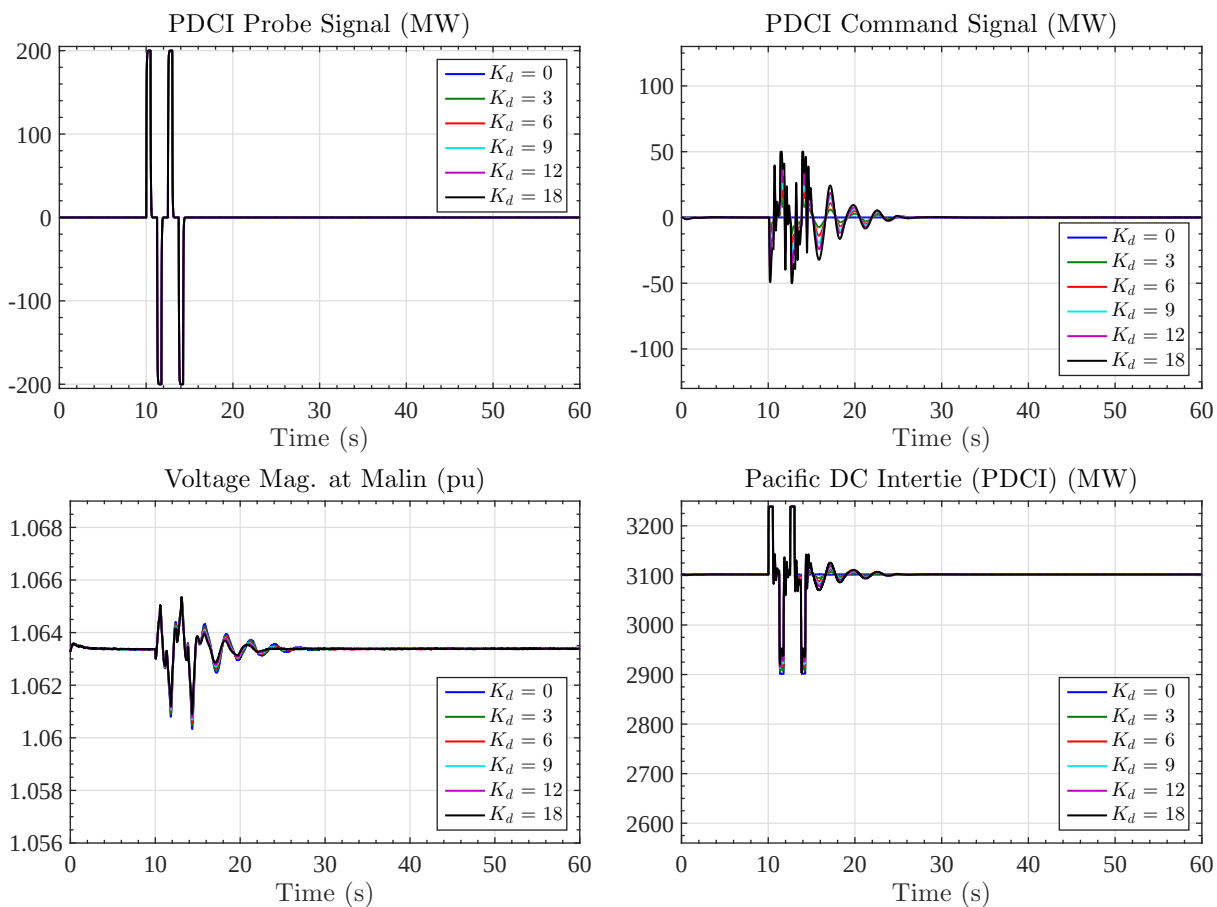


Figure 187. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses with control limit of 50 MW.

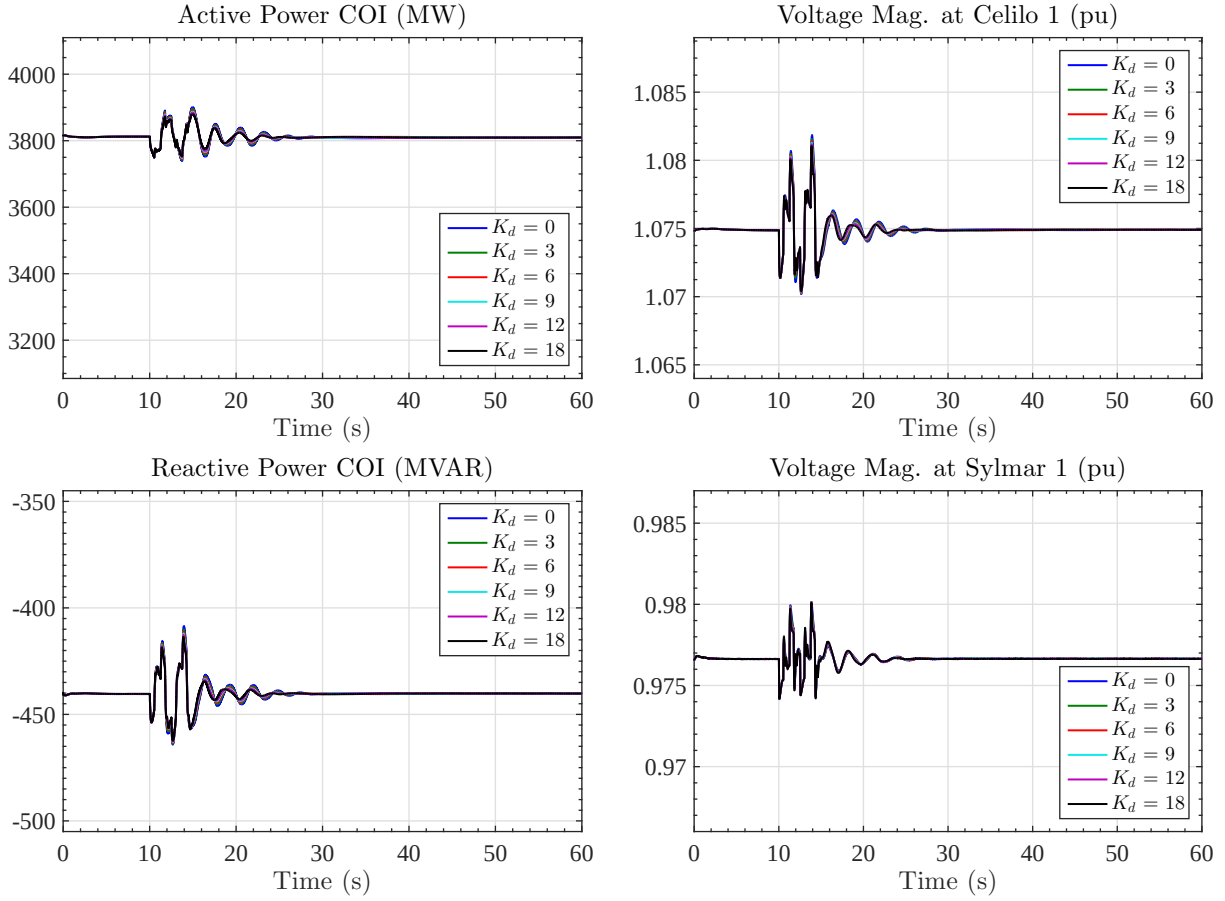


Figure 188. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses with control limit of 50 MW.

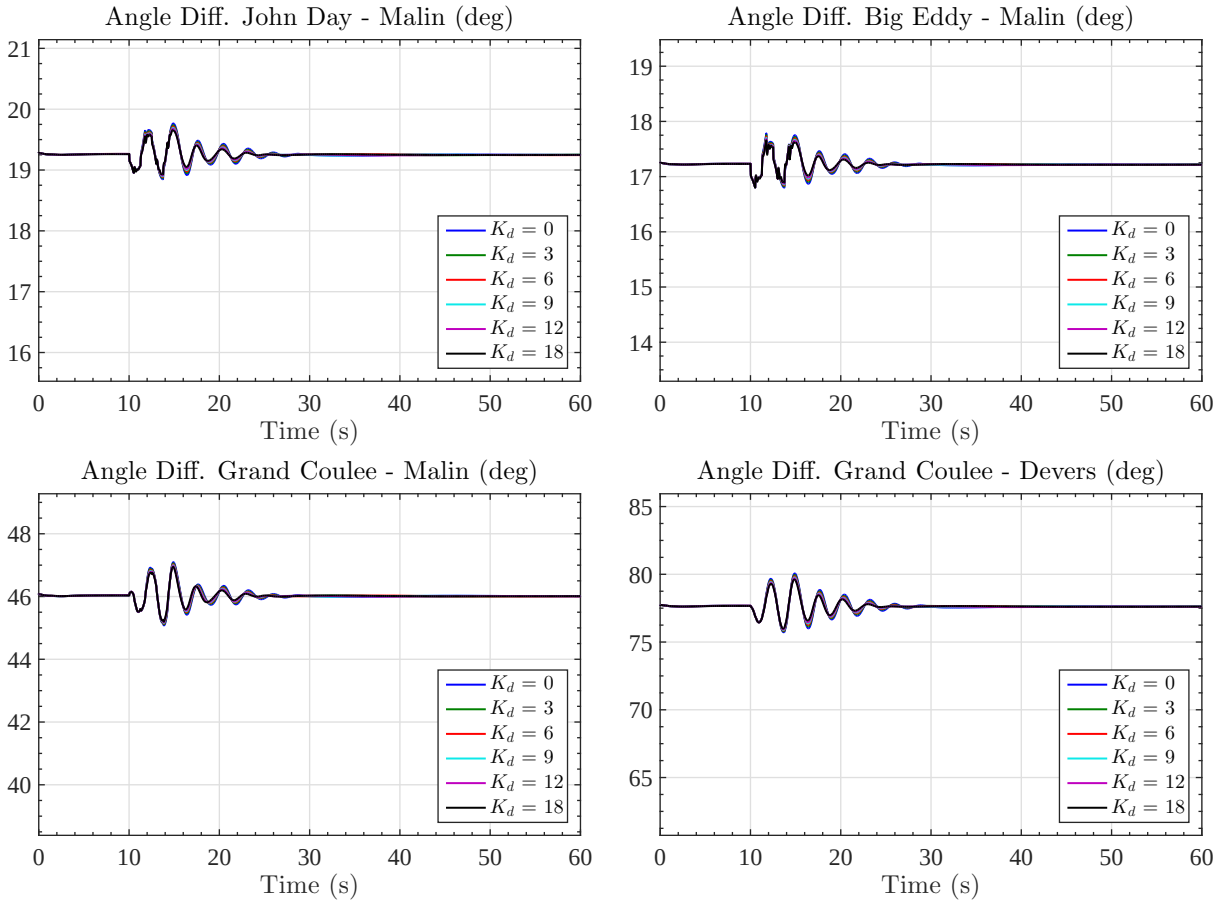


Figure 189. Angle differences. Event: 200 MW pulses with control limit of 50 MW.

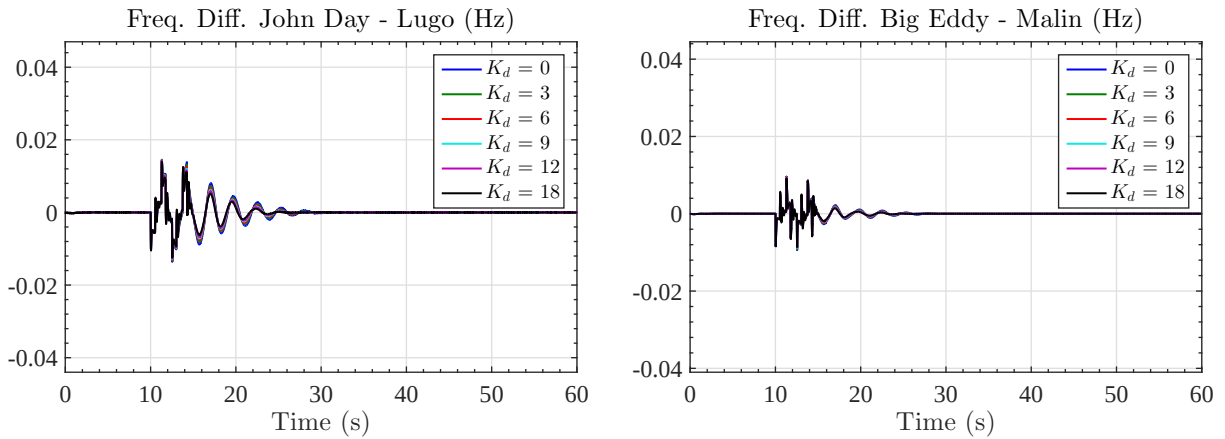


Figure 190. Frequency differences. Event: 200 MW pulses with control limit of 50 MW.

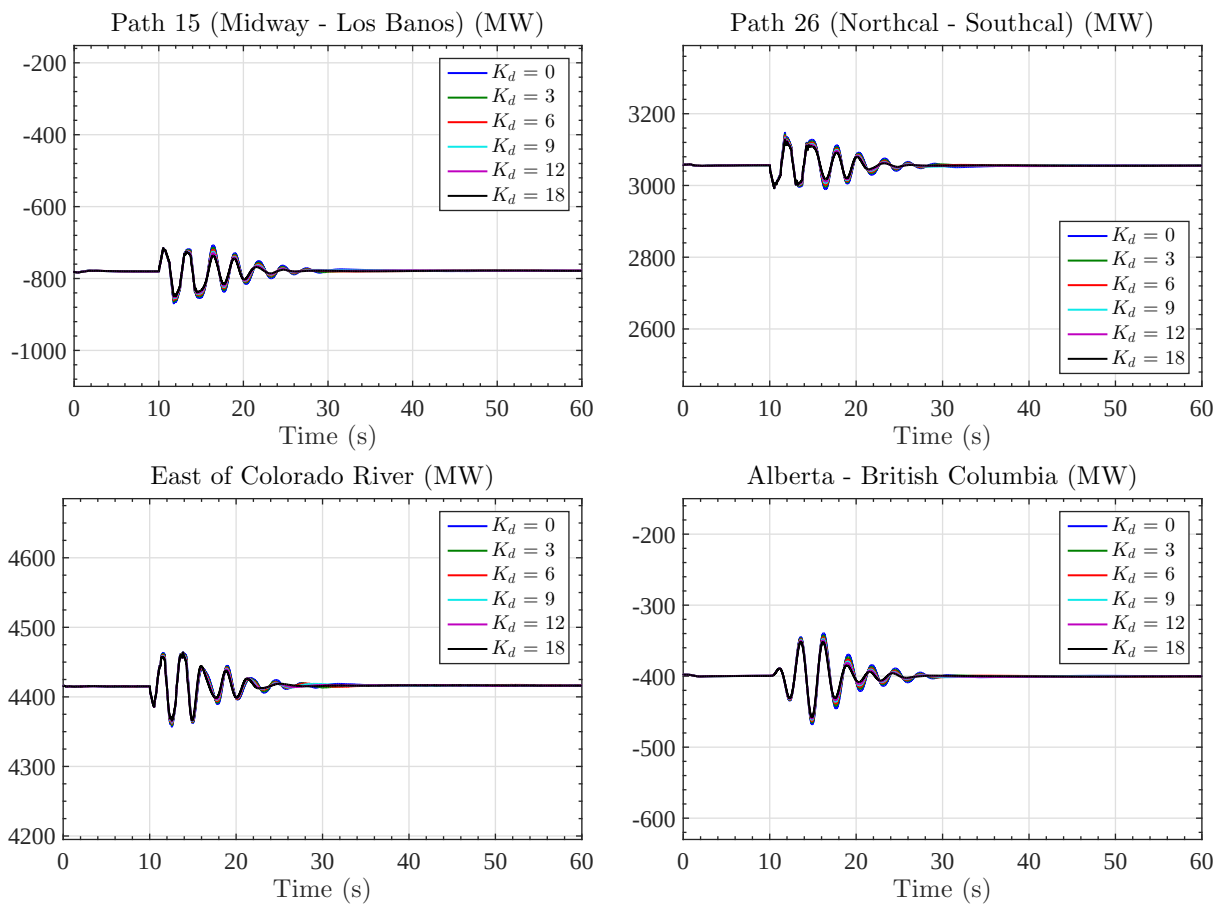


Figure 191. Active power flows. Event: 200 MW pulses with control limit of 50 MW.

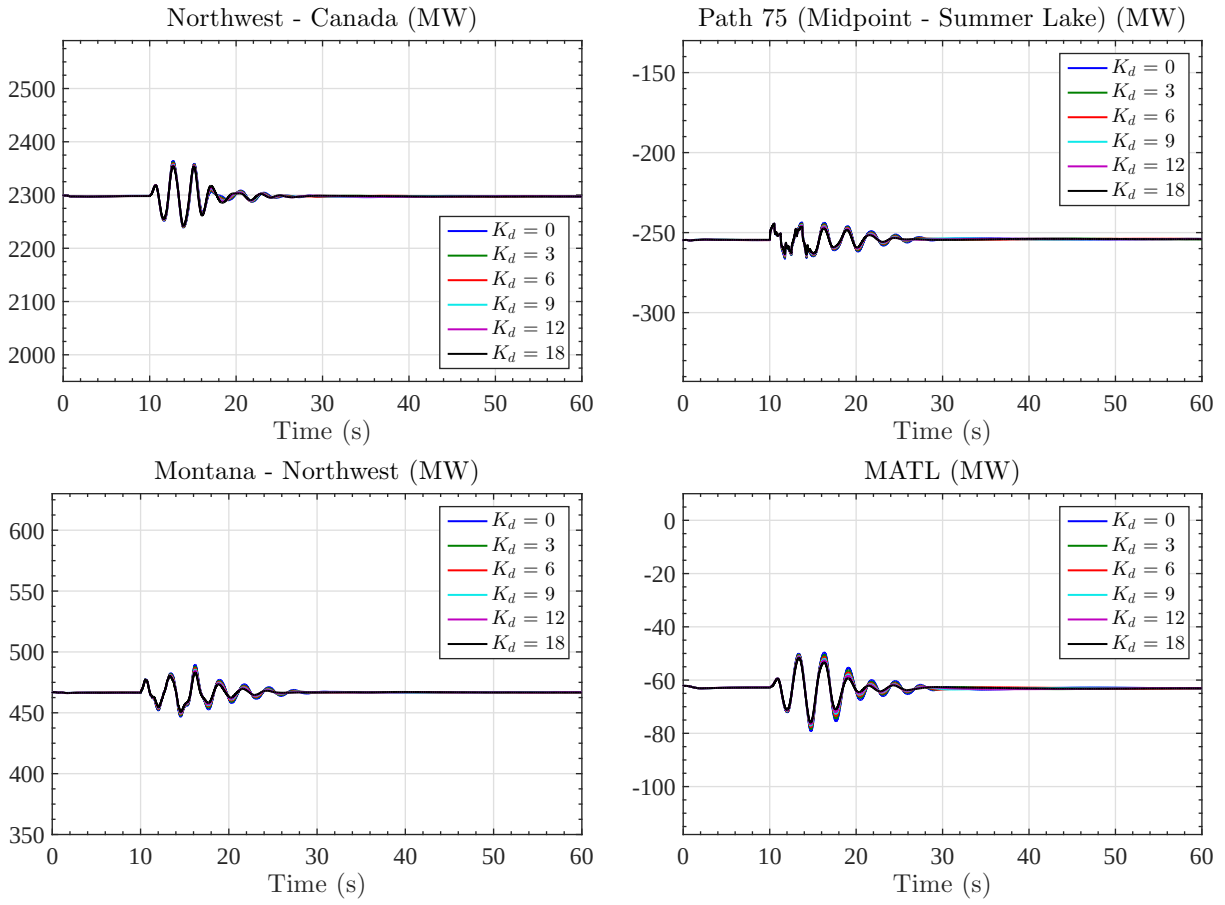


Figure 192. Active power flows. Event: 200 MW pulses with control limit of 50 MW.

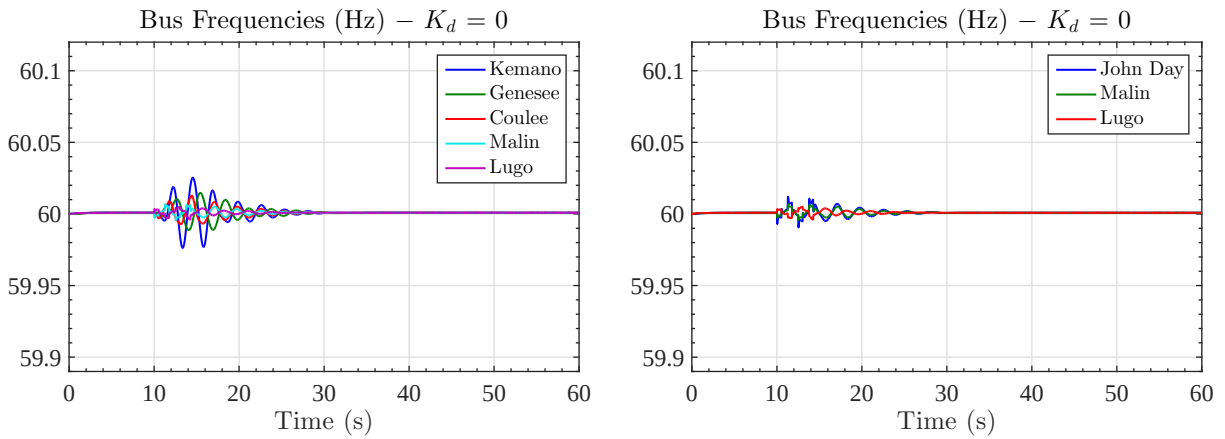


Figure 193. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

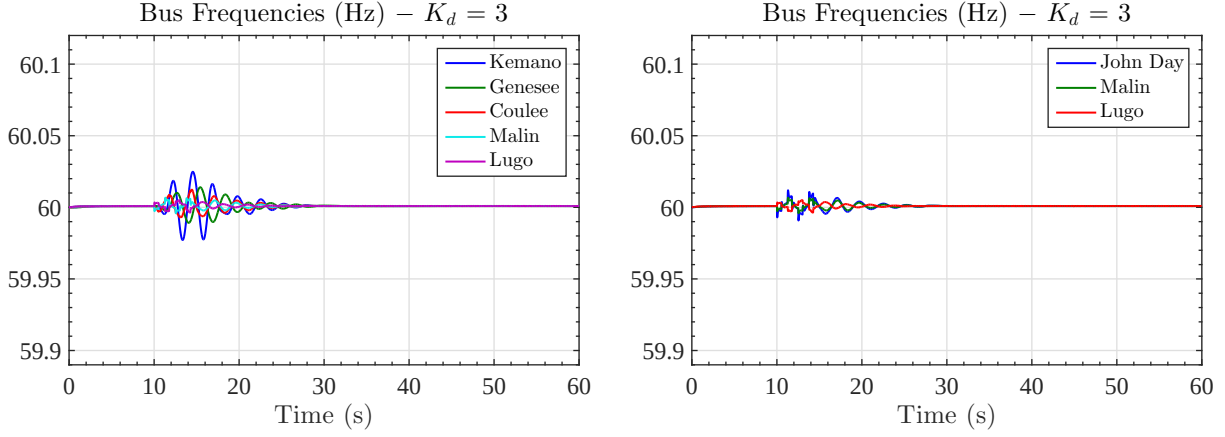


Figure 194. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

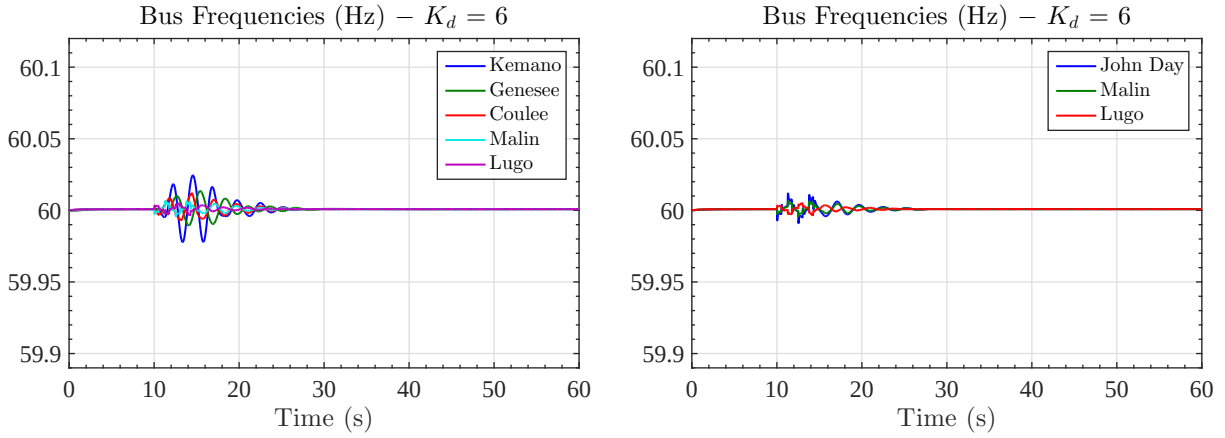


Figure 195. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

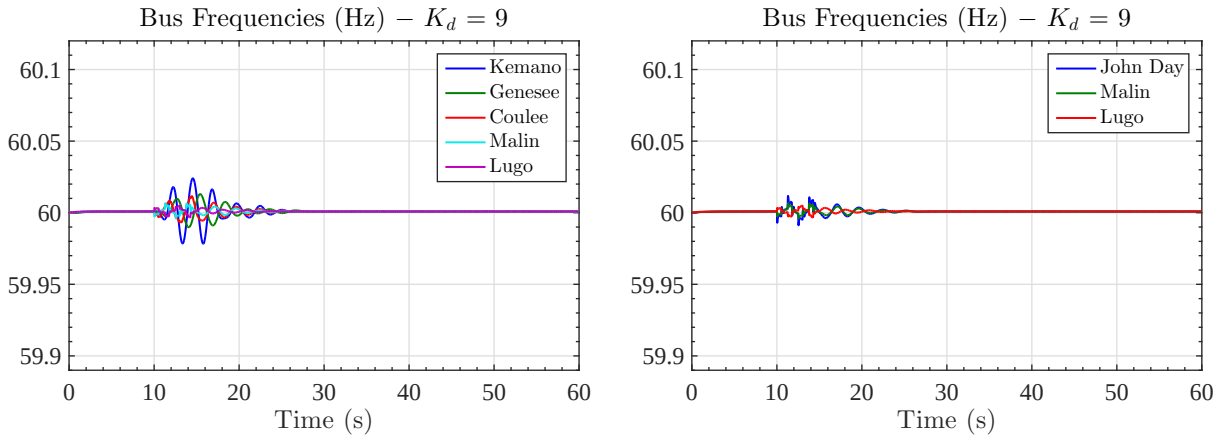


Figure 196. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

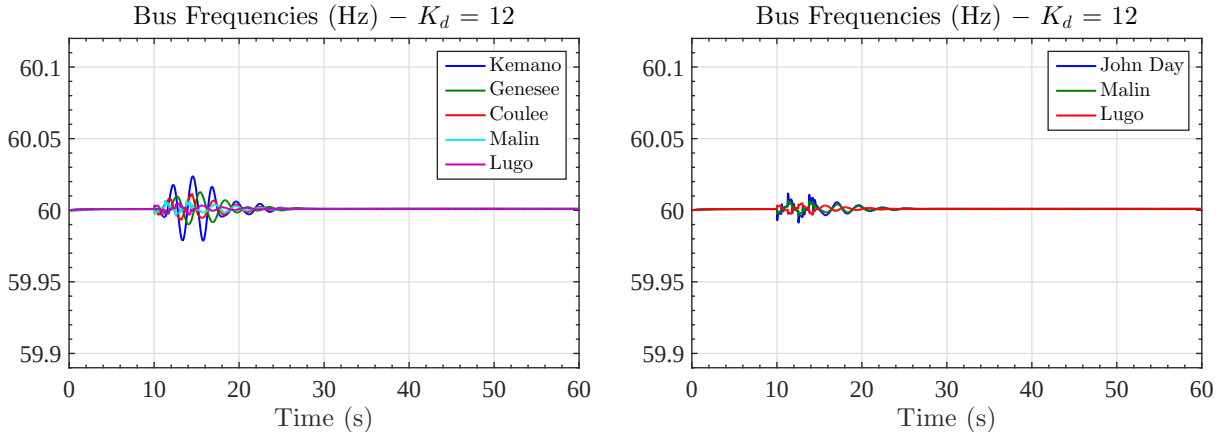


Figure 197. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

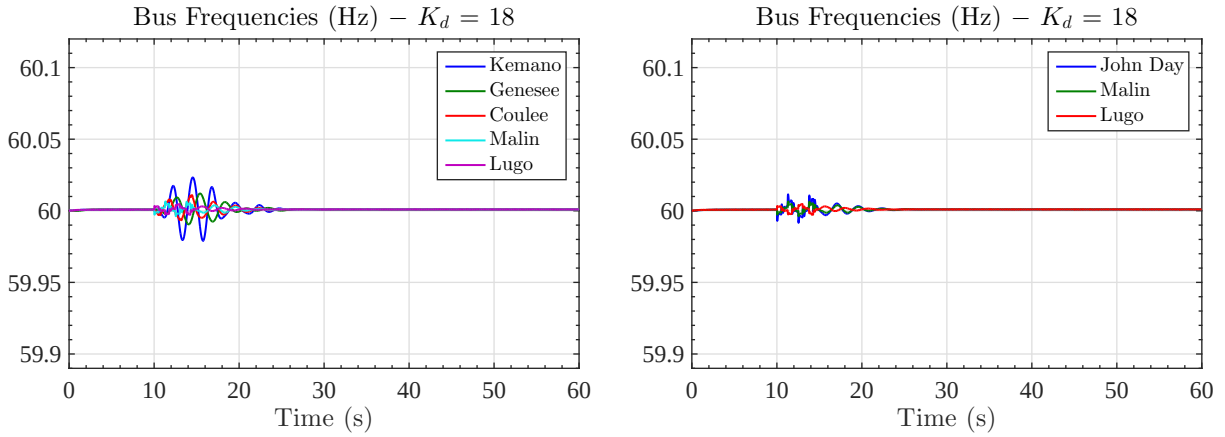


Figure 198. Bus frequencies. Event: 200 MW pulses with control limit of 50 MW.

3.2.4. Test System: Heavy Summer 2016. Event: 200 MW pulses with control limit of 35 MW

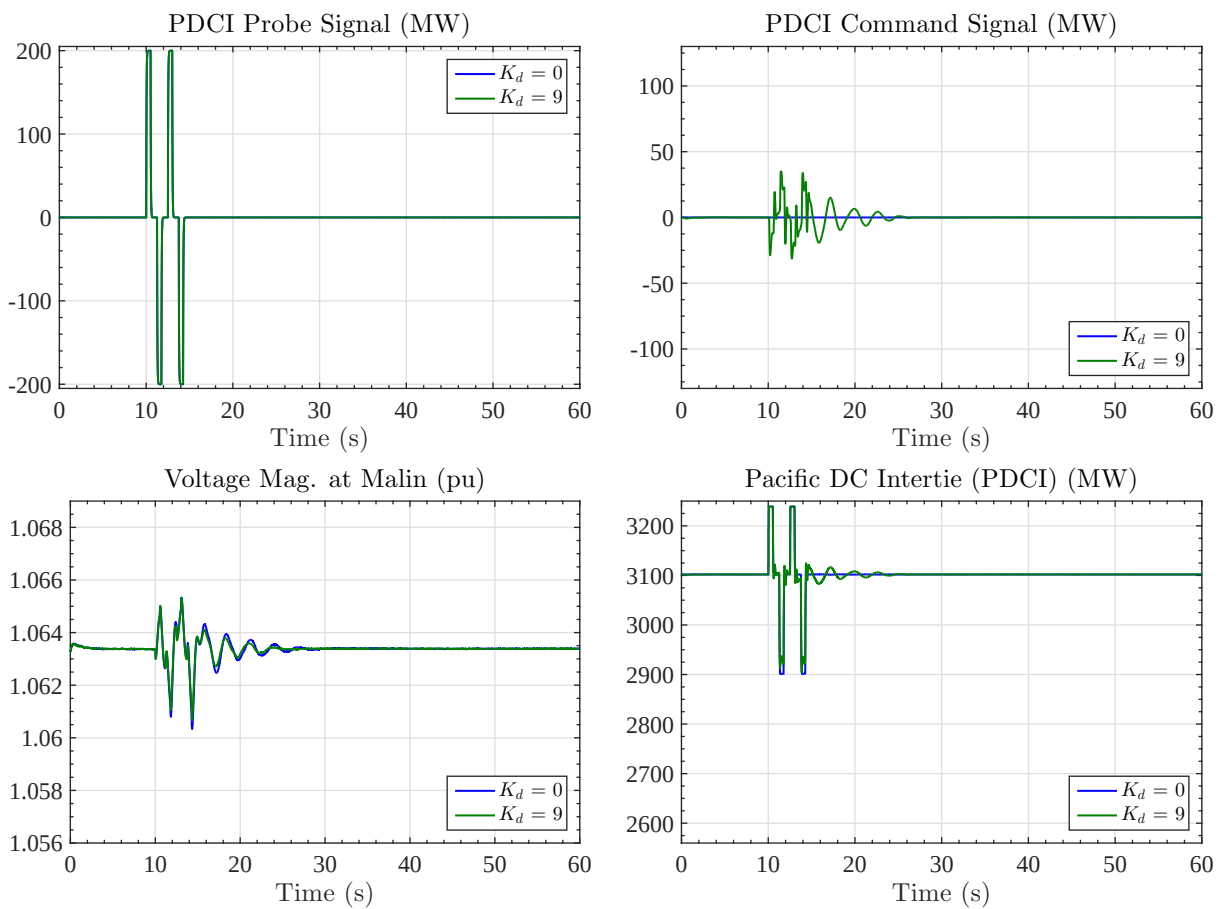


Figure 199. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses with control limit of 35 MW.

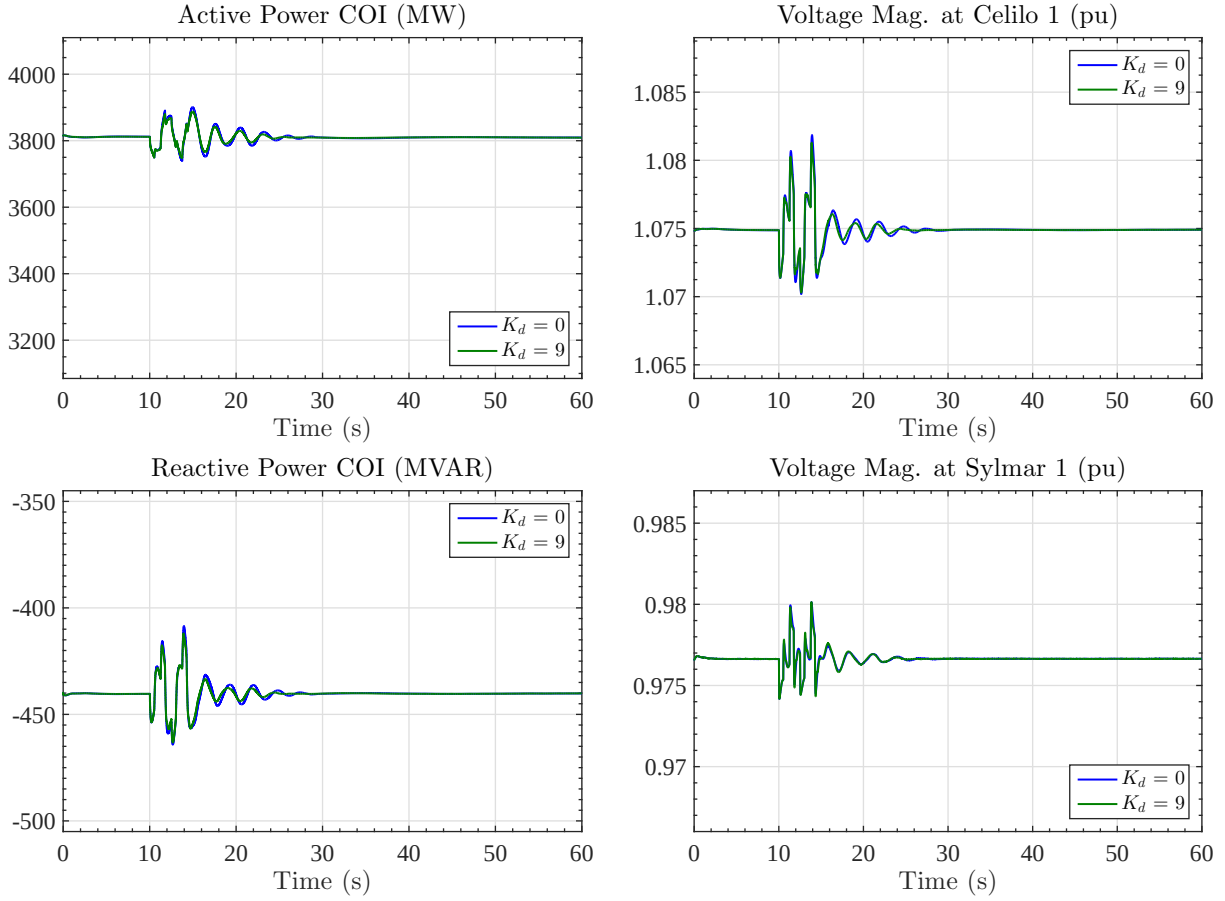


Figure 200. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses with control limit of 35 MW.

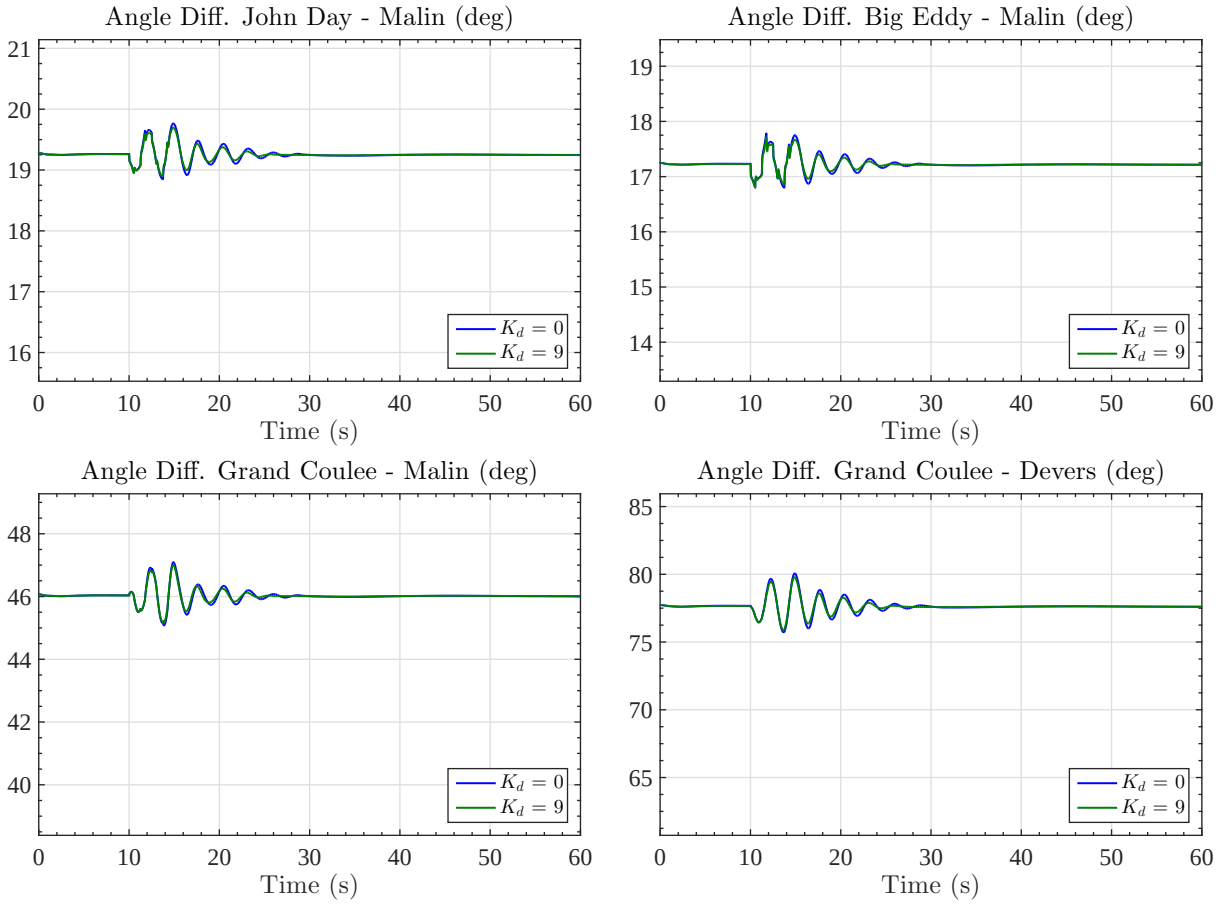


Figure 201. Angle differences. Event: 200 MW pulses with control limit of 35 MW.

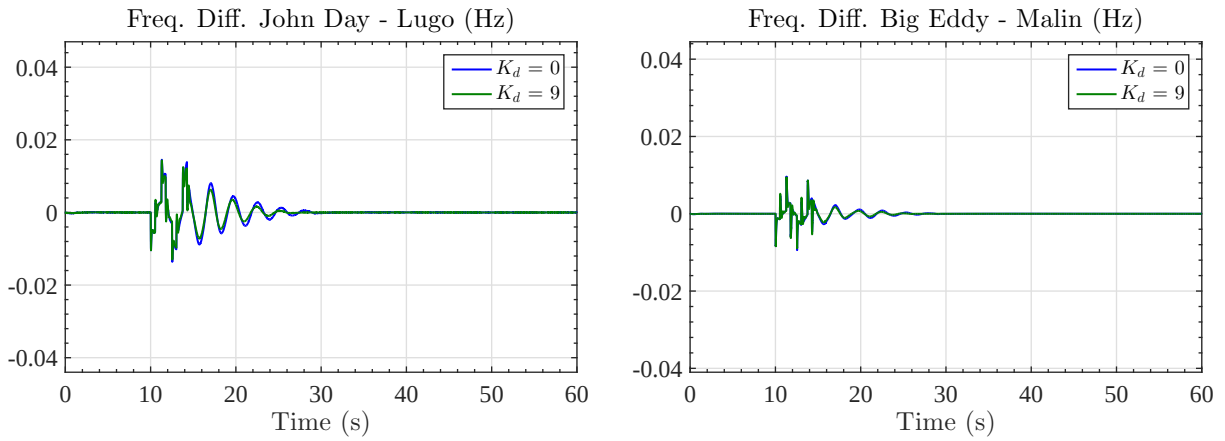


Figure 202. Frequency differences. Event: 200 MW pulses with control limit of 35 MW.

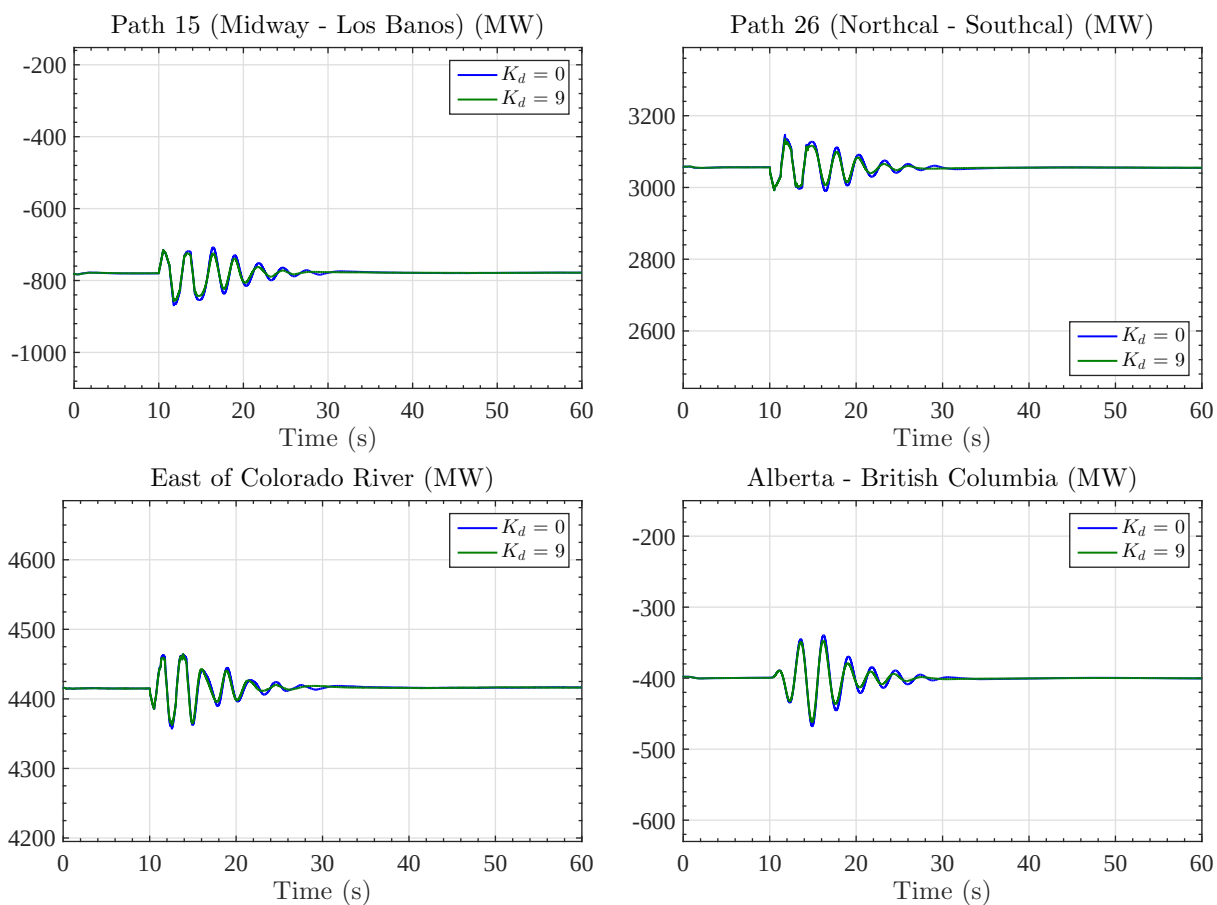


Figure 203. Active power flows. Event: 200 MW pulses with control limit of 35 MW.

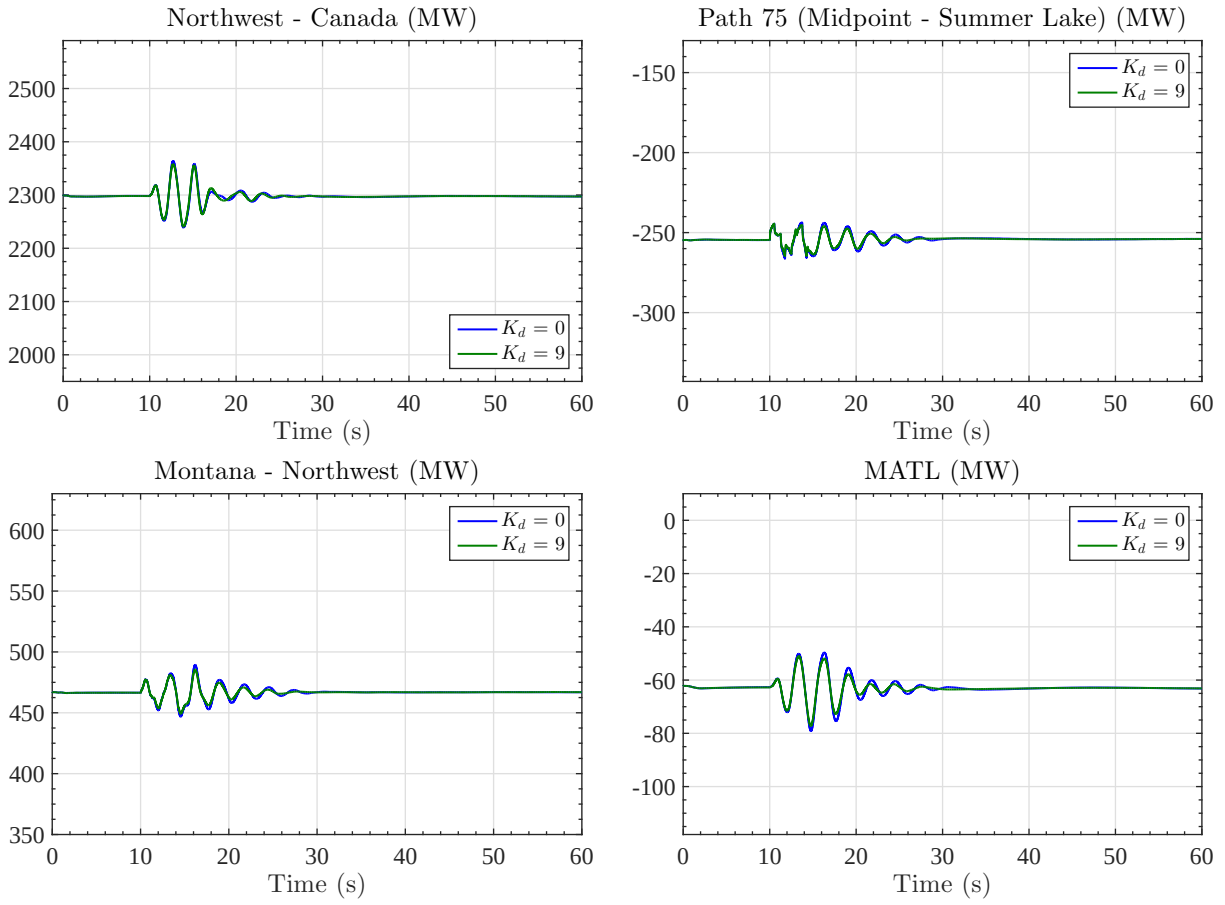


Figure 204. Active power flows. Event: 200 MW pulses with control limit of 35 MW.

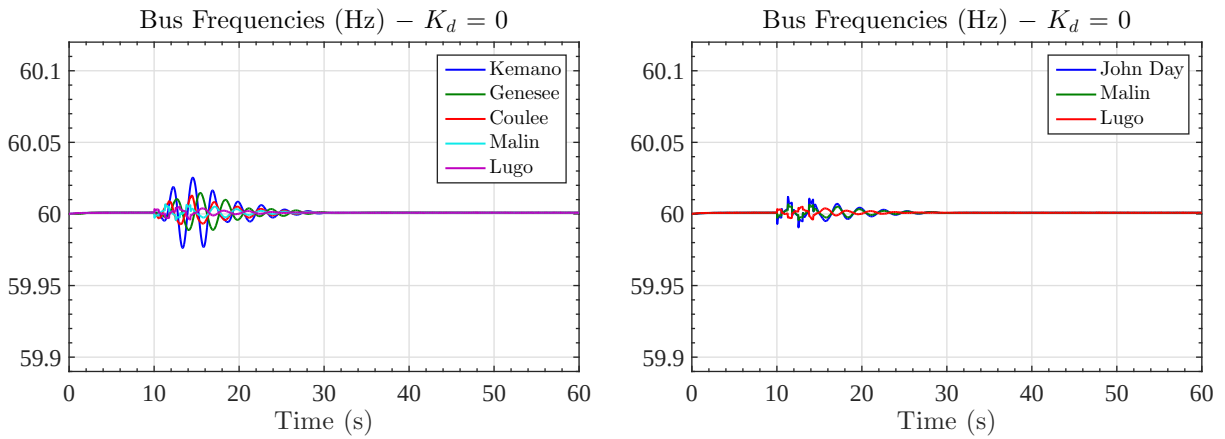


Figure 205. Bus frequencies. Event: 200 MW pulses with control limit of 35 MW.

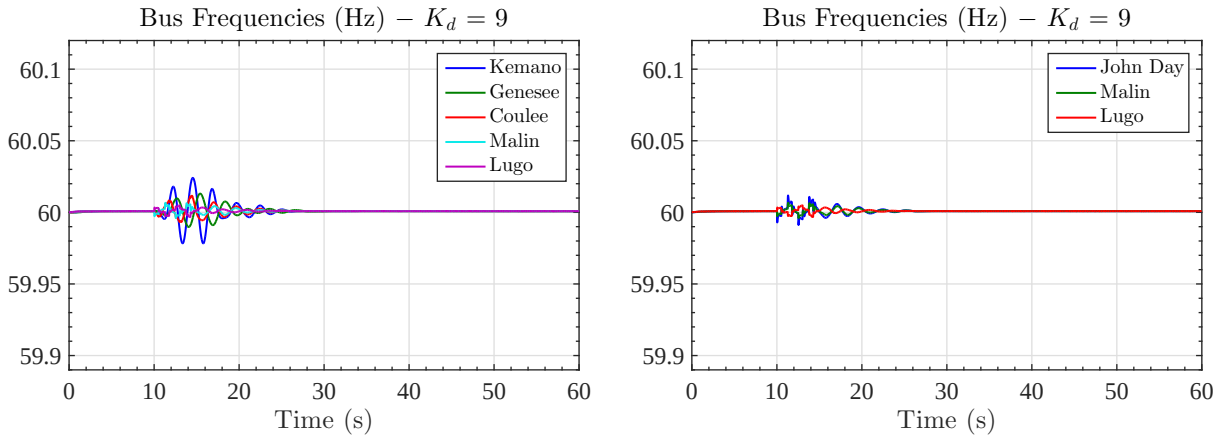


Figure 206. Bus frequencies. Event: 200 MW pulses with control limit of 35 MW.

3.2.5. Test System: Heavy Summer 2016. Event: MSF 1/30/1/100 with amplitude of 20MW

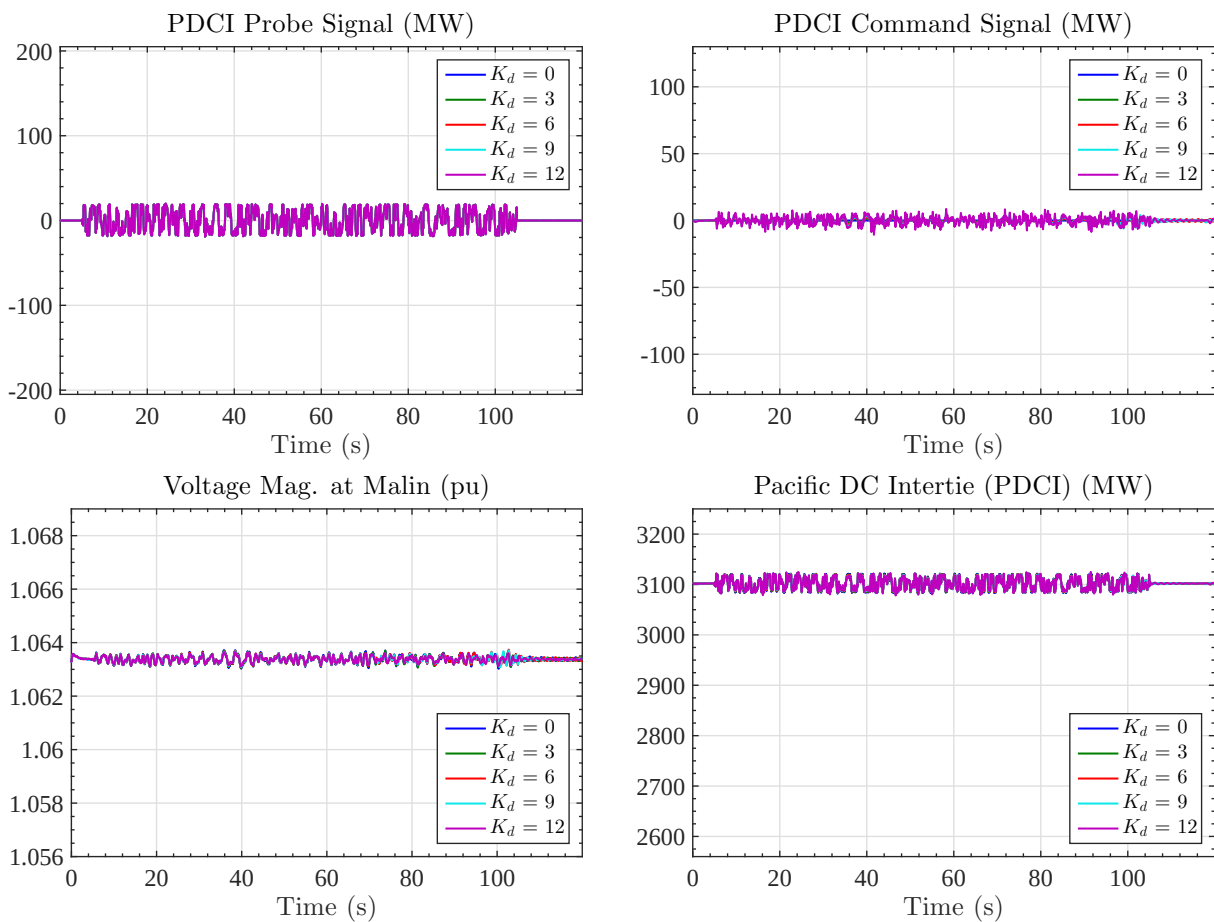


Figure 207. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 1/30/1/100 with amplitude of 20MW.

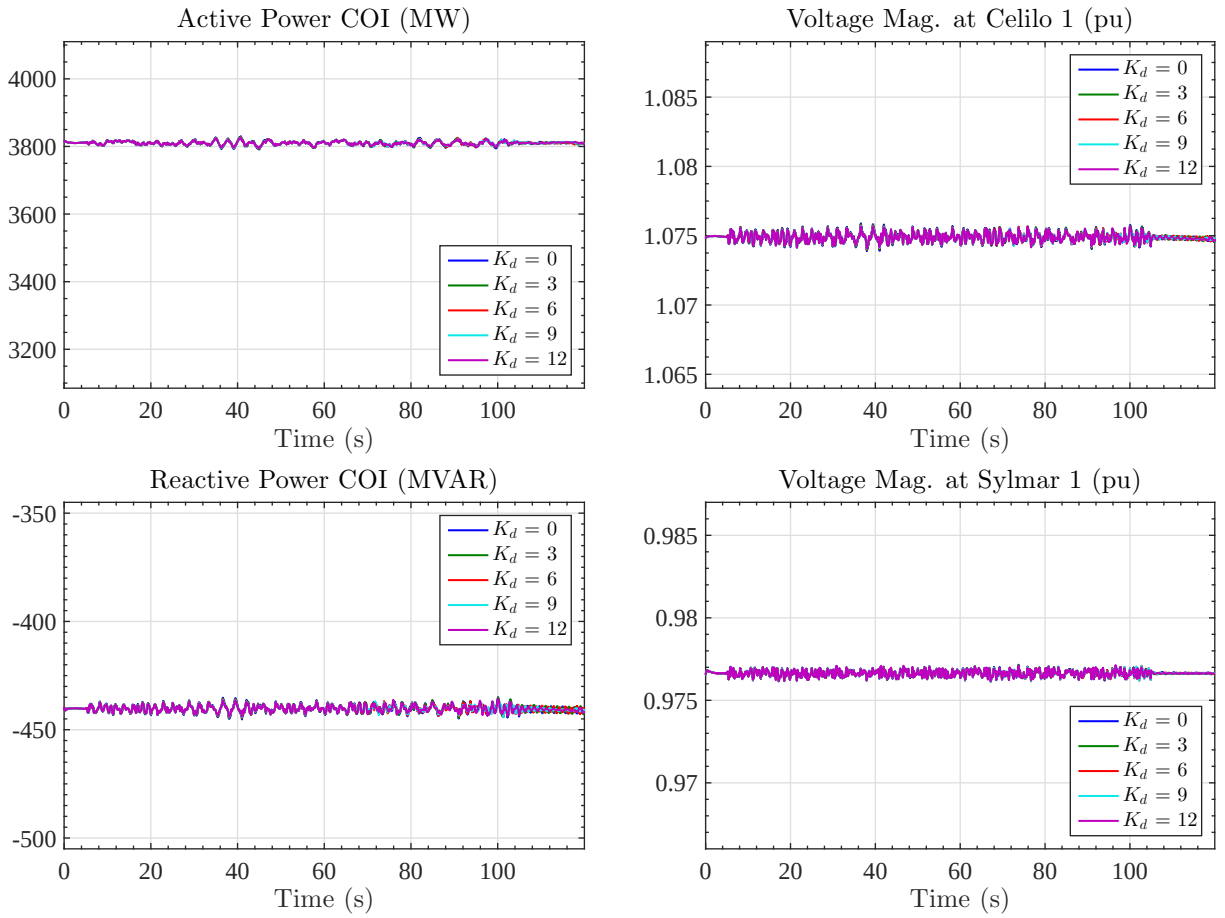


Figure 208. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 1/30/1/100 with amplitude of 20MW.

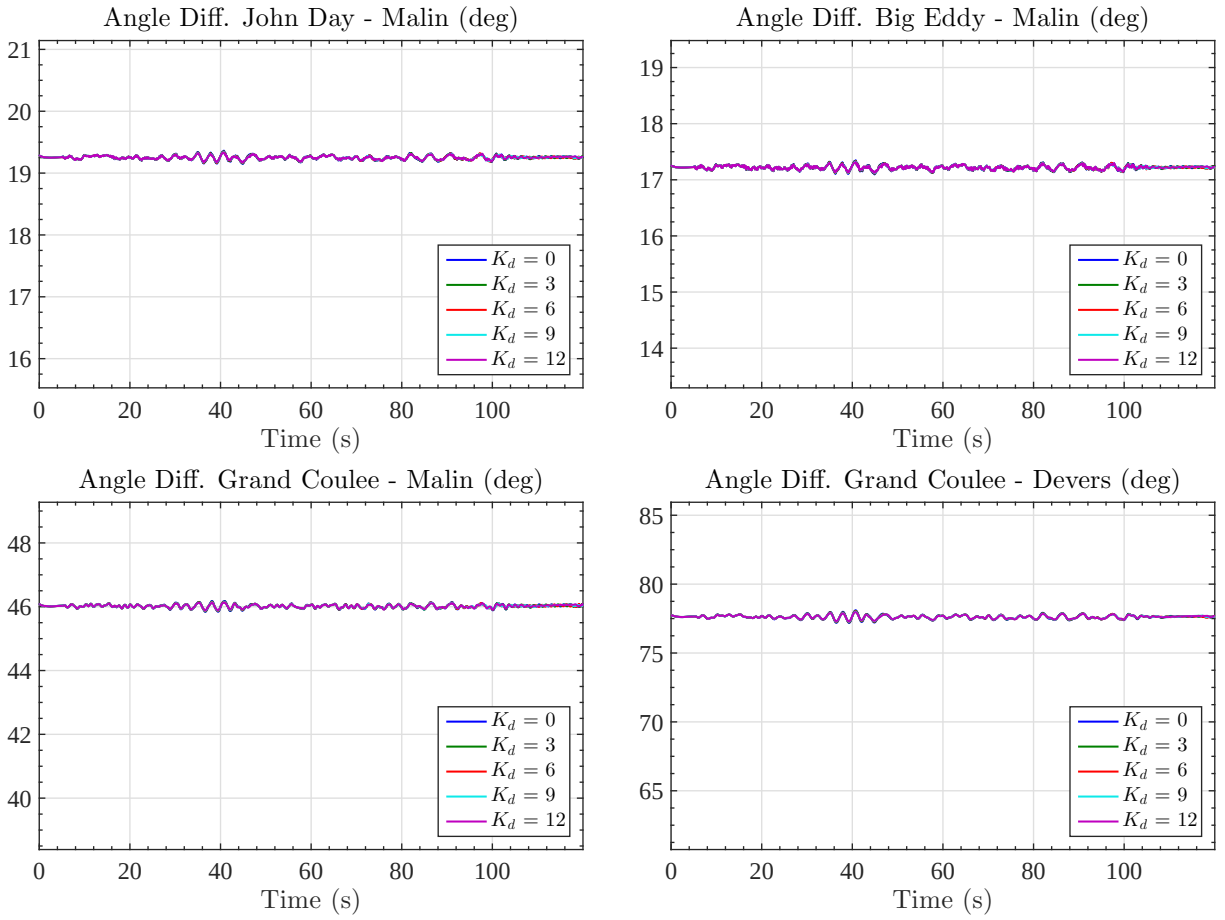


Figure 209. Angle differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

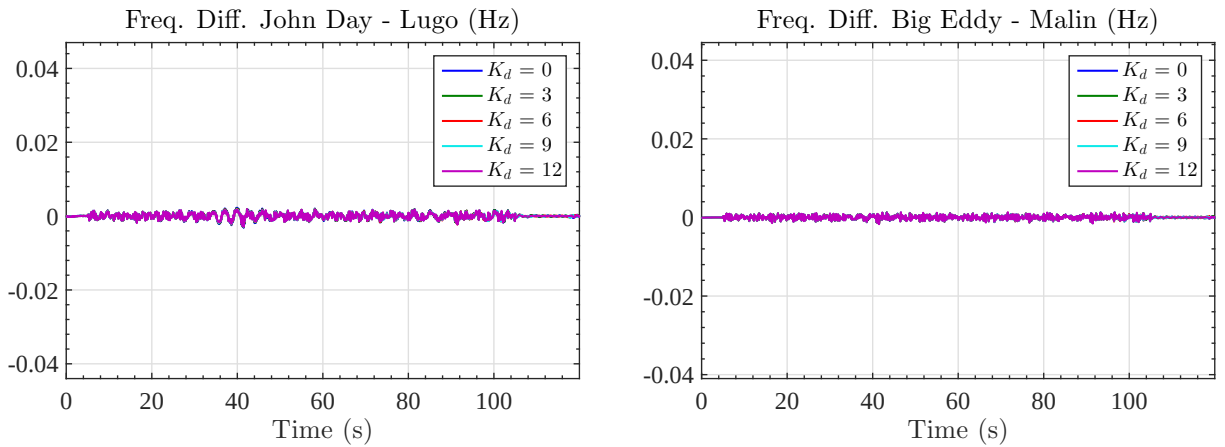


Figure 210. Frequency differences. Event: MSF 1/30/1/100 with amplitude of 20MW.

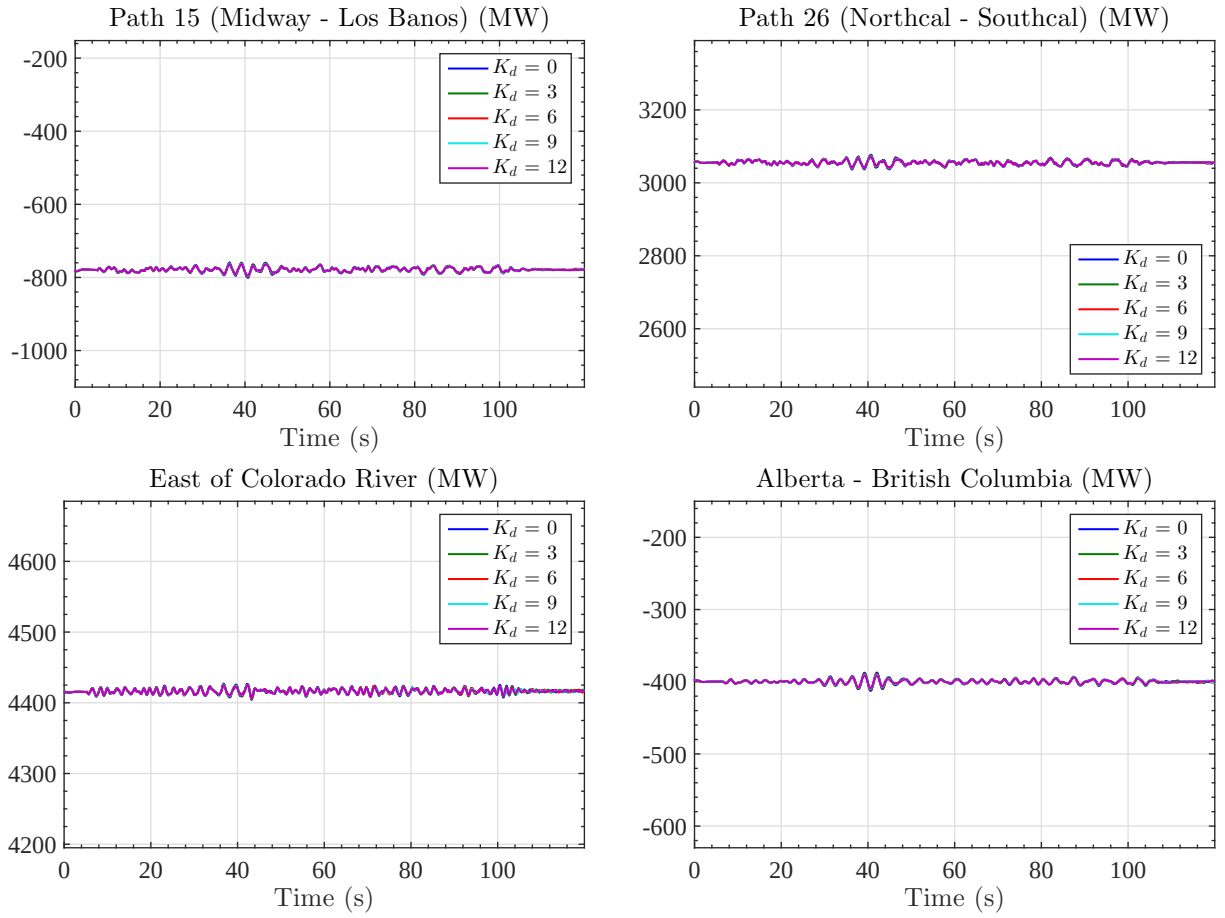


Figure 211. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

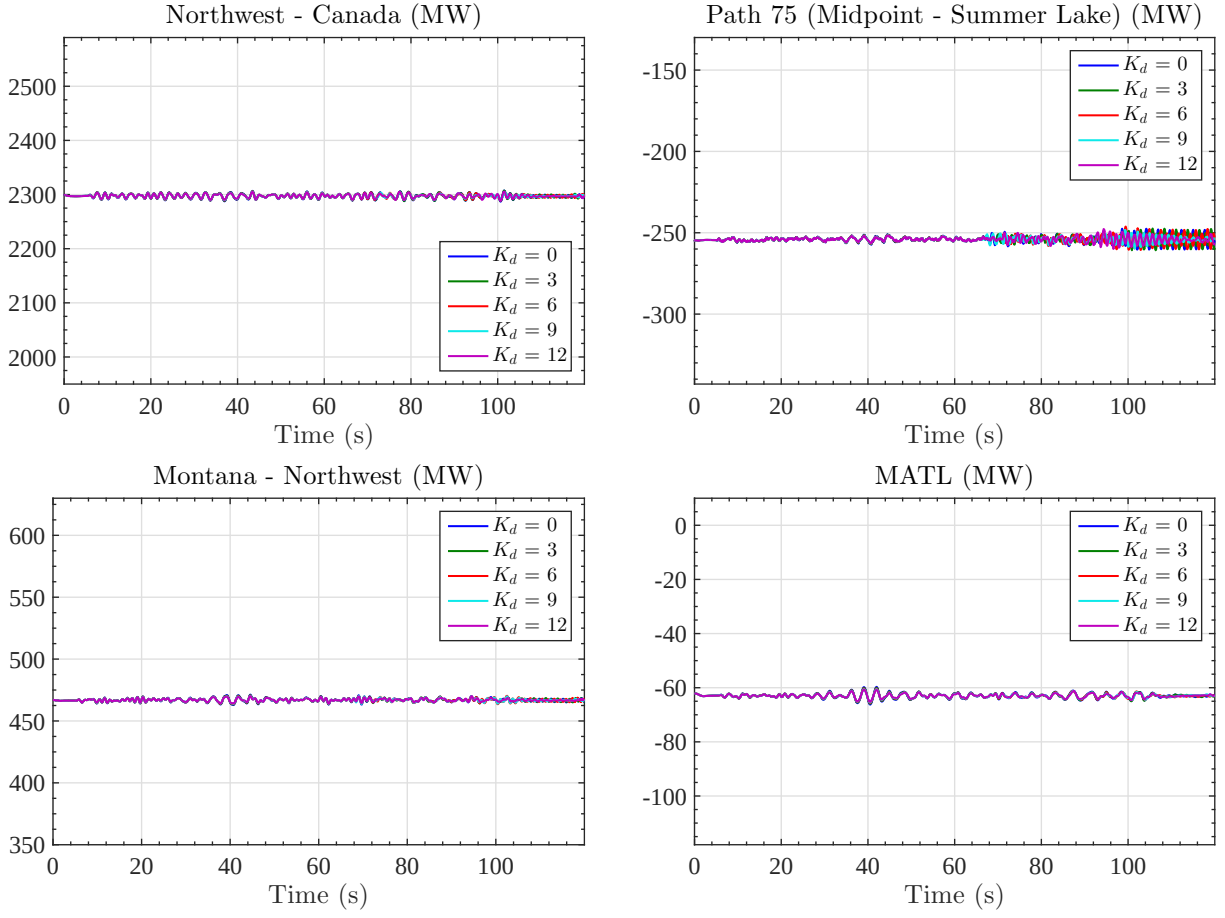


Figure 212. Active power flows. Event: MSF 1/30/1/100 with amplitude of 20MW.

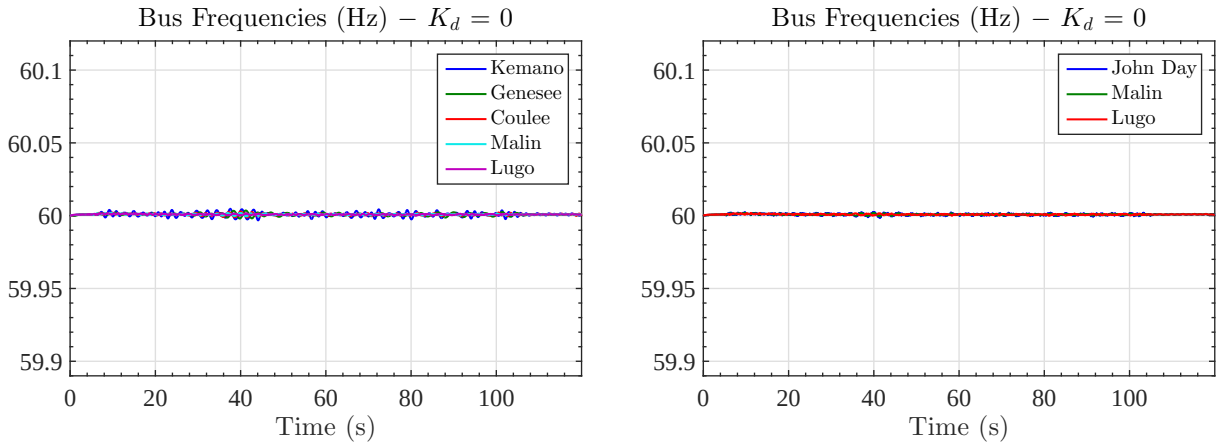


Figure 213. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

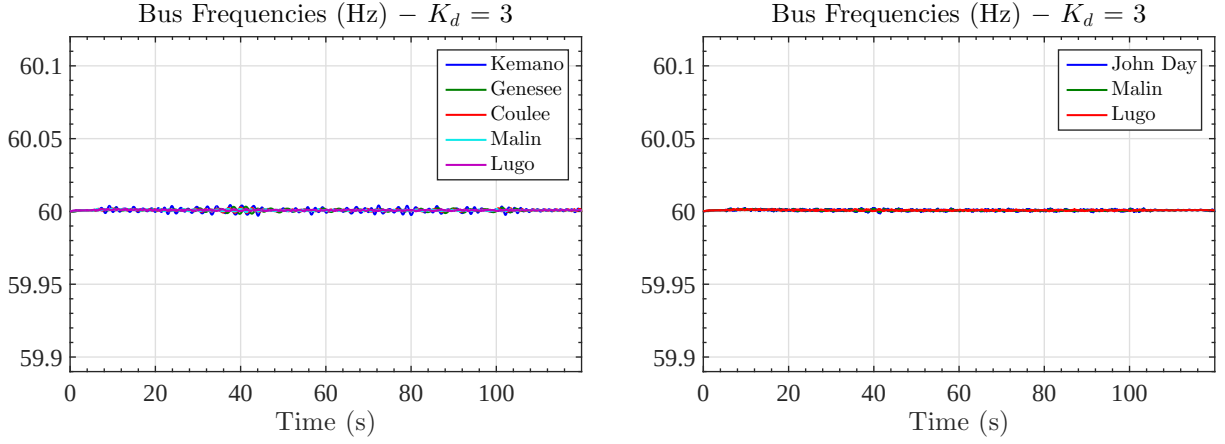


Figure 214. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

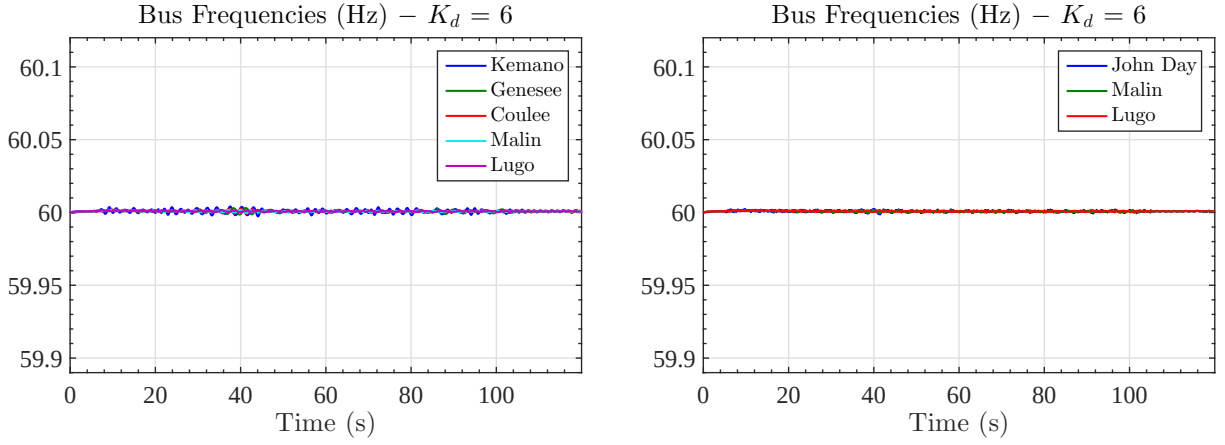


Figure 215. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

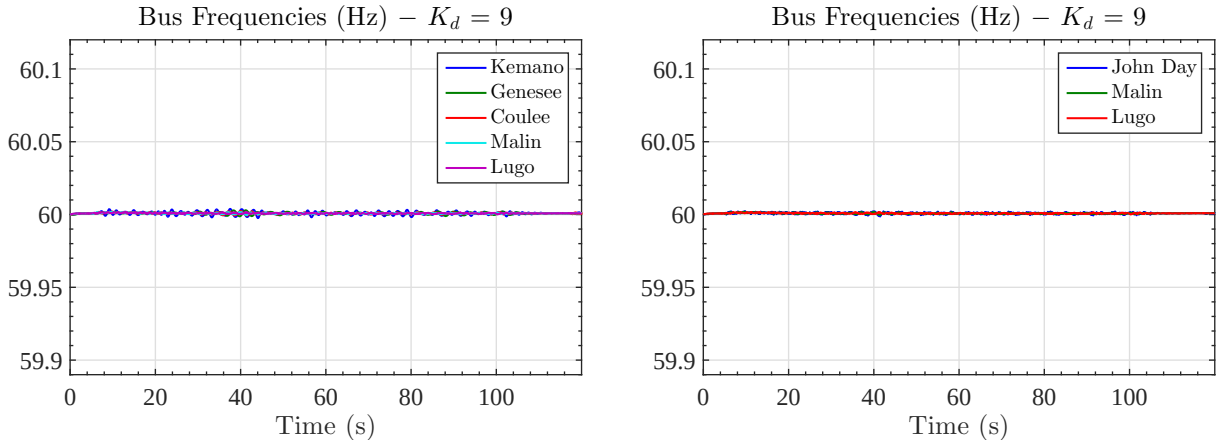


Figure 216. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

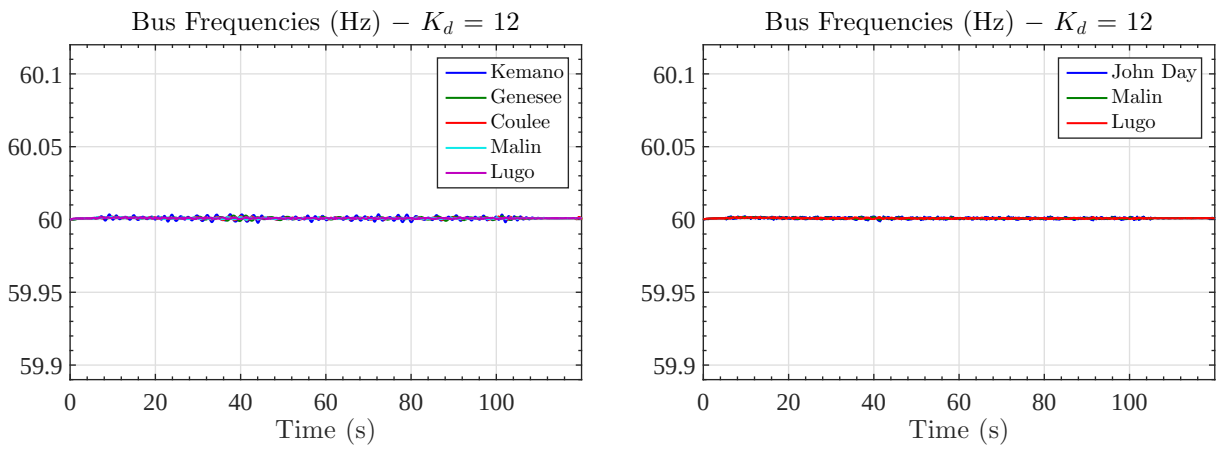


Figure 217. Bus frequencies. Event: MSF 1/30/1/100 with amplitude of 20MW.

3.2.6. *Test System: Heavy Summer 2016. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW*

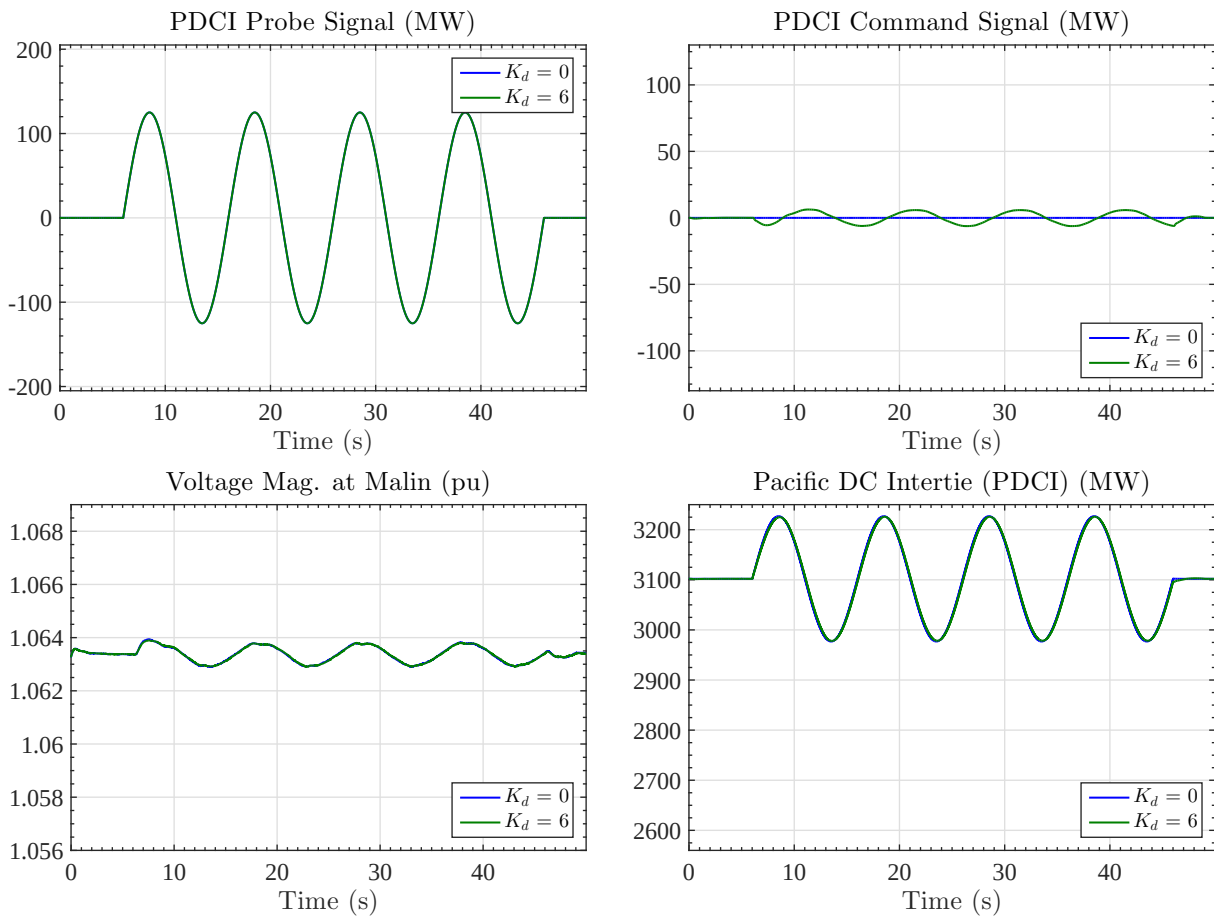


Figure 218. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

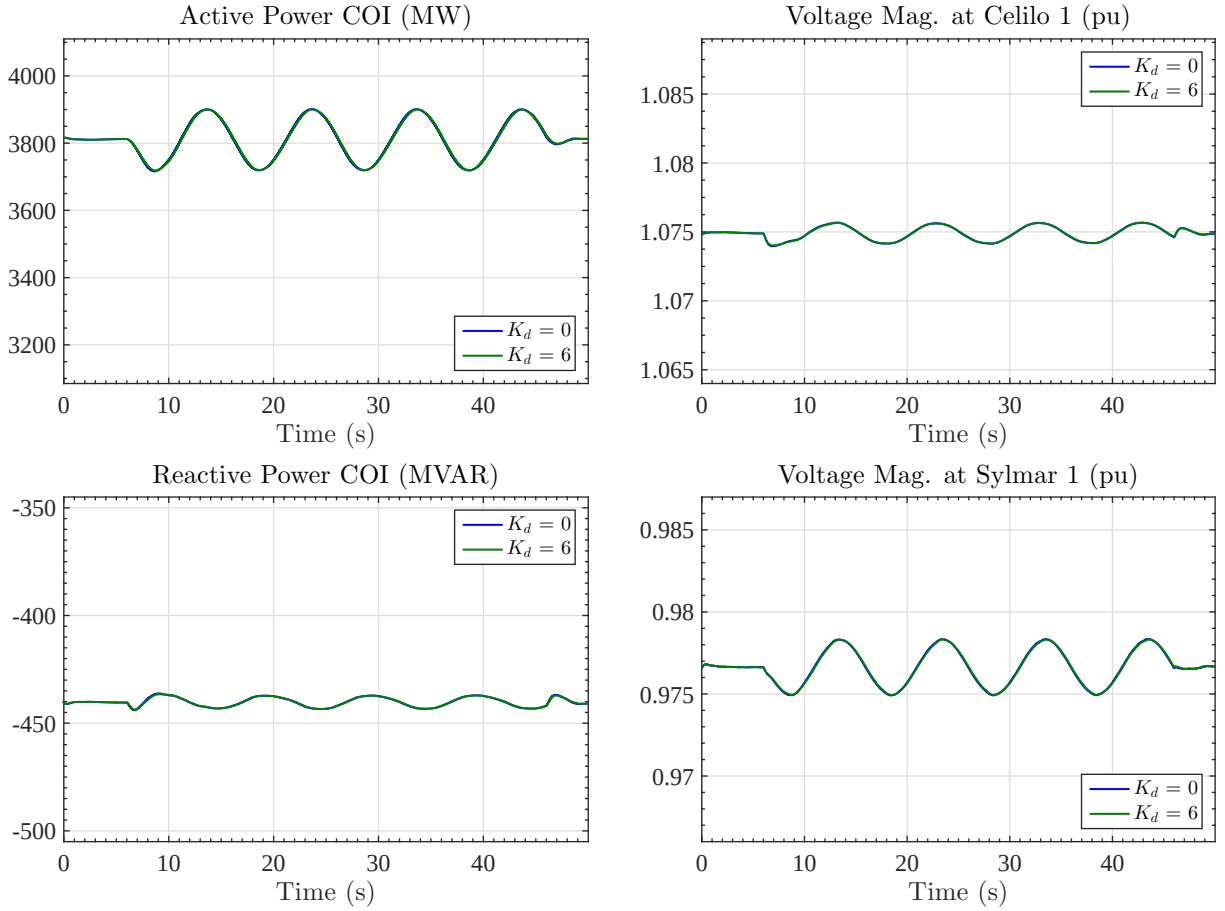


Figure 219. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

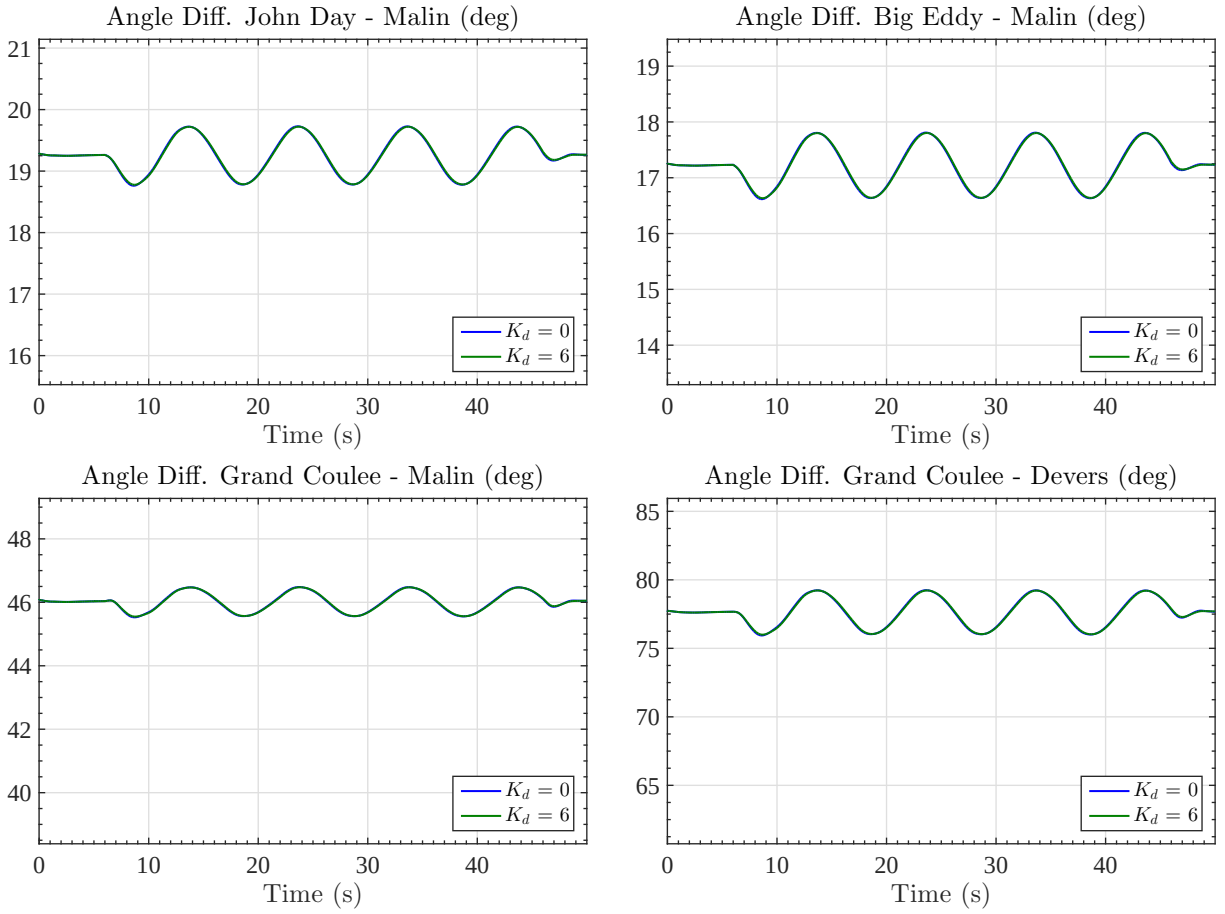


Figure 220. Angle differences. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

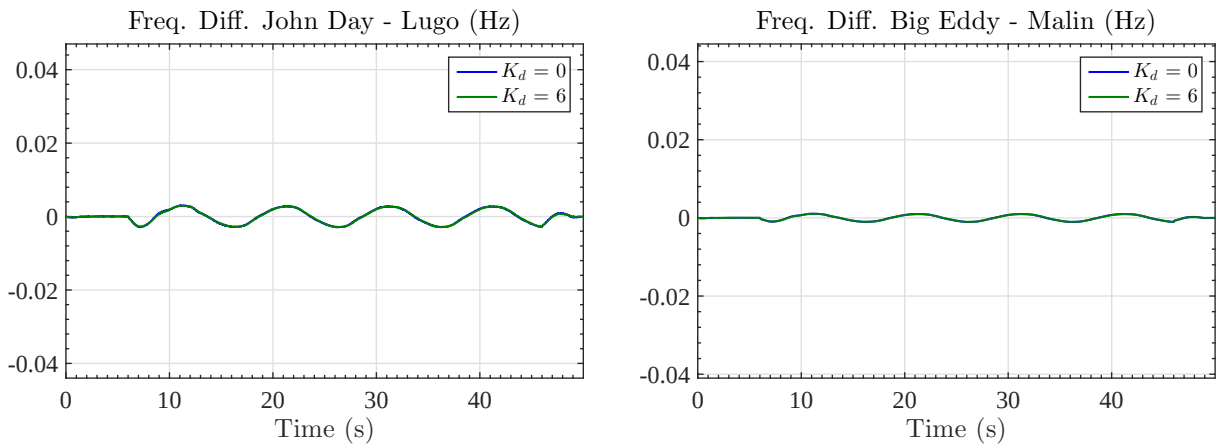


Figure 221. Frequency differences. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

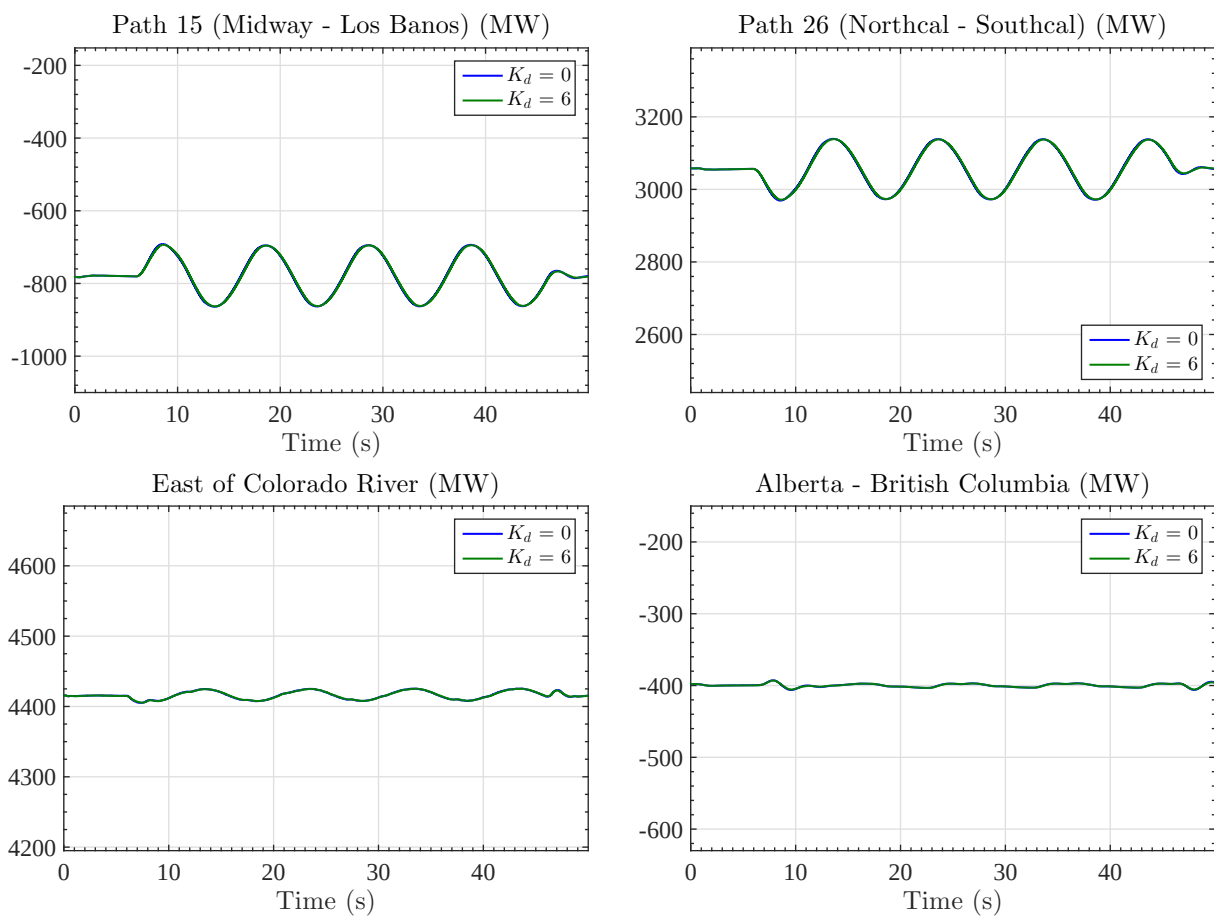


Figure 222. Active power flows. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

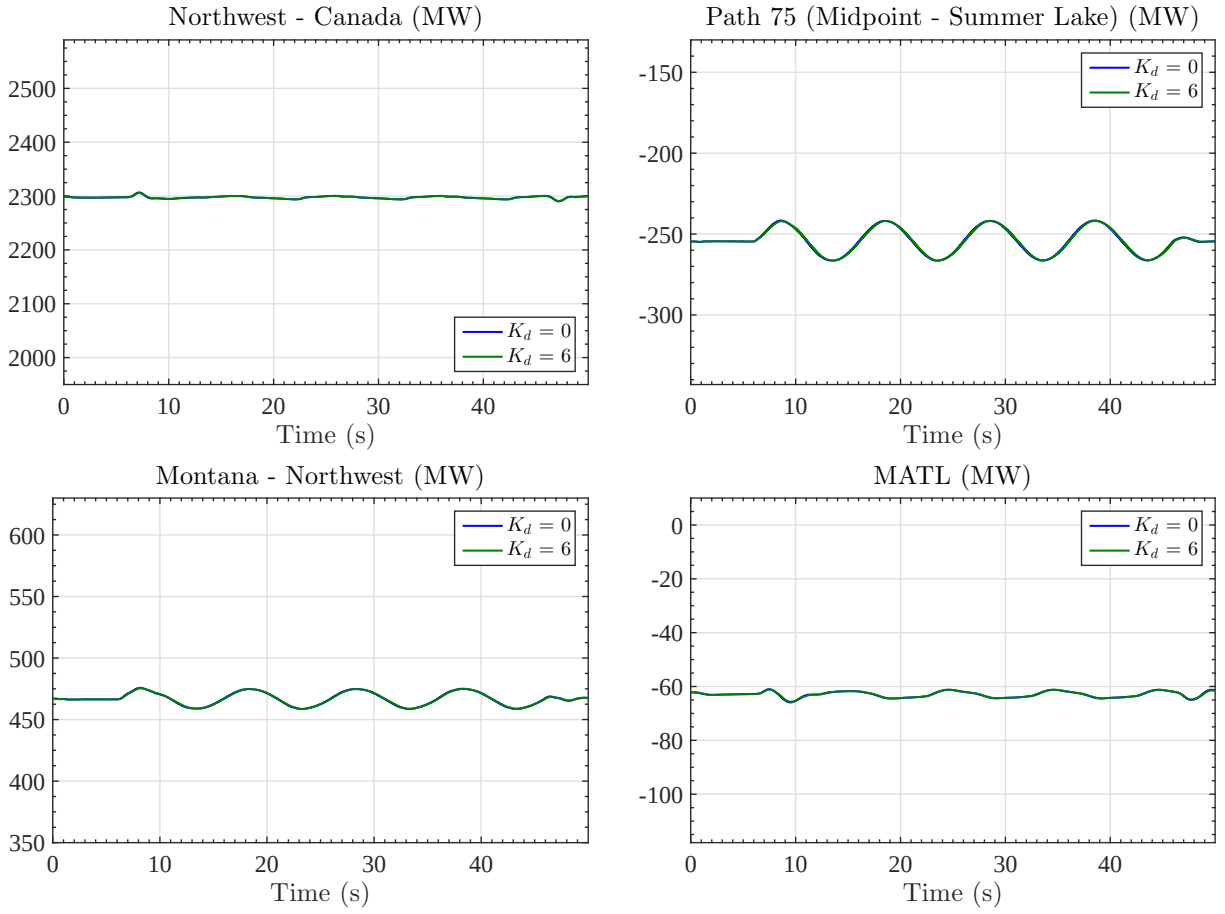


Figure 223. Active power flows. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

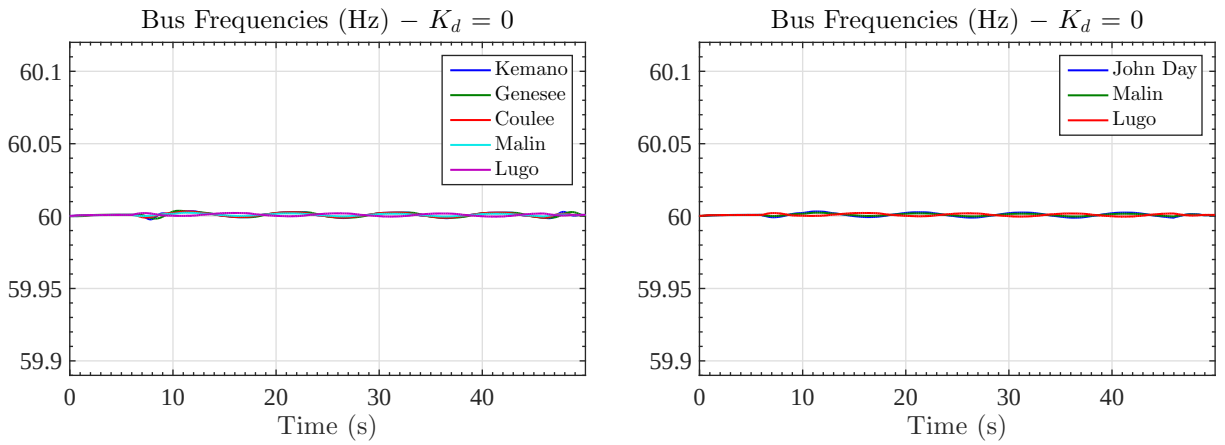


Figure 224. Bus frequencies. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

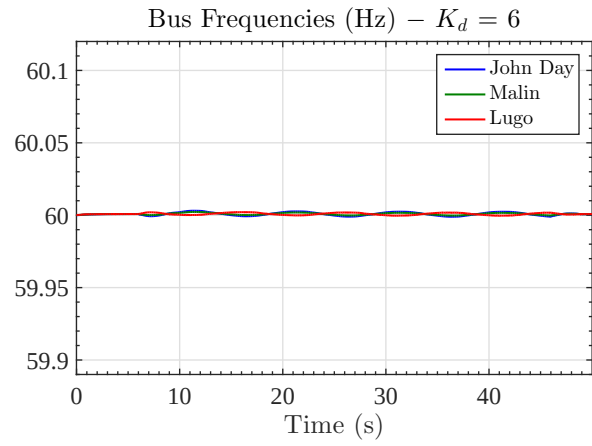
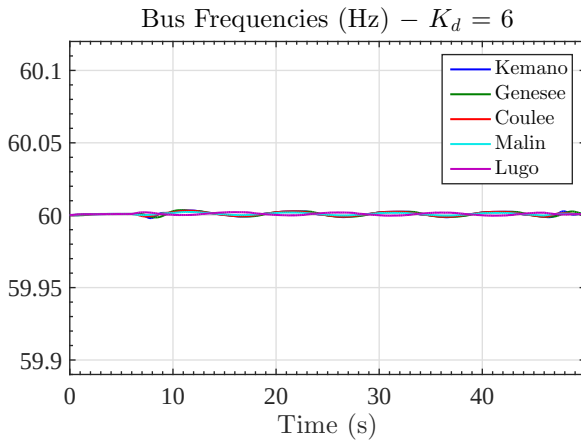


Figure 225. Bus frequencies. Event: SF 0.1/4x with amplitude of 125 MW controller limit of 35 MW.

4. CASE STUDY: LIGHT SUMMER 2016 - LARGE EVENTS WHILE TESTING

4.1. Closed Loop Testing

4.1.1. Test System: Light Summer 2016. Event: Chief Joe Brake followed by forced oscillation

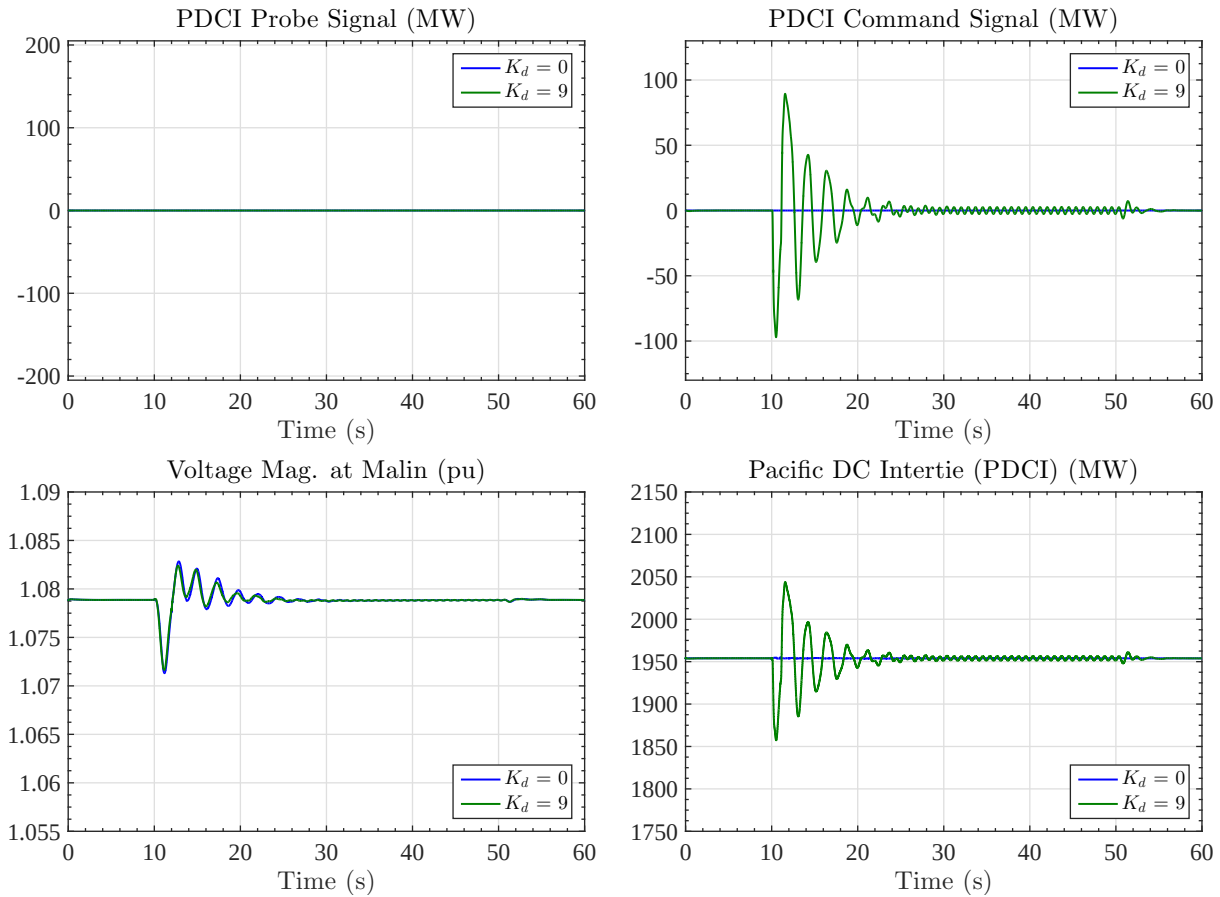


Figure 226. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake followed by forced oscillation.

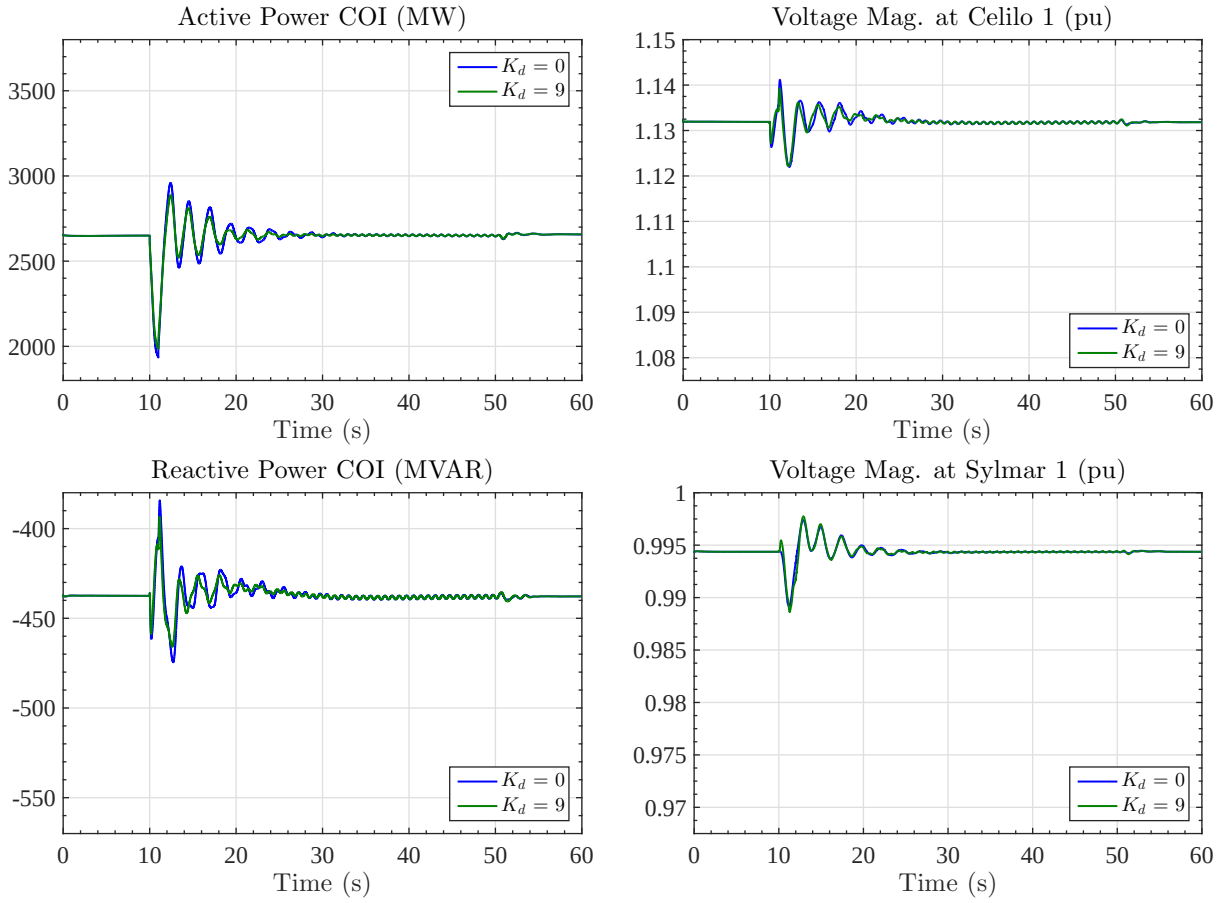


Figure 227. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake followed by forced oscillation.

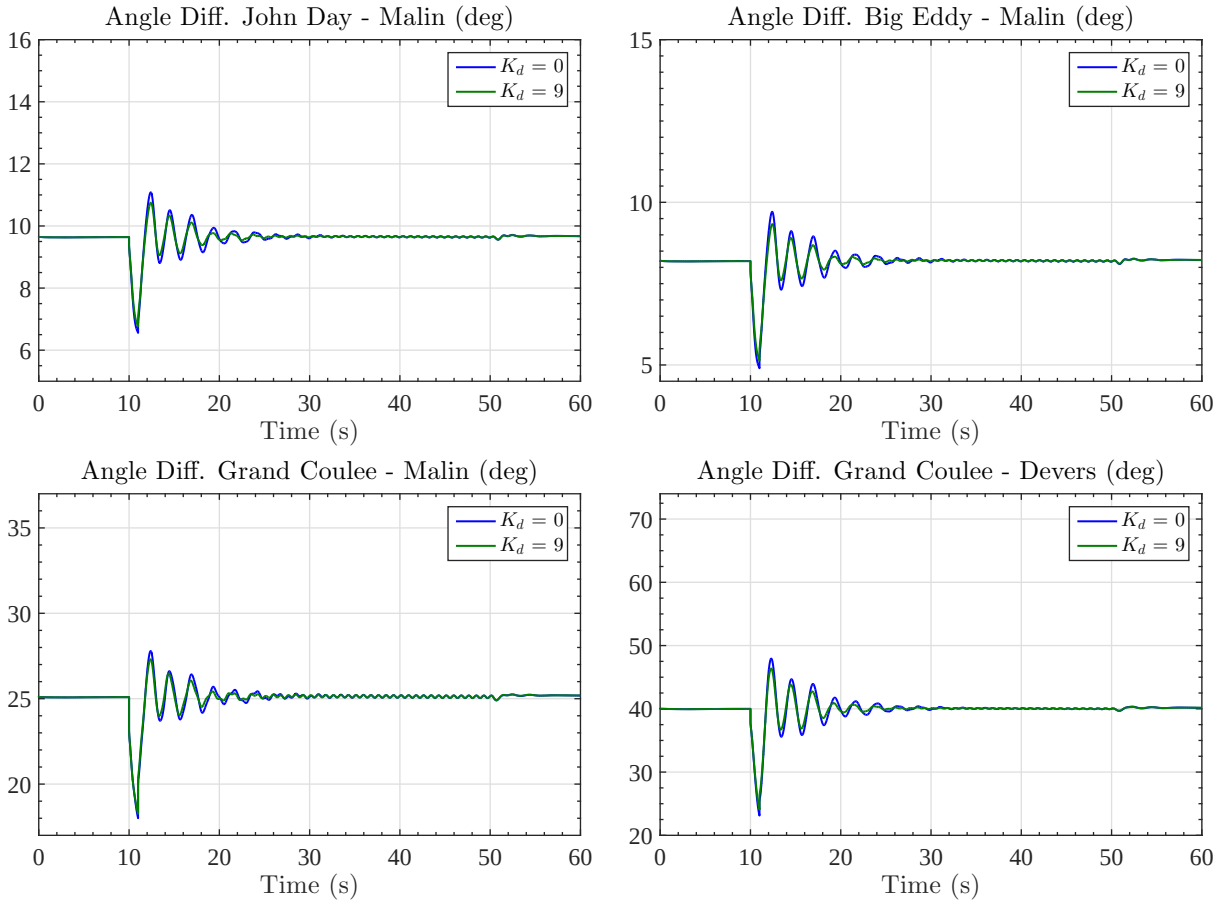


Figure 228. Angle differences. Event: Chief Joe Brake followed by forced oscillation.

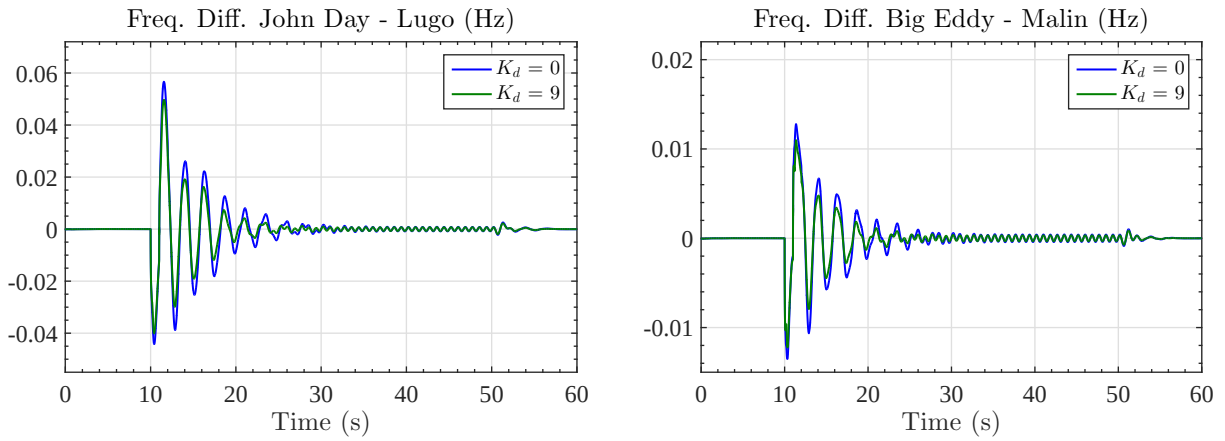


Figure 229. Frequency differences. Event: Chief Joe Brake followed by forced oscillation.

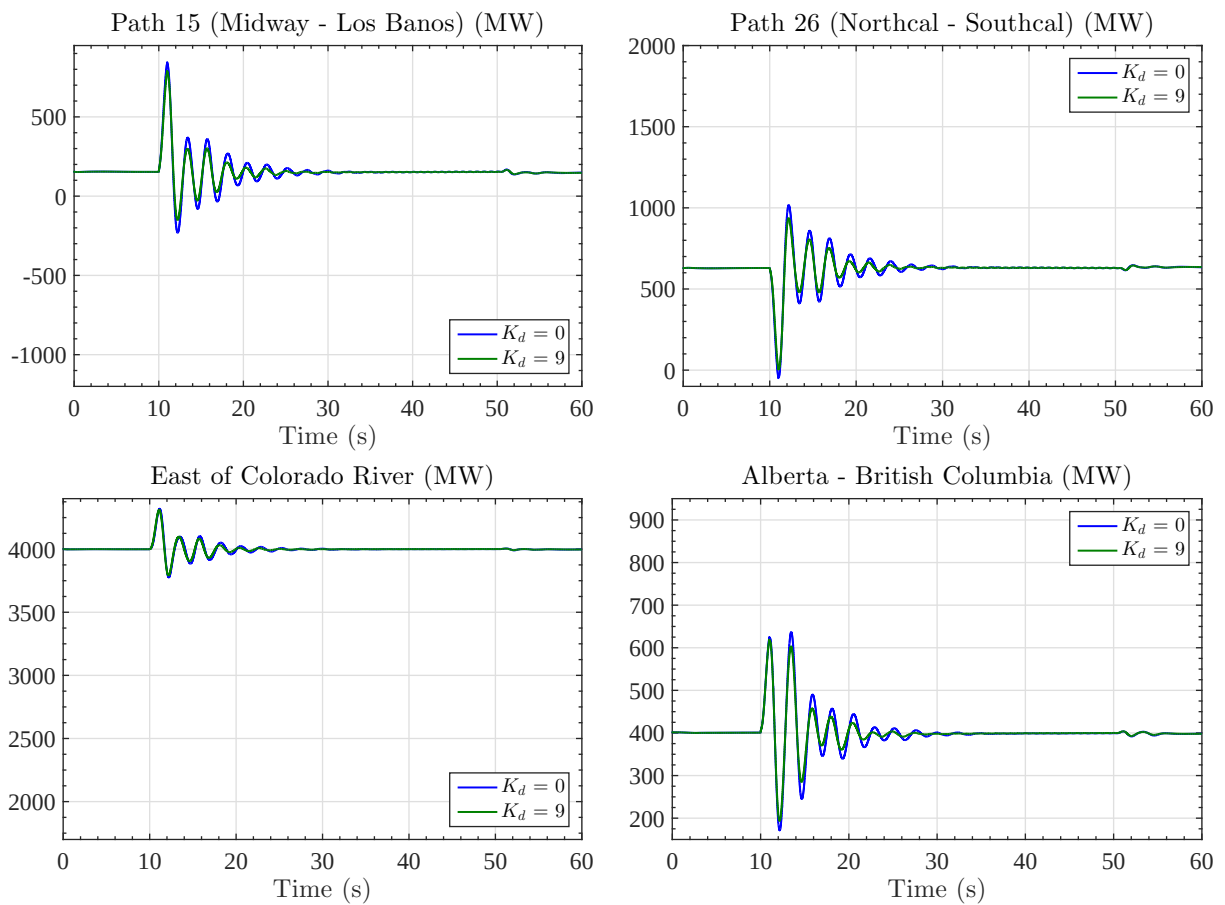


Figure 230. Active power flows. Event: Chief Joe Brake followed by forced oscillation.

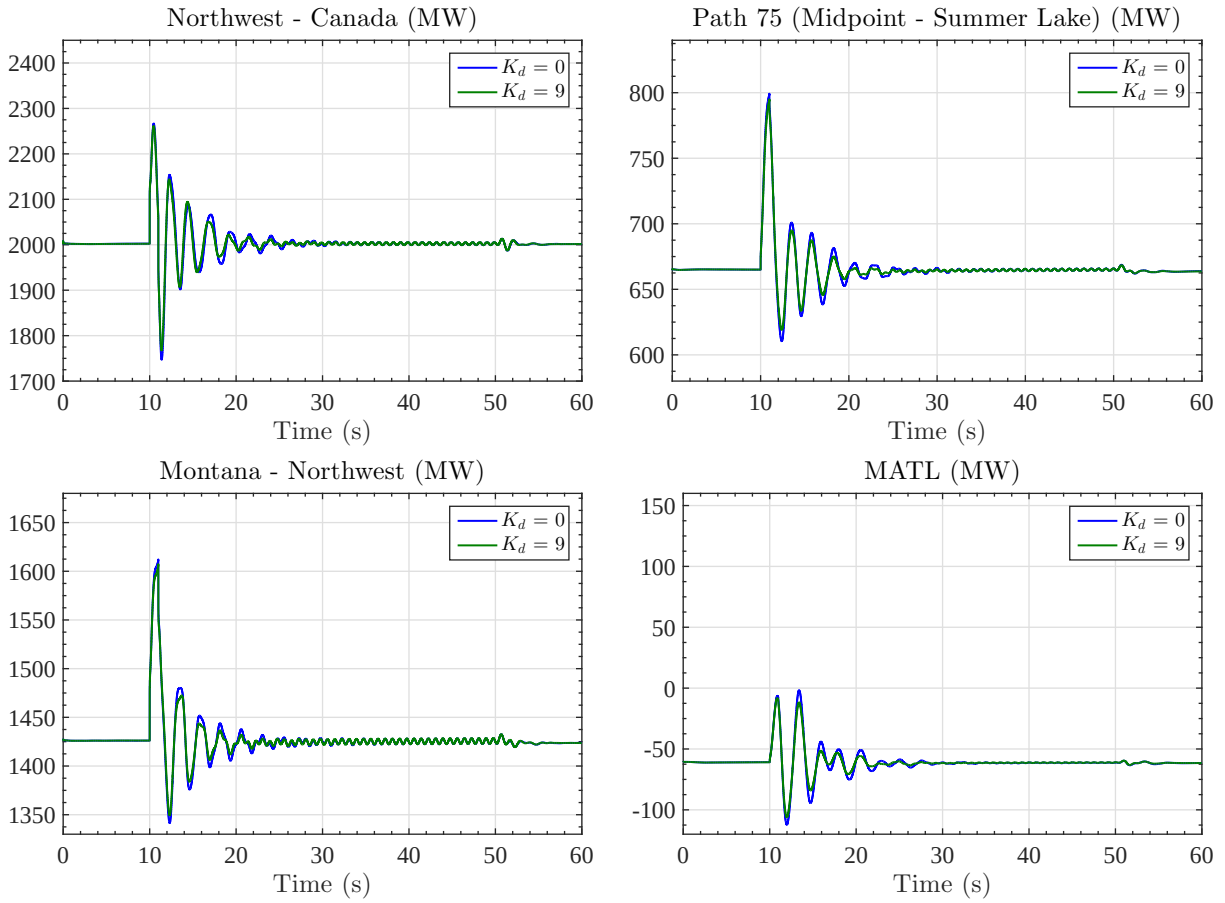


Figure 231. Active power flows. Event: Chief Joe Brake followed by forced oscillation.

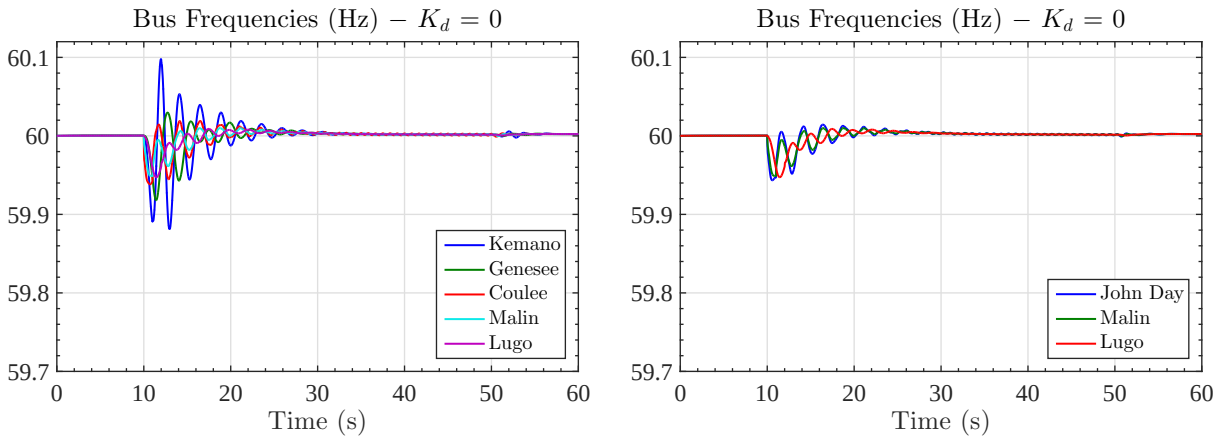


Figure 232. Bus frequencies. Event: Chief Joe Brake followed by forced oscillation.

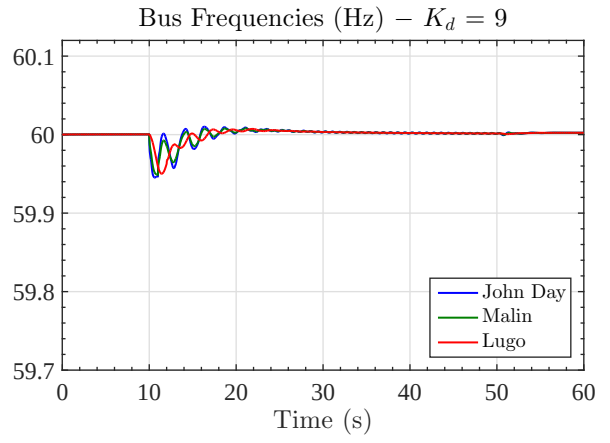
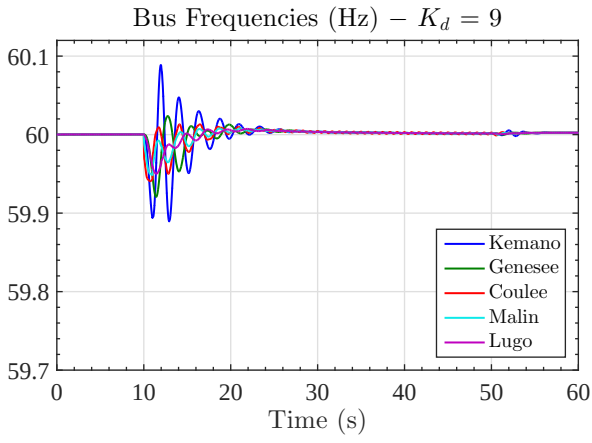


Figure 233. Bus frequencies. Event: Chief Joe Brake followed by forced oscillation.

4.1.2. Test System: Light Summer 2016. Event: Chief Joe Brake followed by double Palo Verde outage

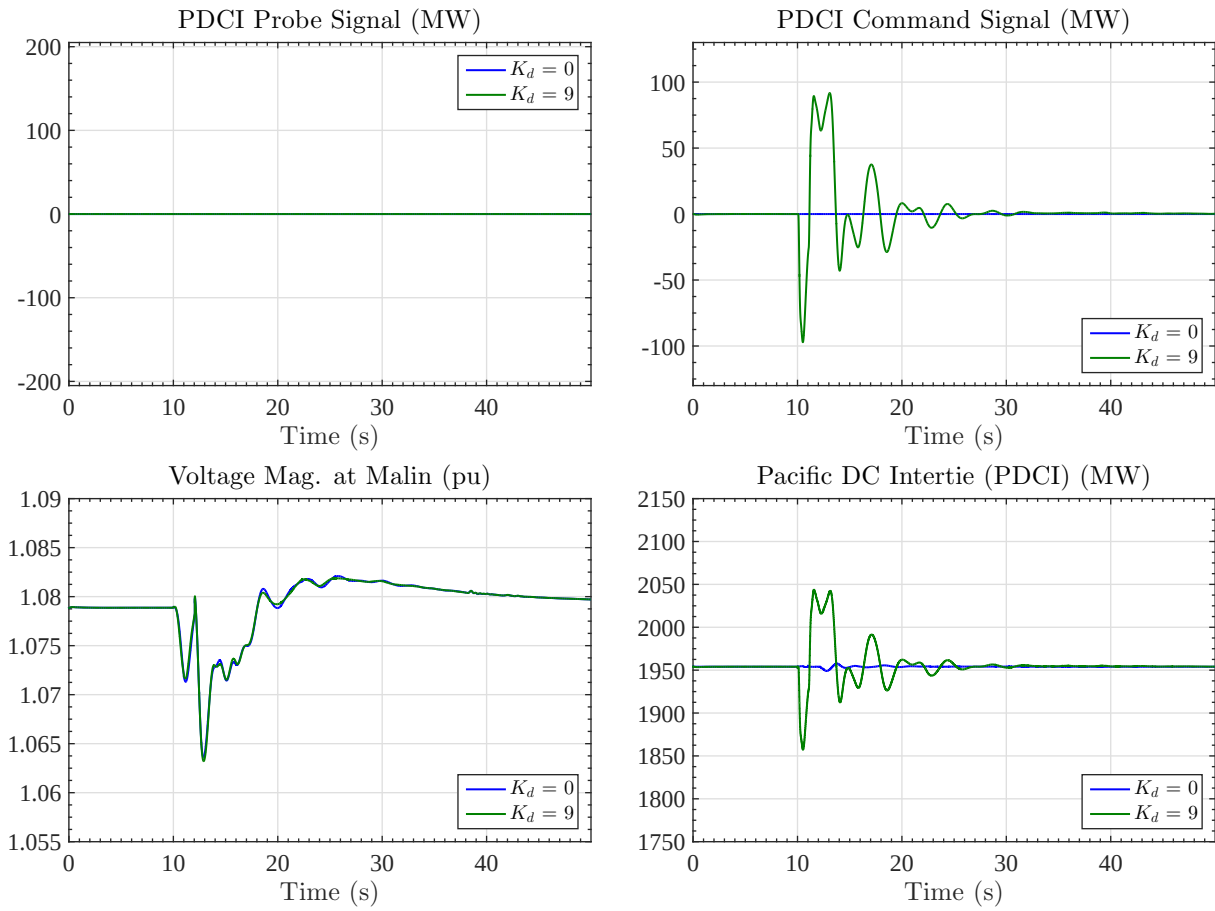


Figure 234. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake followed by double Palo Verde outage.

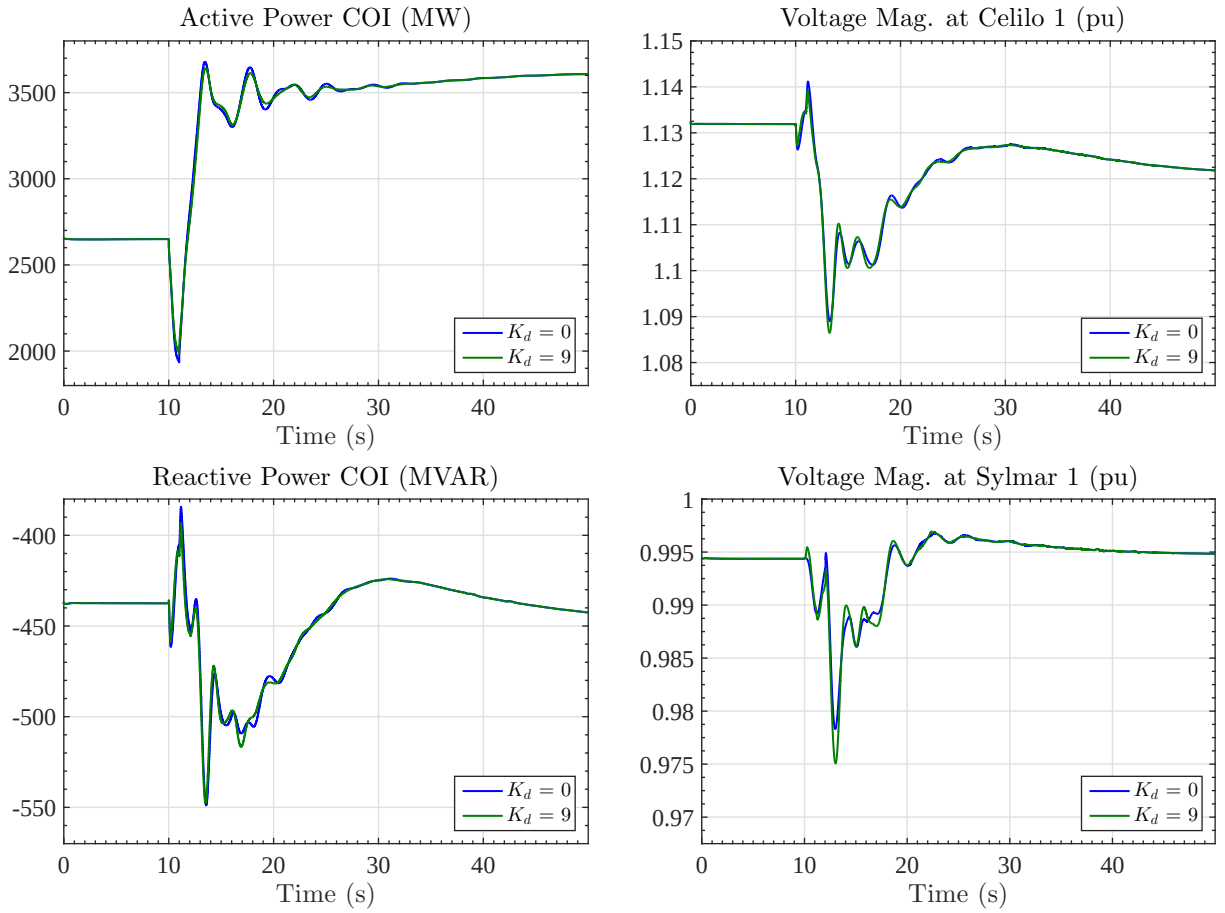


Figure 235. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake followed by double Palo Verde outage.

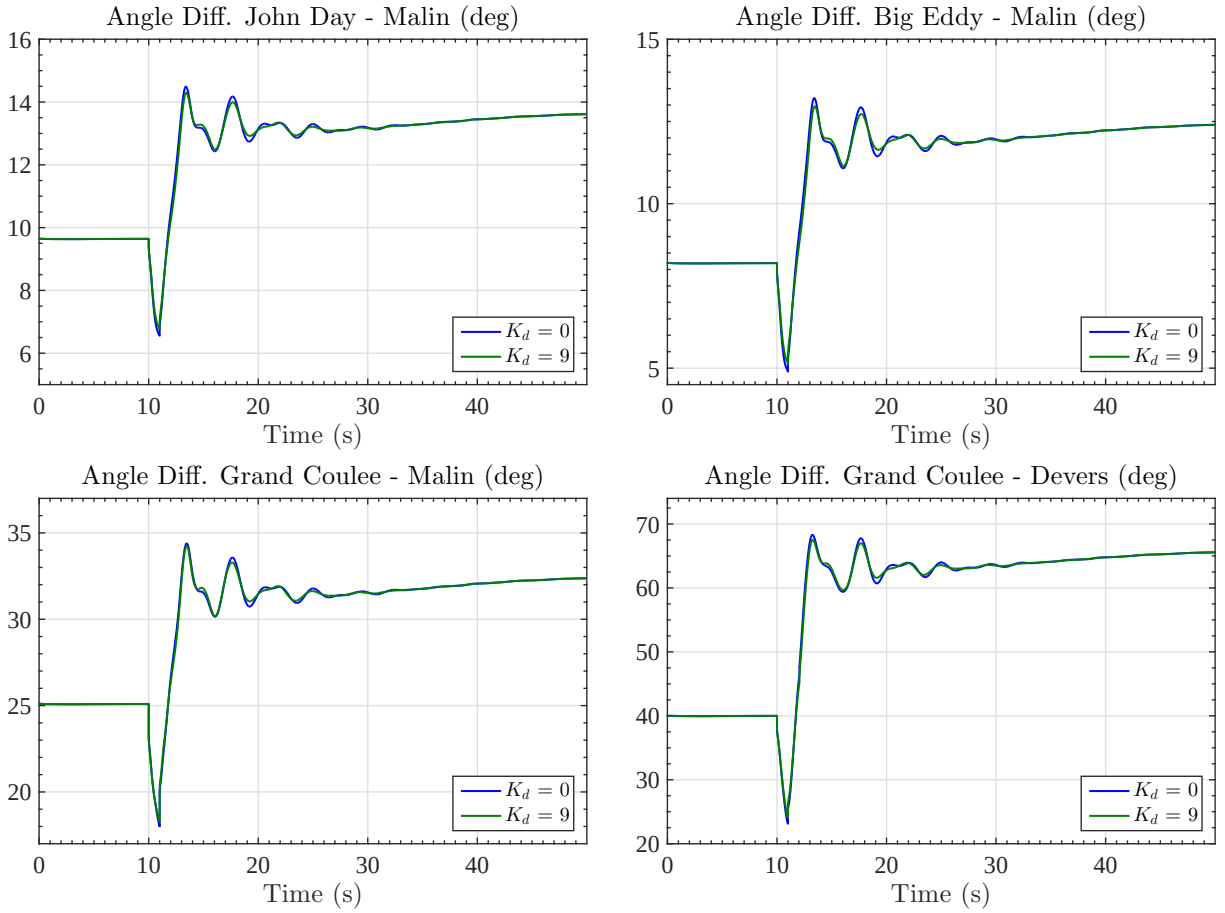


Figure 236. Angle differences. Event: Chief Joe Brake followed by double Palo Verde outage.

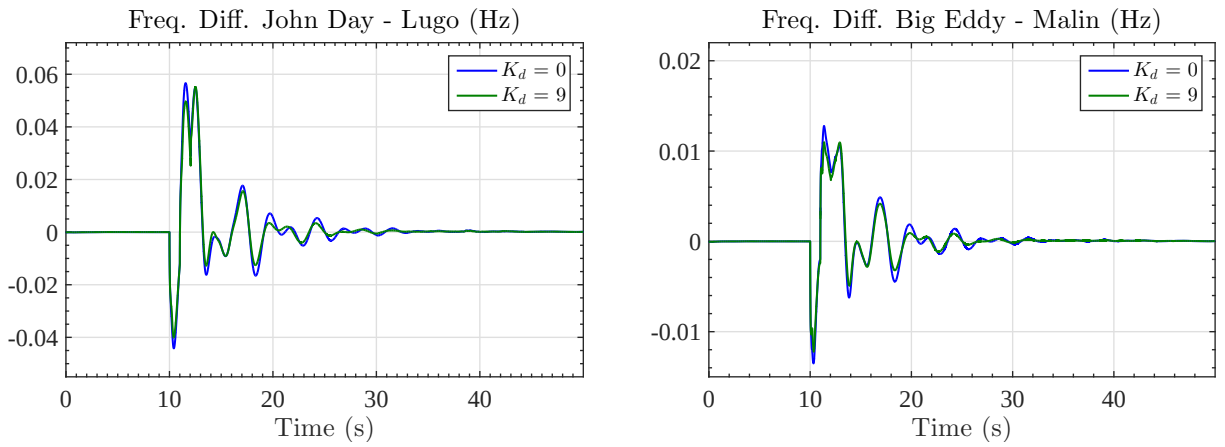


Figure 237. Frequency differences. Event: Chief Joe Brake followed by double Palo Verde outage.

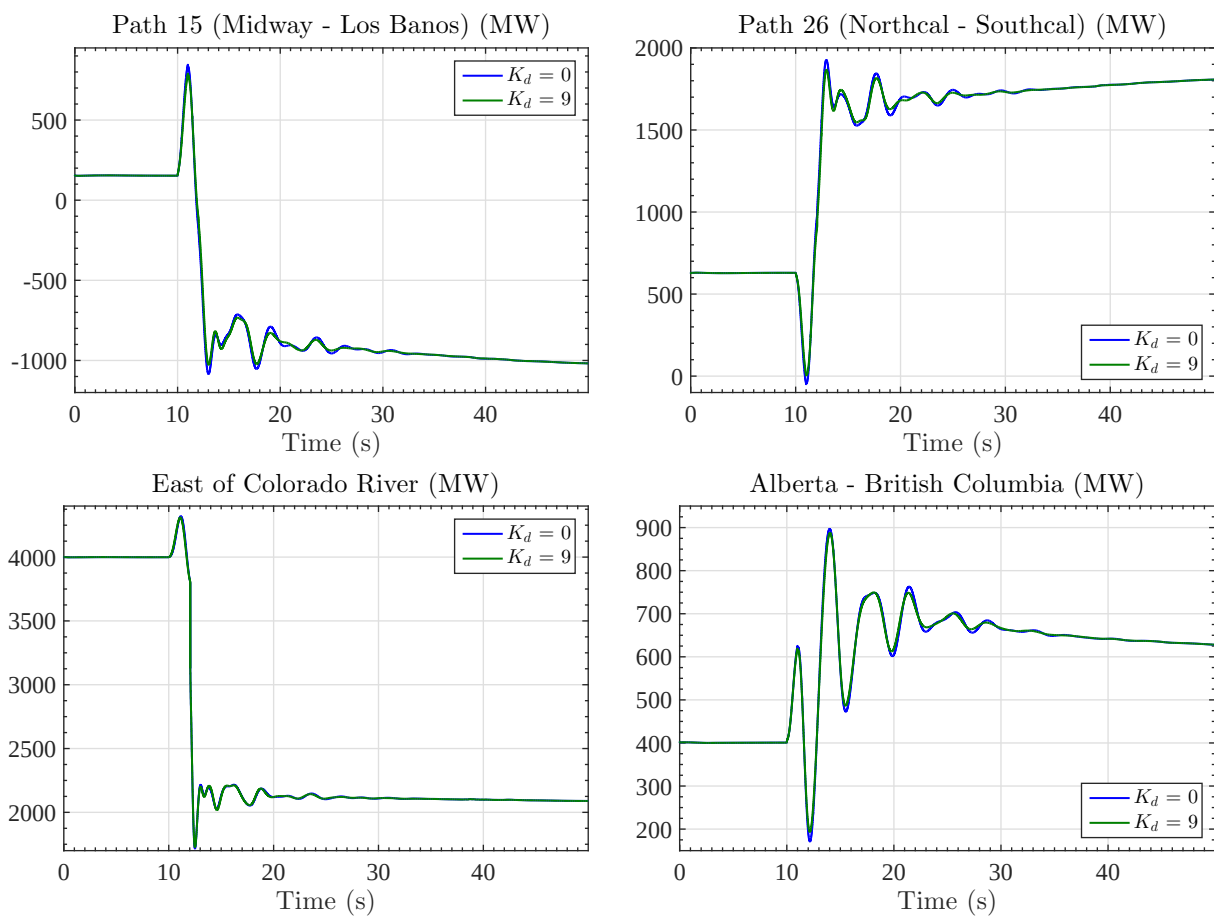


Figure 238. Active power flows. Event: Chief Joe Brake followed by double Palo Verde outage.

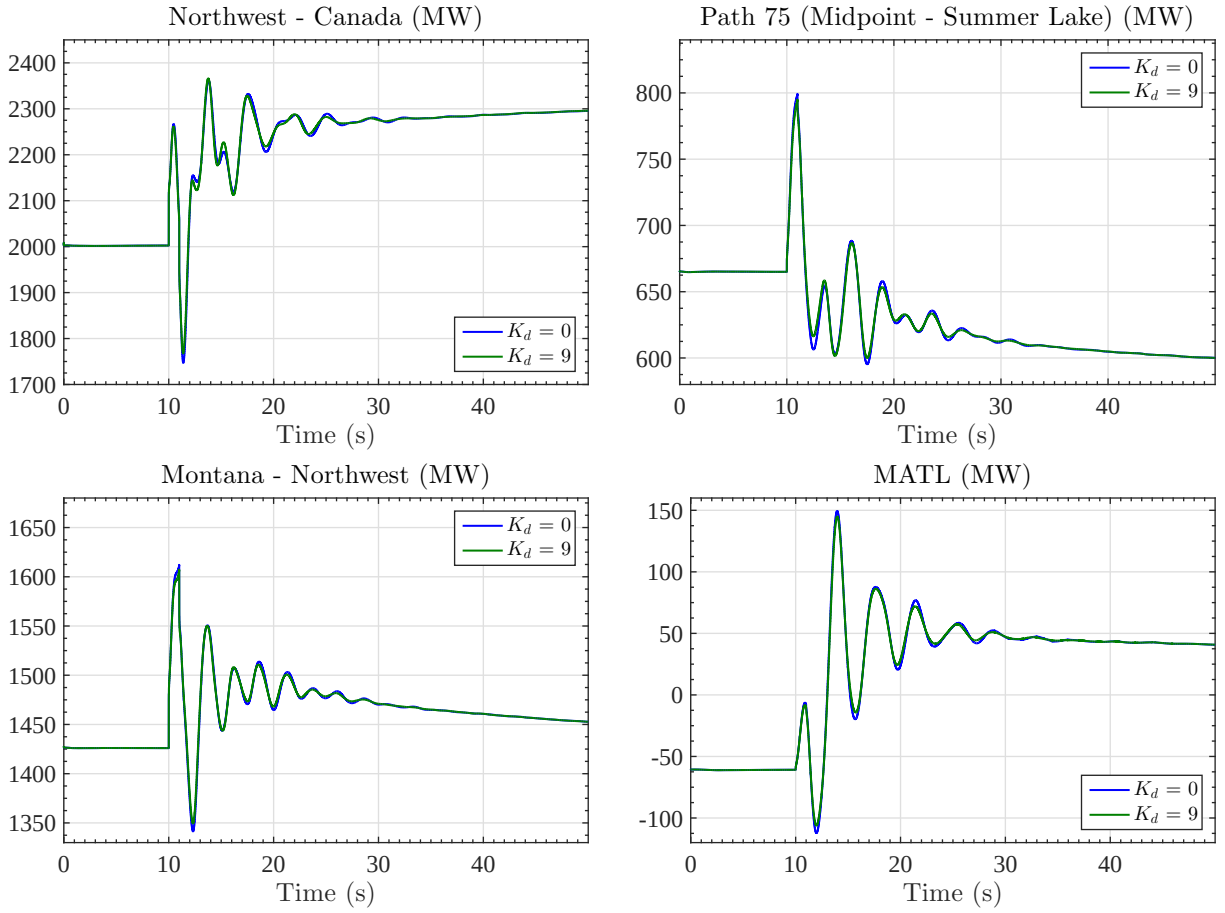


Figure 239. Active power flows. Event: Chief Joe Brake followed by double Palo Verde outage.

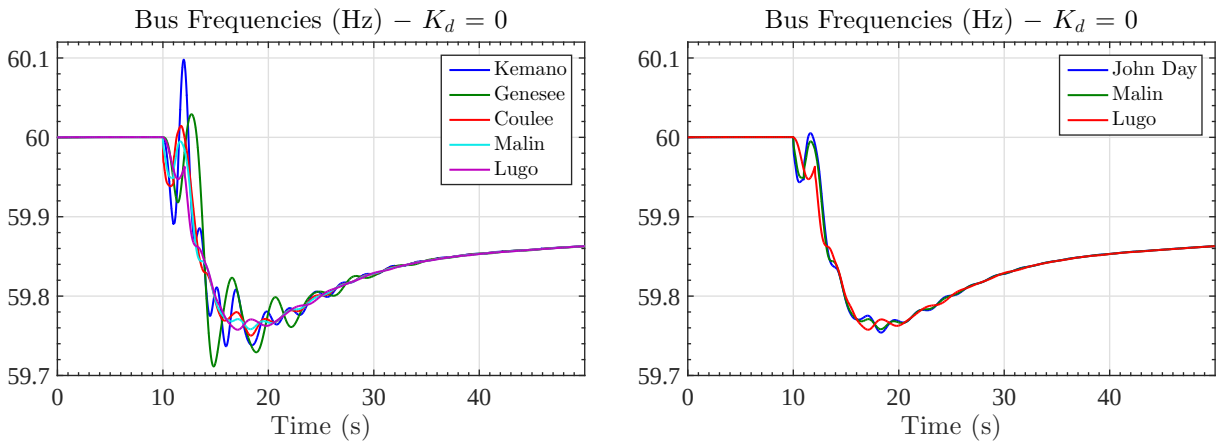


Figure 240. Bus frequencies. Event: Chief Joe Brake followed by double Palo Verde outage.

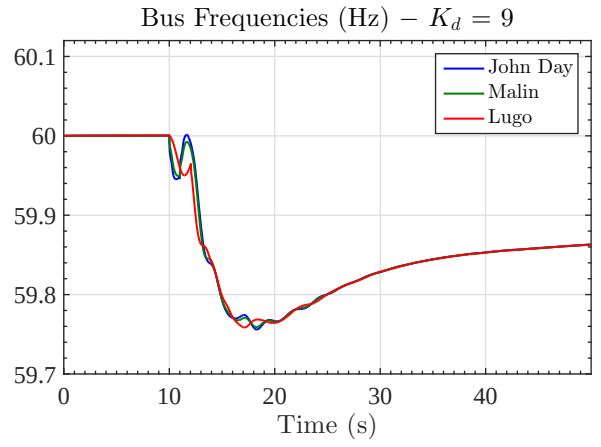
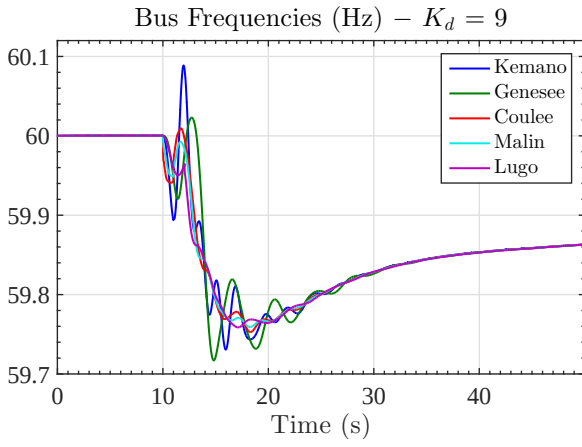


Figure 241. Bus frequencies. Event: Chief Joe Brake followed by double Palo Verde outage.

4.1.3. Test System: Light Summer 2016. Event: Chief Joe Brake followed by CGS outage

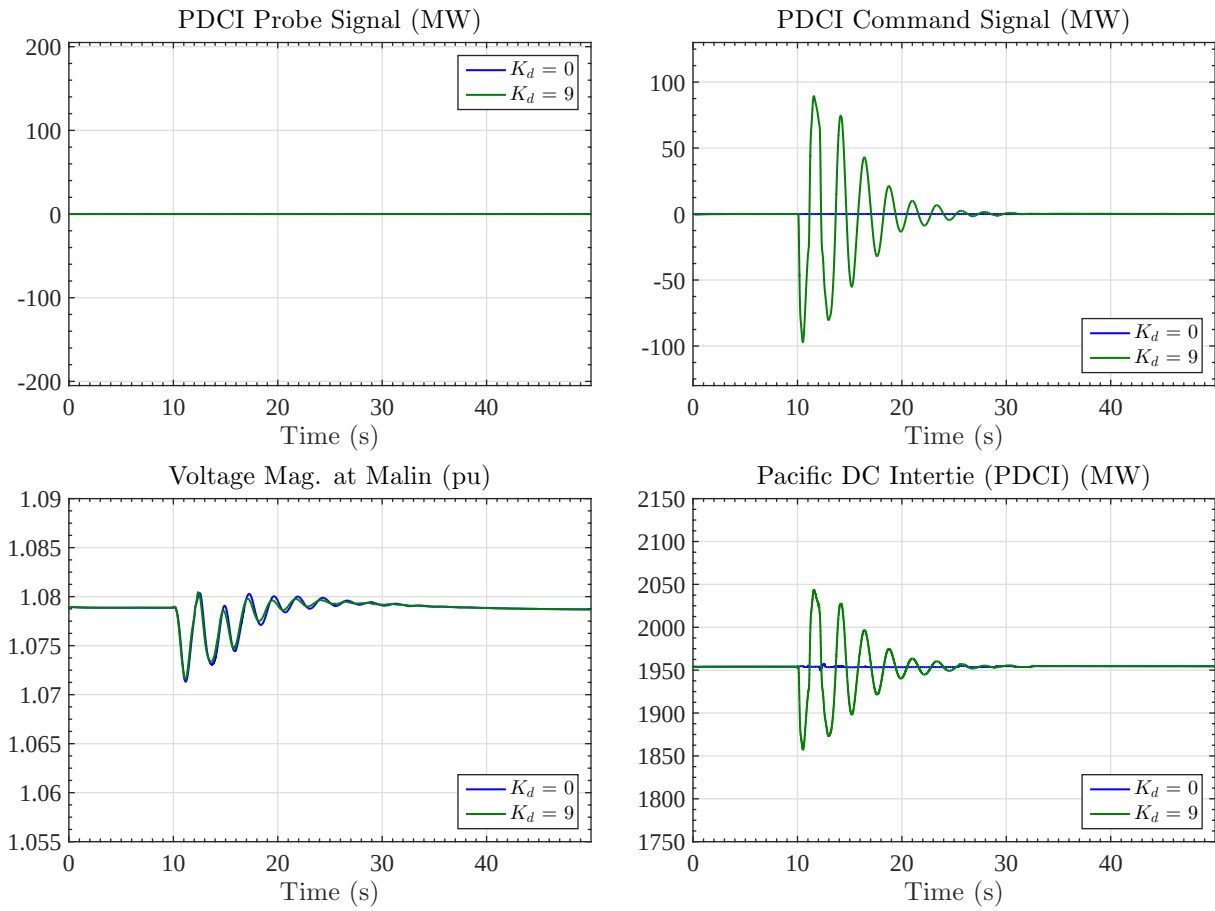


Figure 242. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake followed by CGS outage.

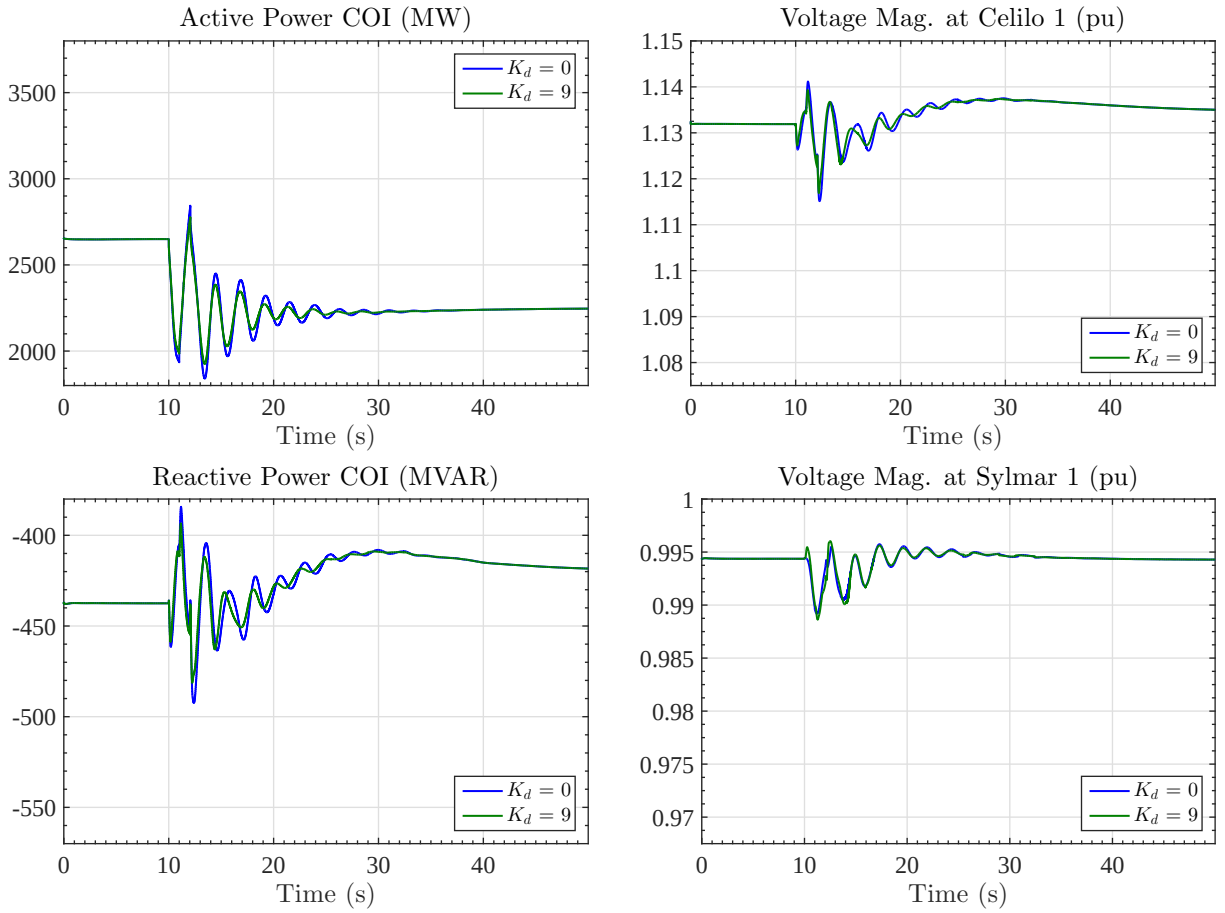


Figure 243. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake followed by CGS outage.

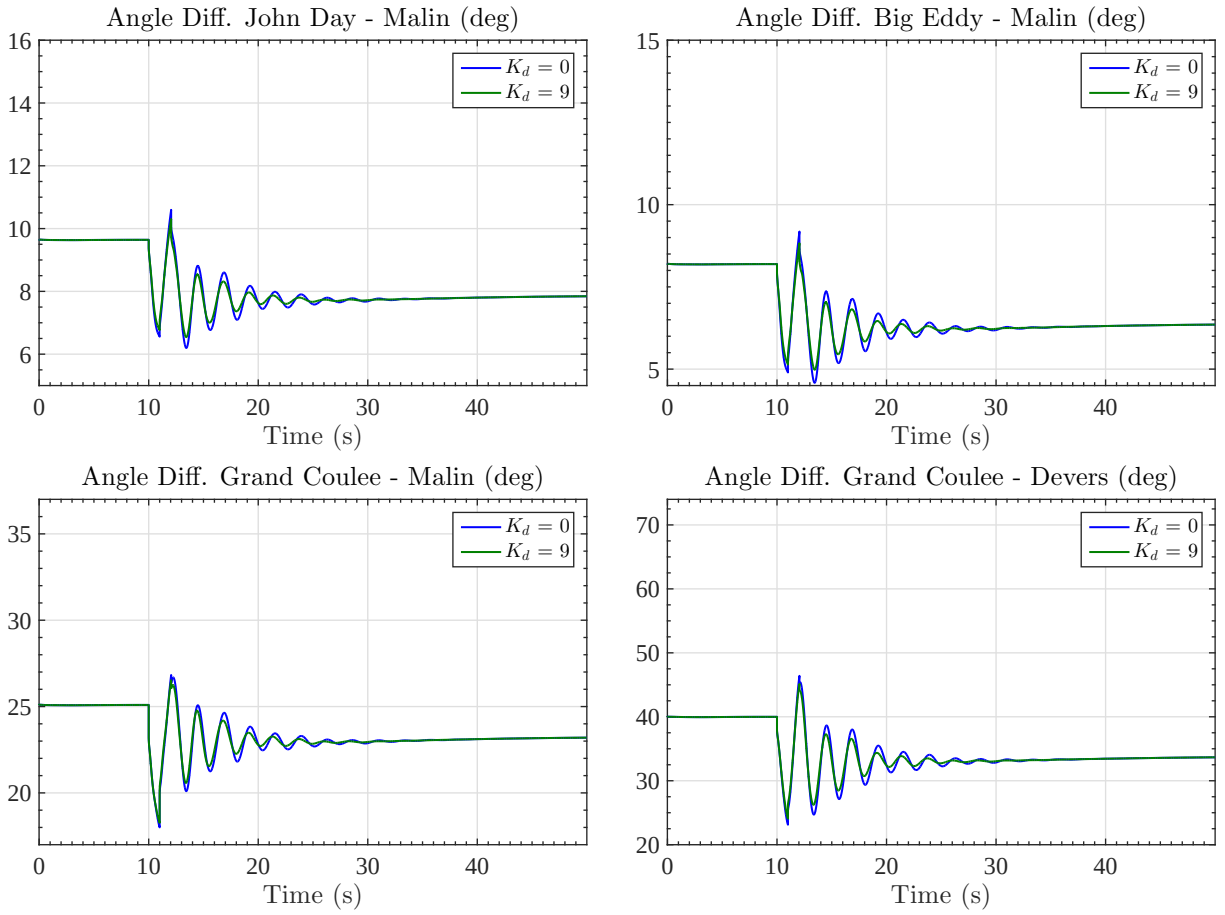


Figure 244. Angle differences. Event: Chief Joe Brake followed by CGS outage.

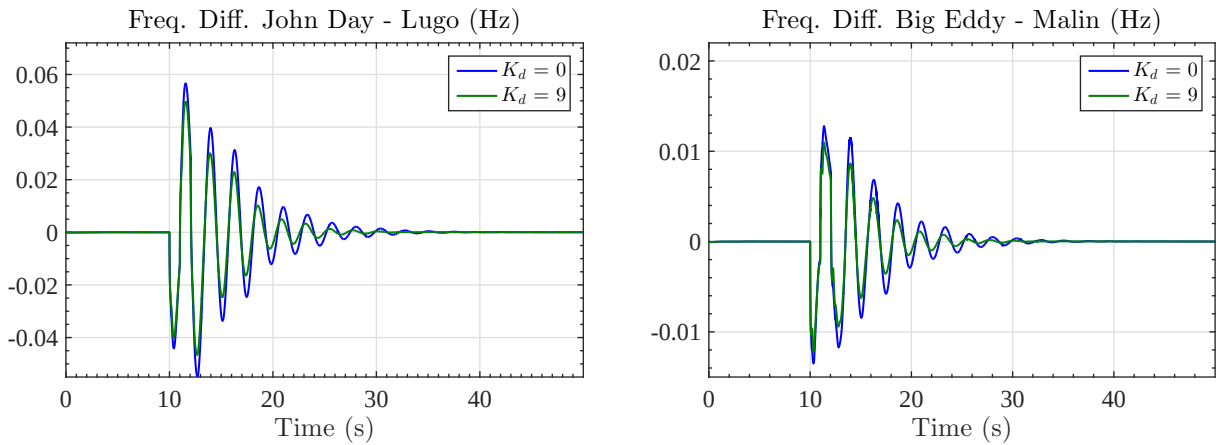


Figure 245. Frequency differences. Event: Chief Joe Brake followed by CGS outage.

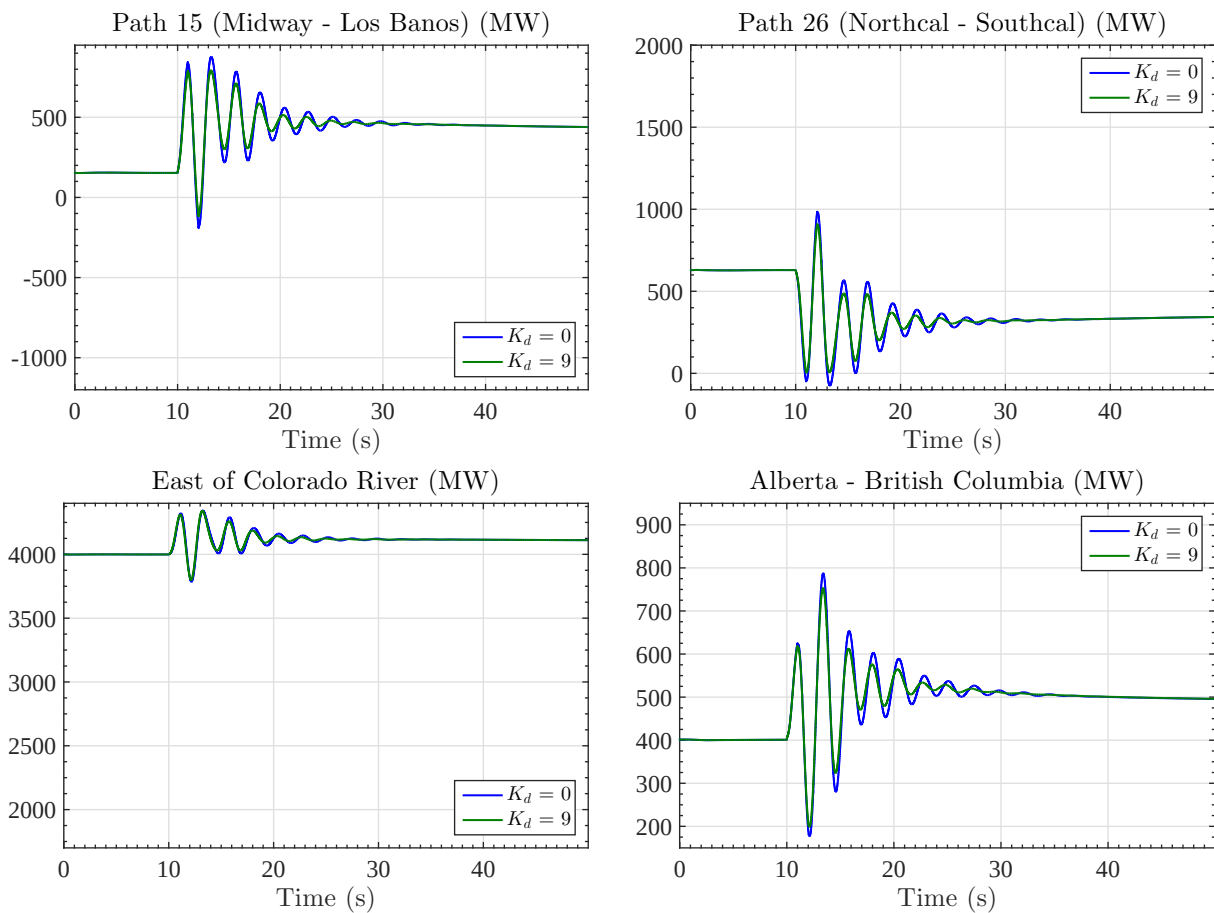


Figure 246. Active power flows. Event: Chief Joe Brake followed by CGS outage.

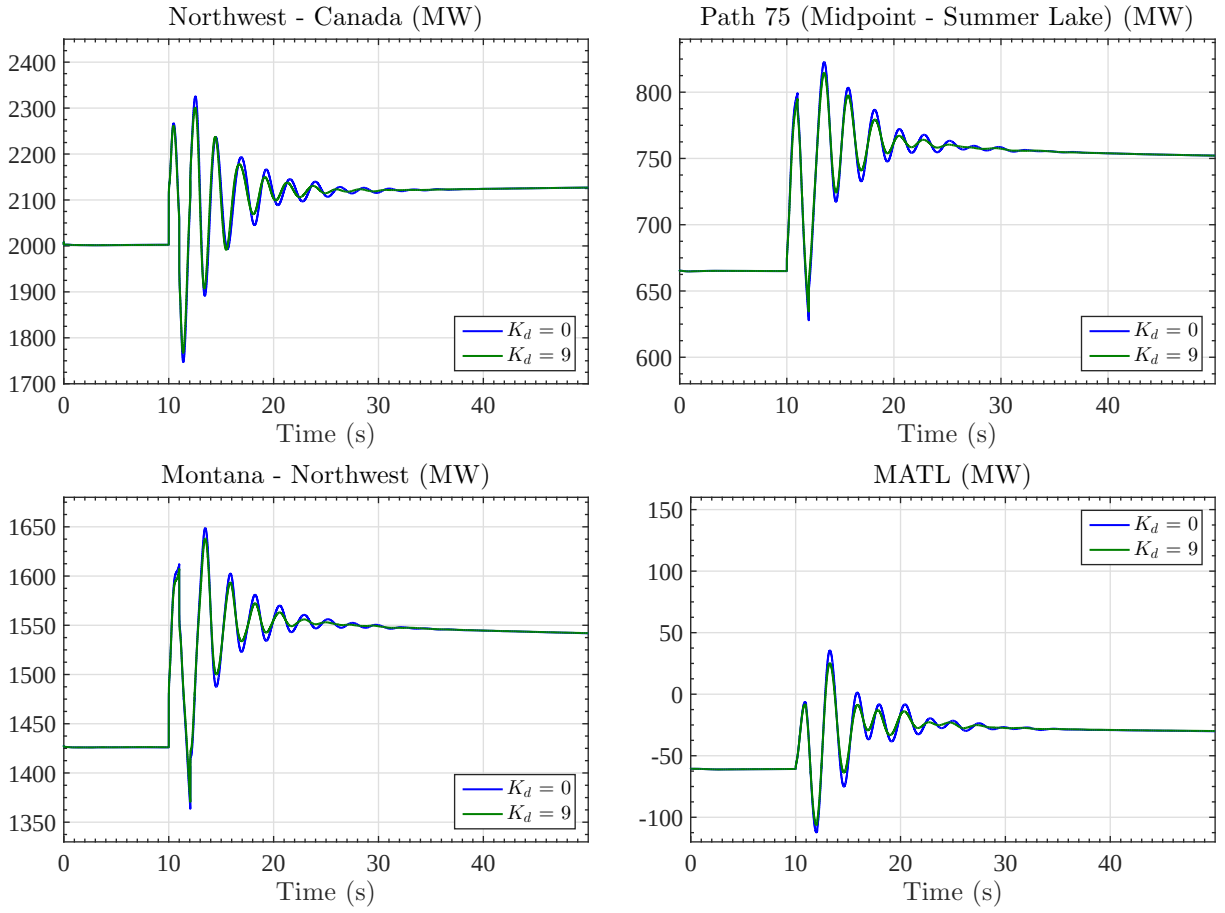


Figure 247. Active power flows. Event: Chief Joe Brake followed by CGS outage.

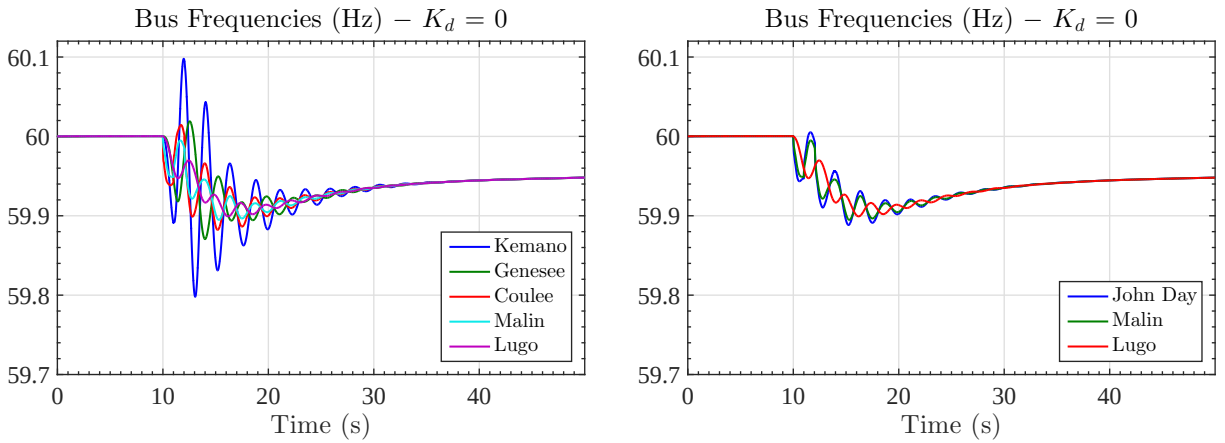


Figure 248. Bus frequencies. Event: Chief Joe Brake followed by CGS outage.

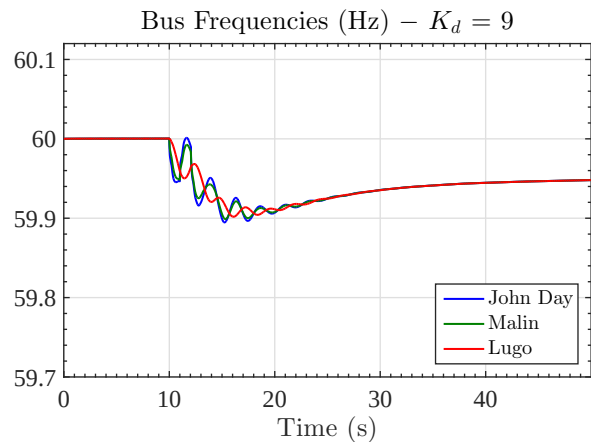
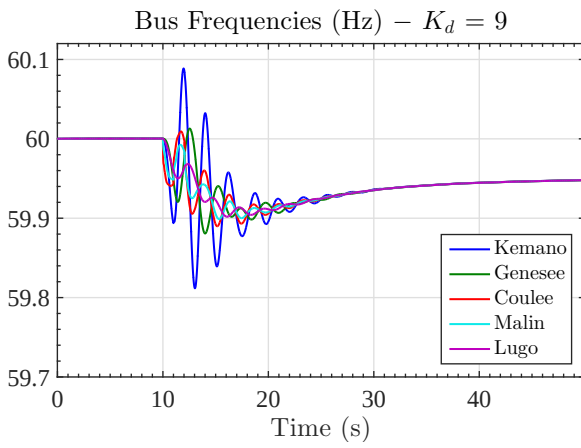


Figure 249. Bus frequencies. Event: Chief Joe Brake followed by CGS outage.

4.1.4. Test System: Light Summer 2016. Event: 200 MW pulses followed by forced oscillation

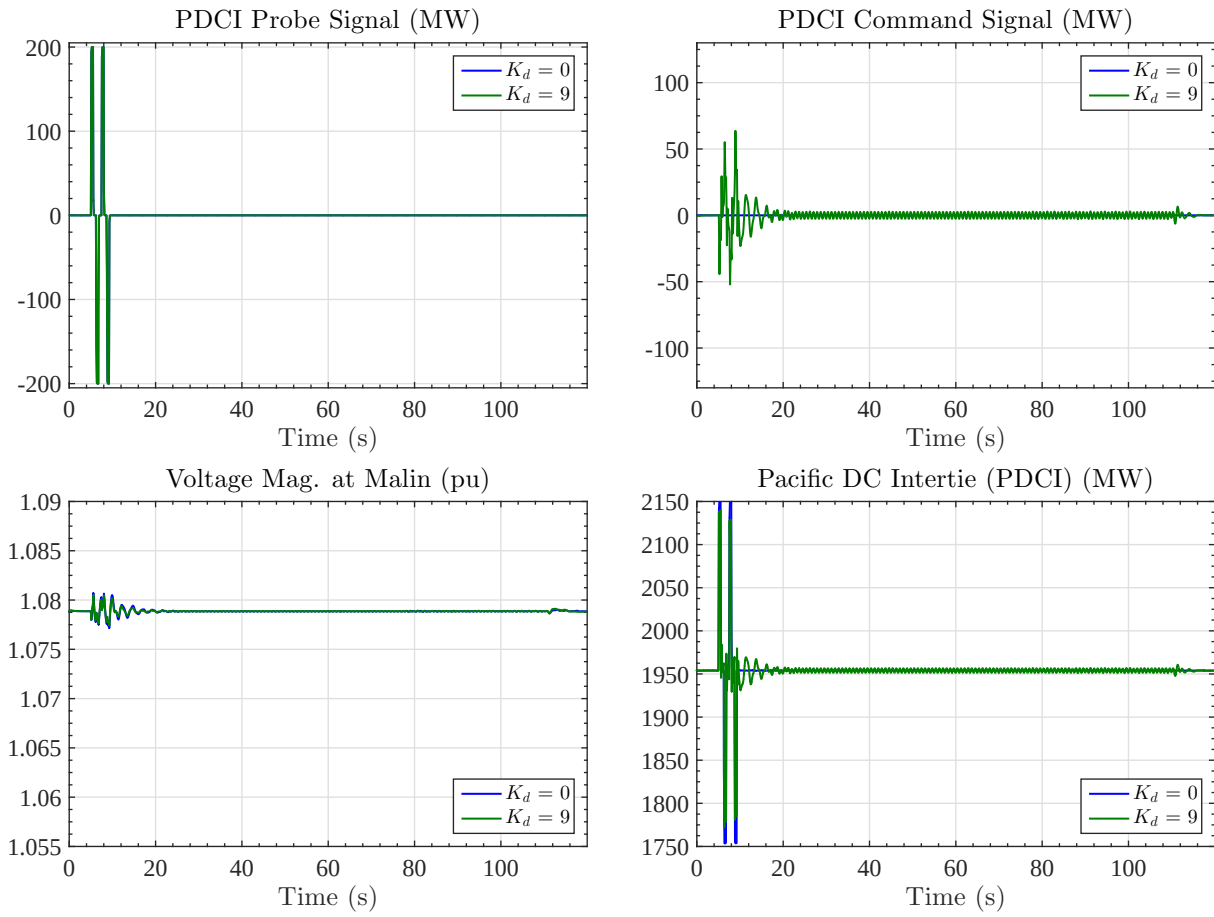


Figure 250. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses followed by forced oscillation.

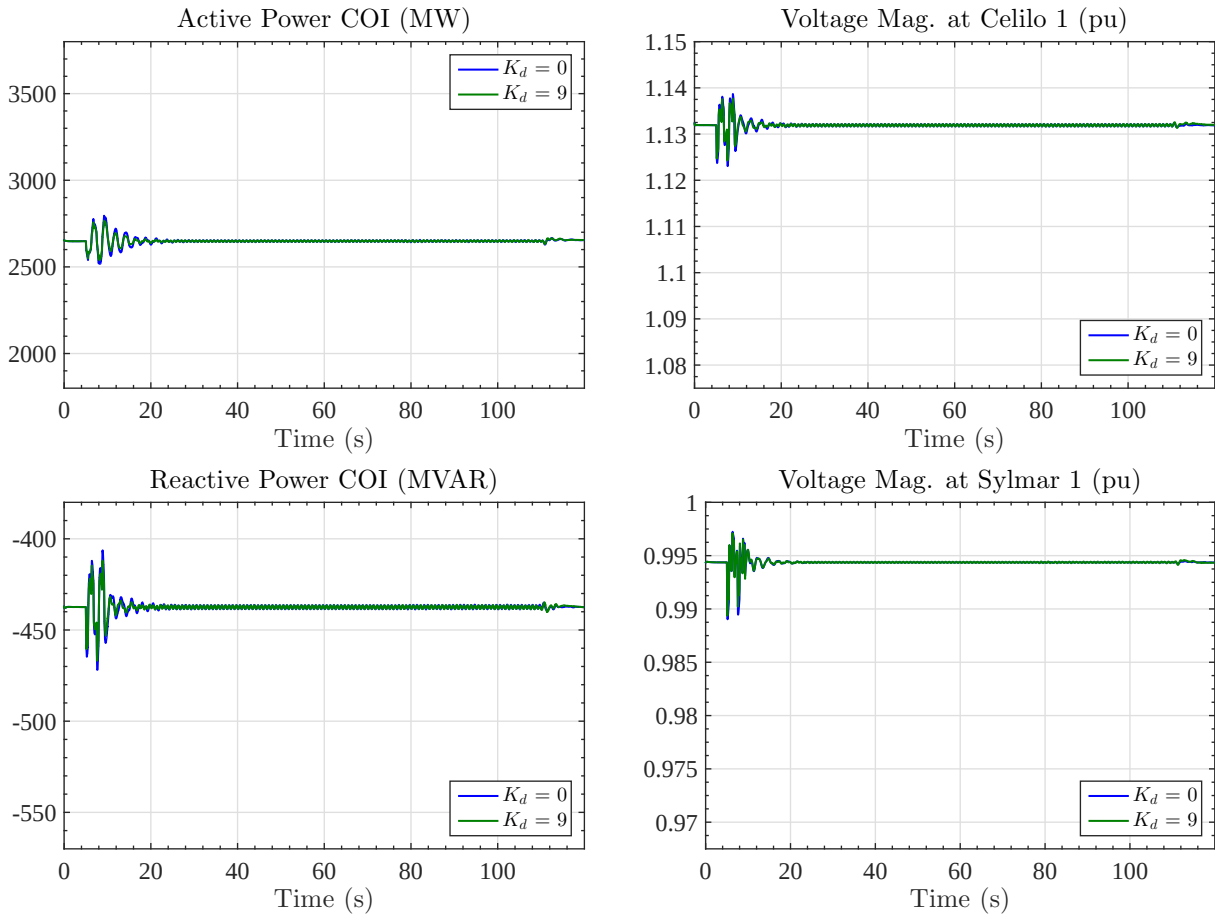


Figure 251. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses followed by forced oscillation.

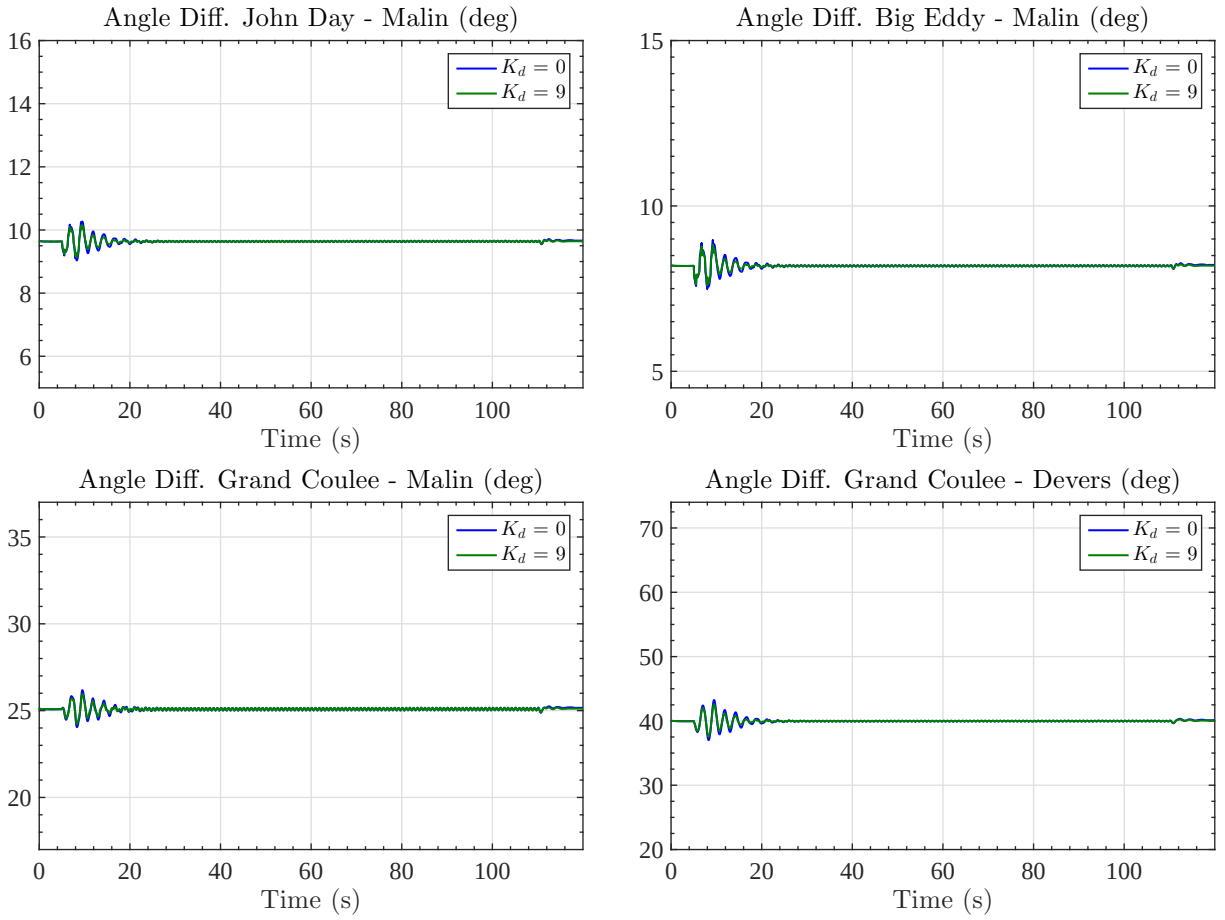


Figure 252. Angle differences. Event: 200 MW pulses followed by forced oscillation.

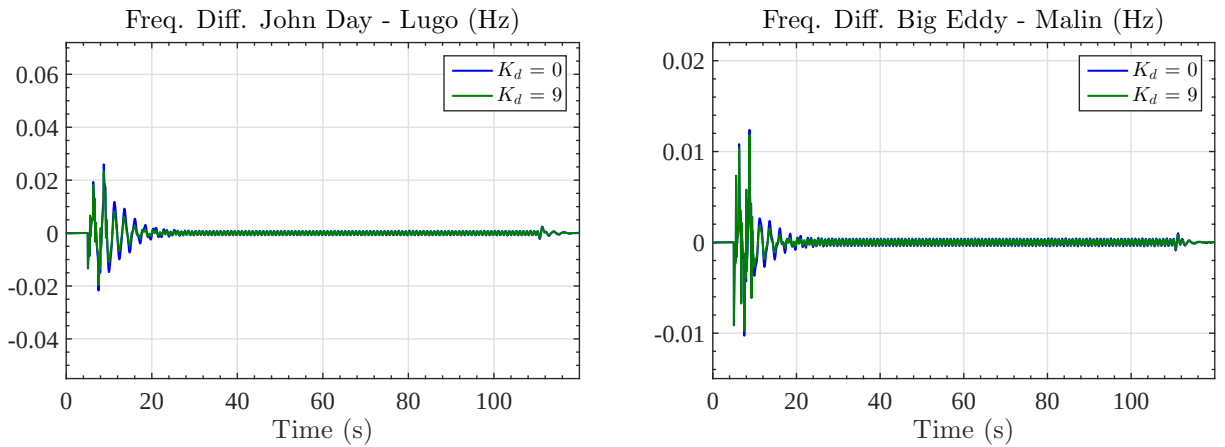


Figure 253. Frequency differences. Event: 200 MW pulses followed by forced oscillation.

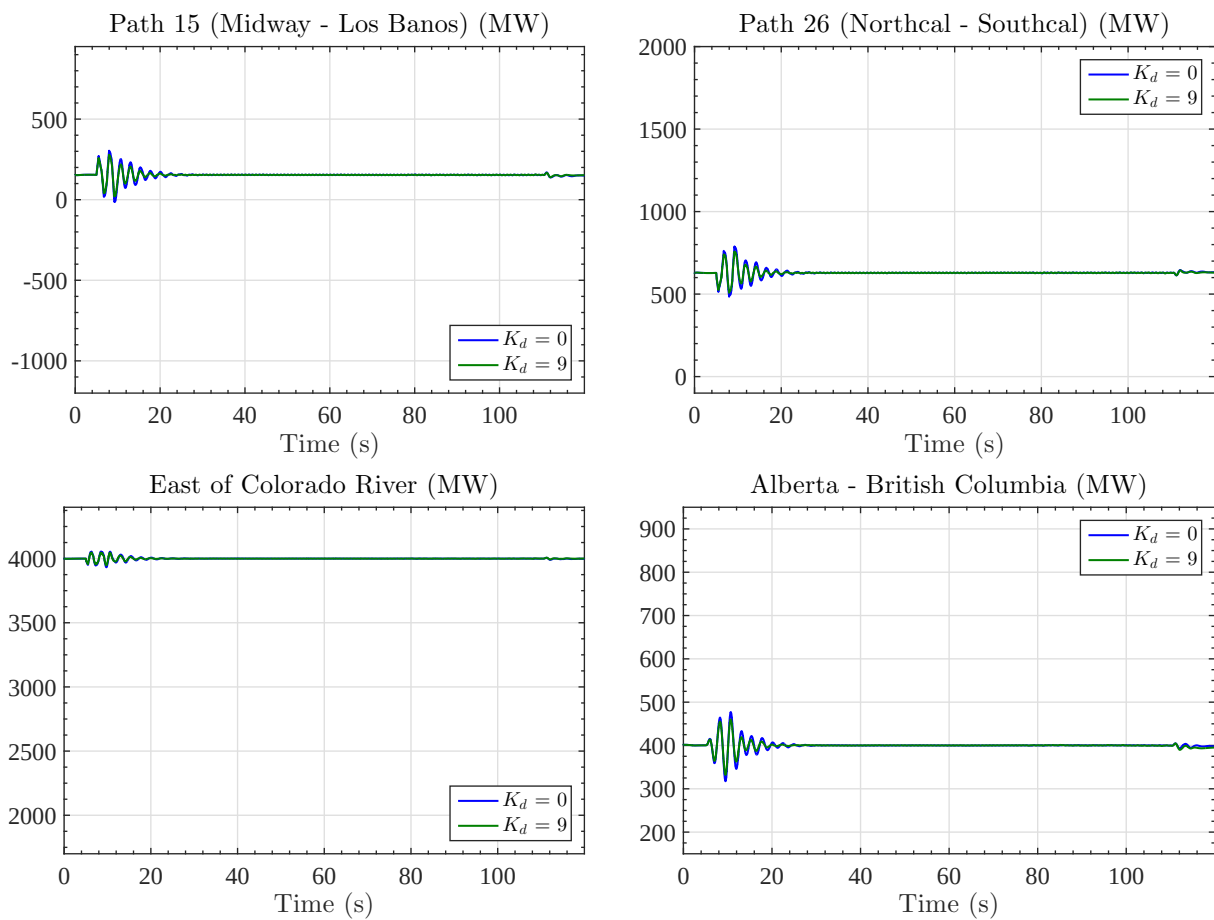


Figure 254. Active power flows. Event: 200 MW pulses followed by forced oscillation.

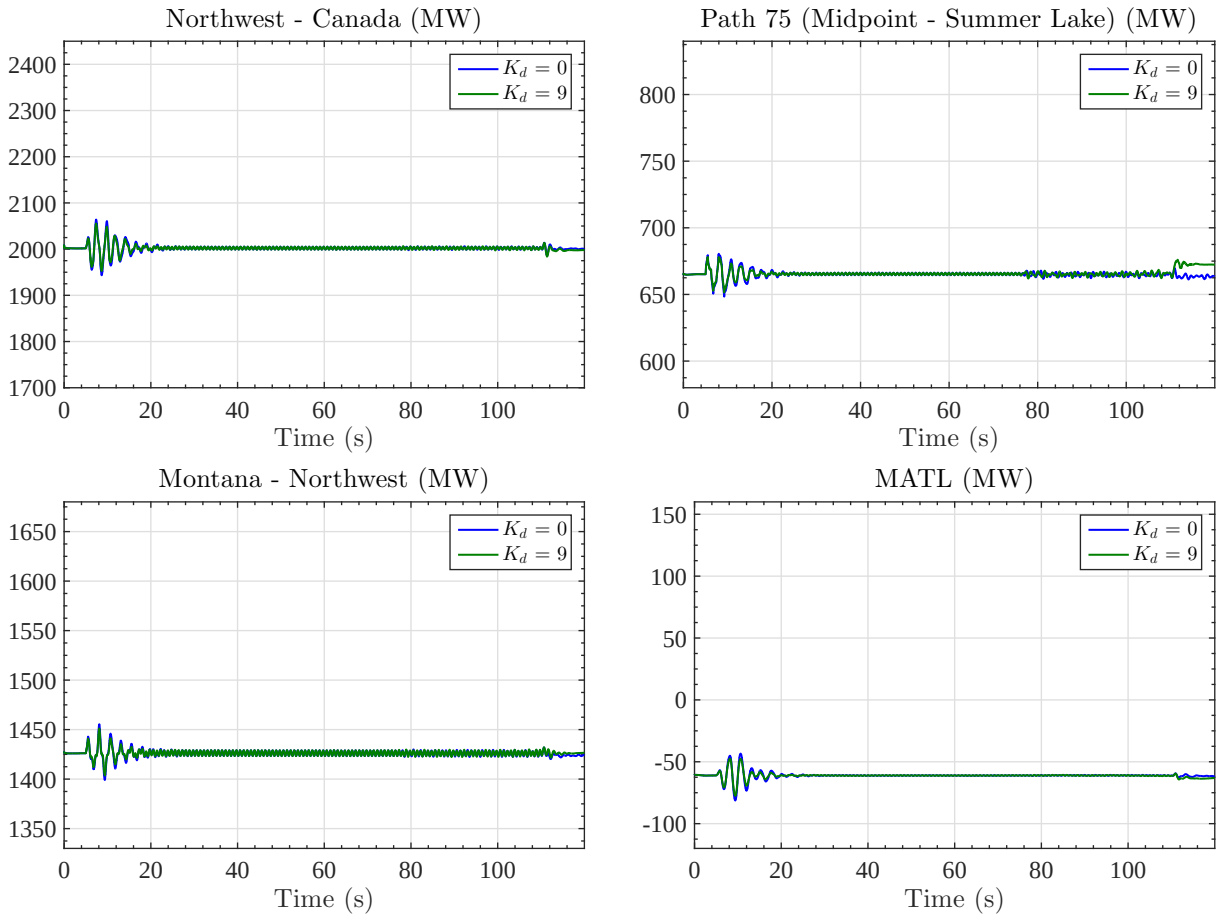


Figure 255. Active power flows. Event: 200 MW pulses followed by forced oscillation.

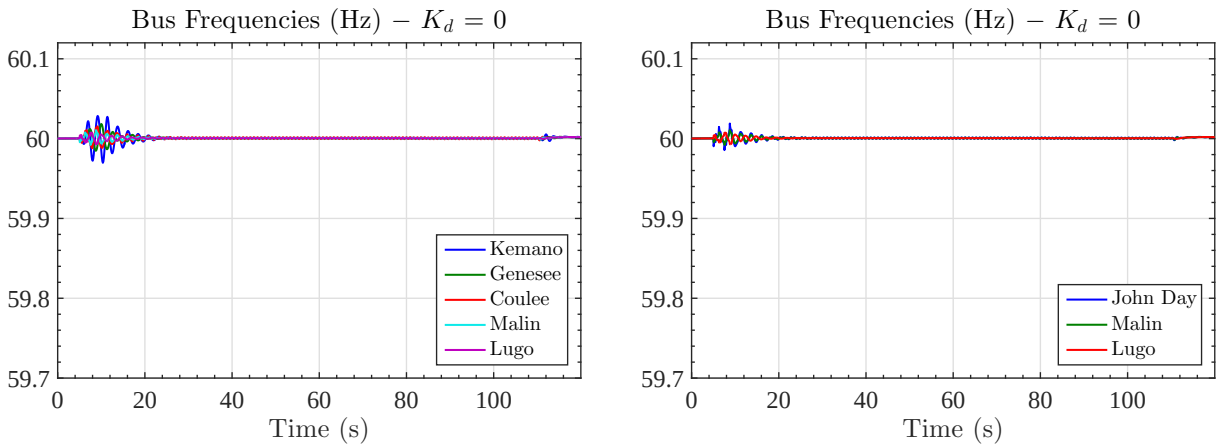


Figure 256. Bus frequencies. Event: 200 MW pulses followed by forced oscillation.

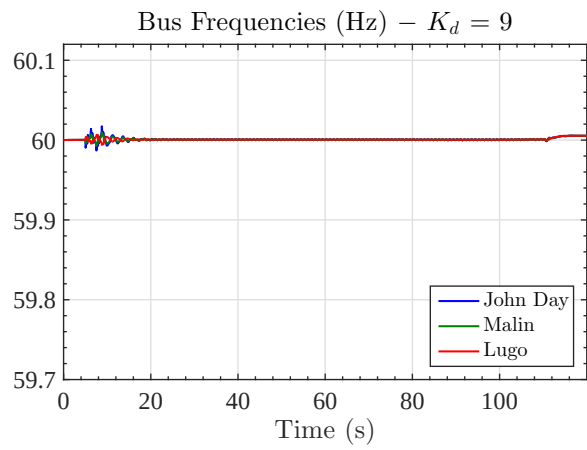
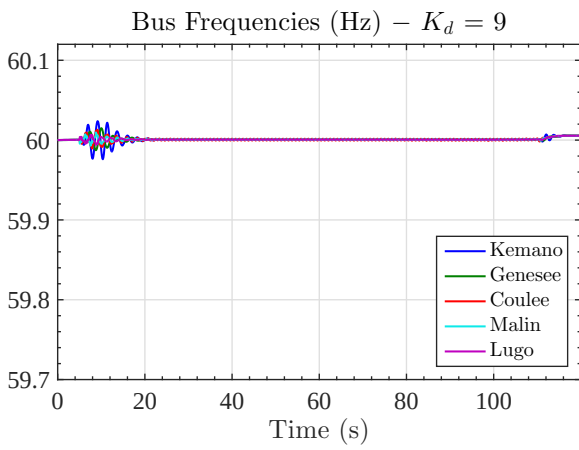


Figure 257. Bus frequencies. Event: 200 MW pulses followed by forced oscillation.

4.1.5. Test System: Light Summer 2016. Event: 200 MW pulses followed by double Palo Verde outage

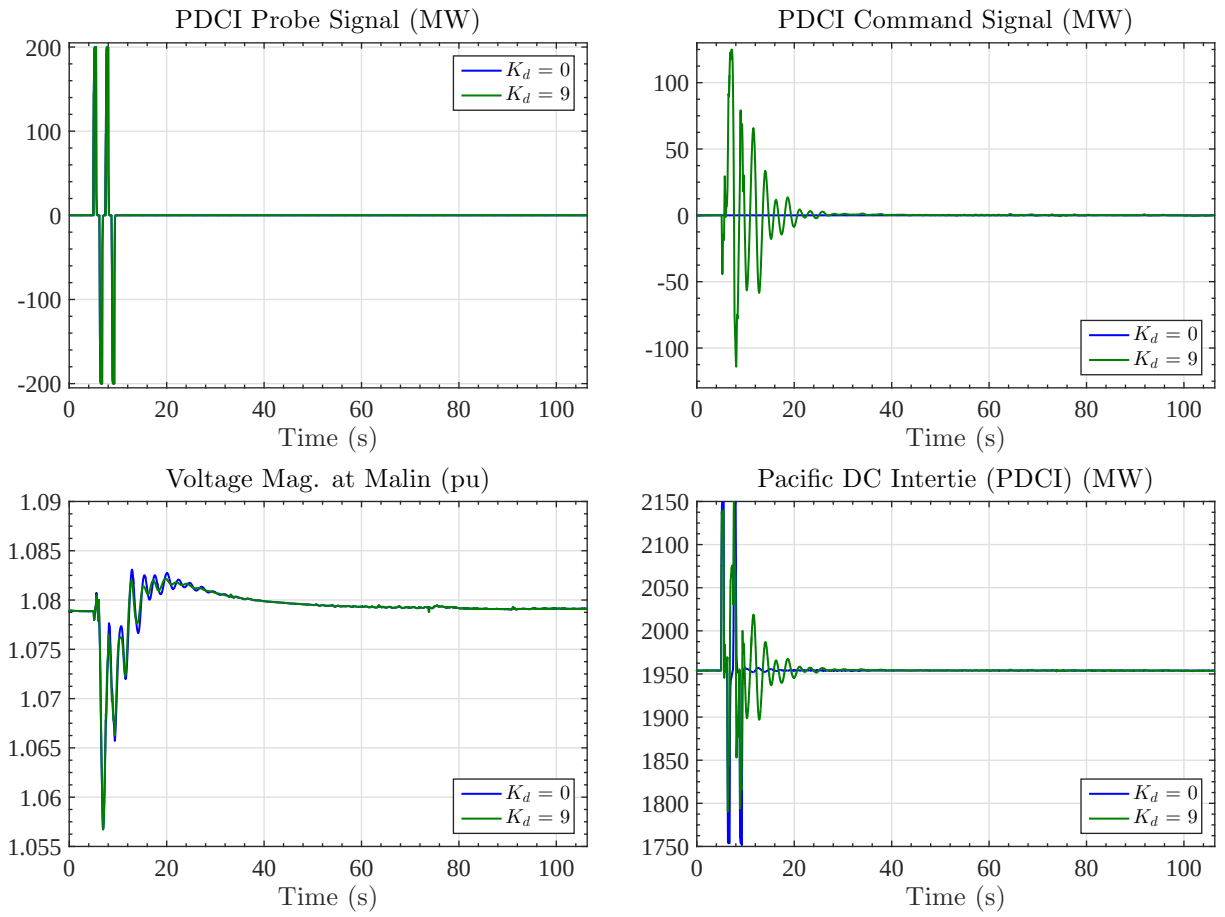


Figure 258. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses followed by double Palo Verde outage.

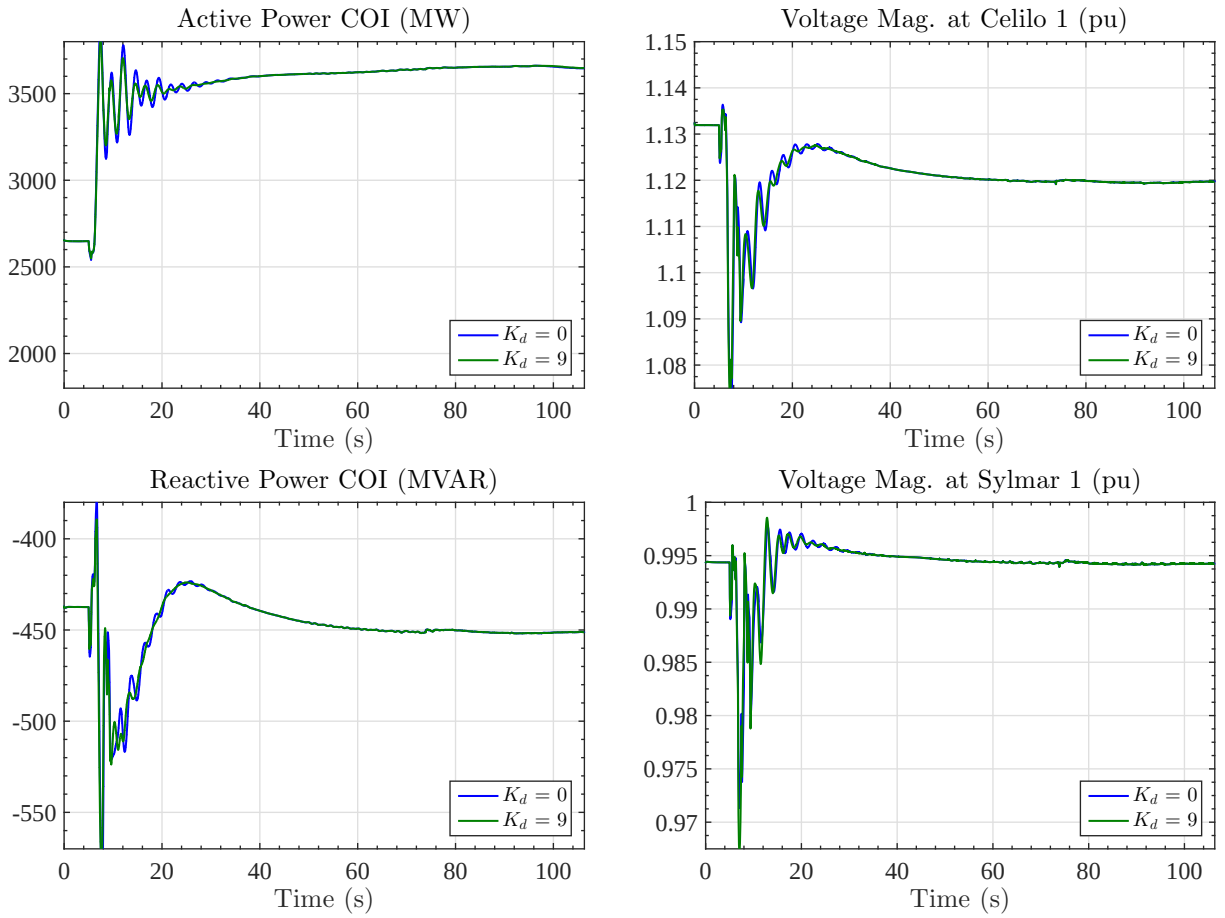


Figure 259. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses followed by double Palo Verde outage.

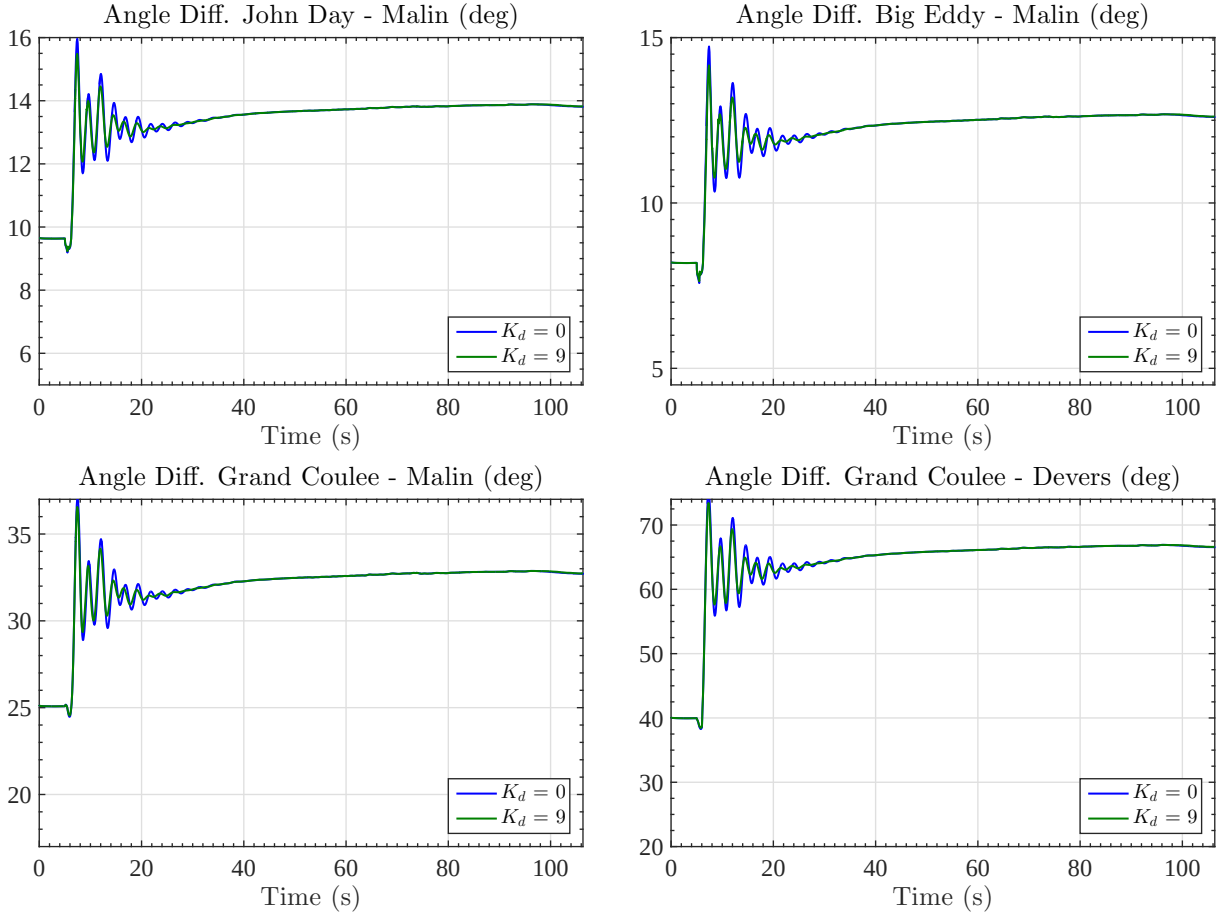


Figure 260. Angle differences. Event: 200 MW pulses followed by double Palo Verde outage.

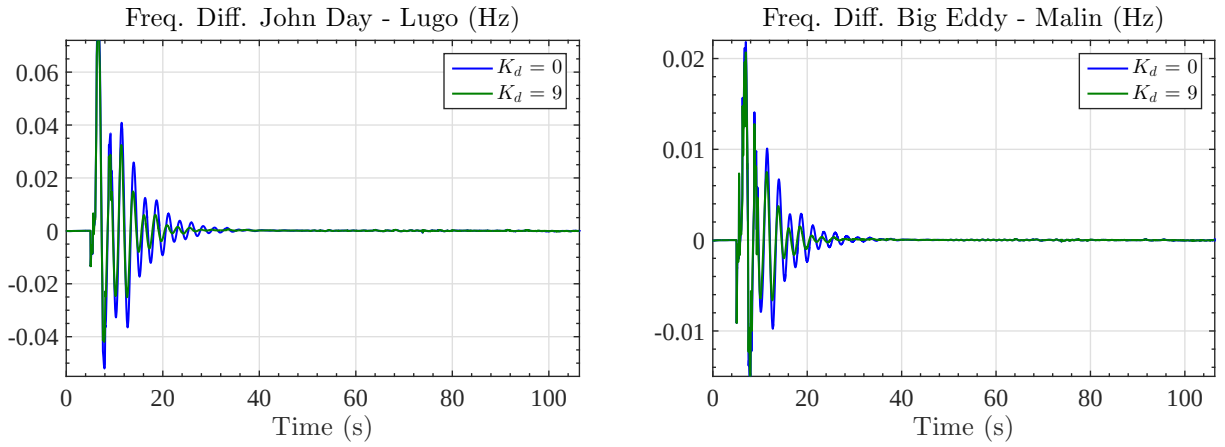


Figure 261. Frequency differences. Event: 200 MW pulses followed by double Palo Verde outage.

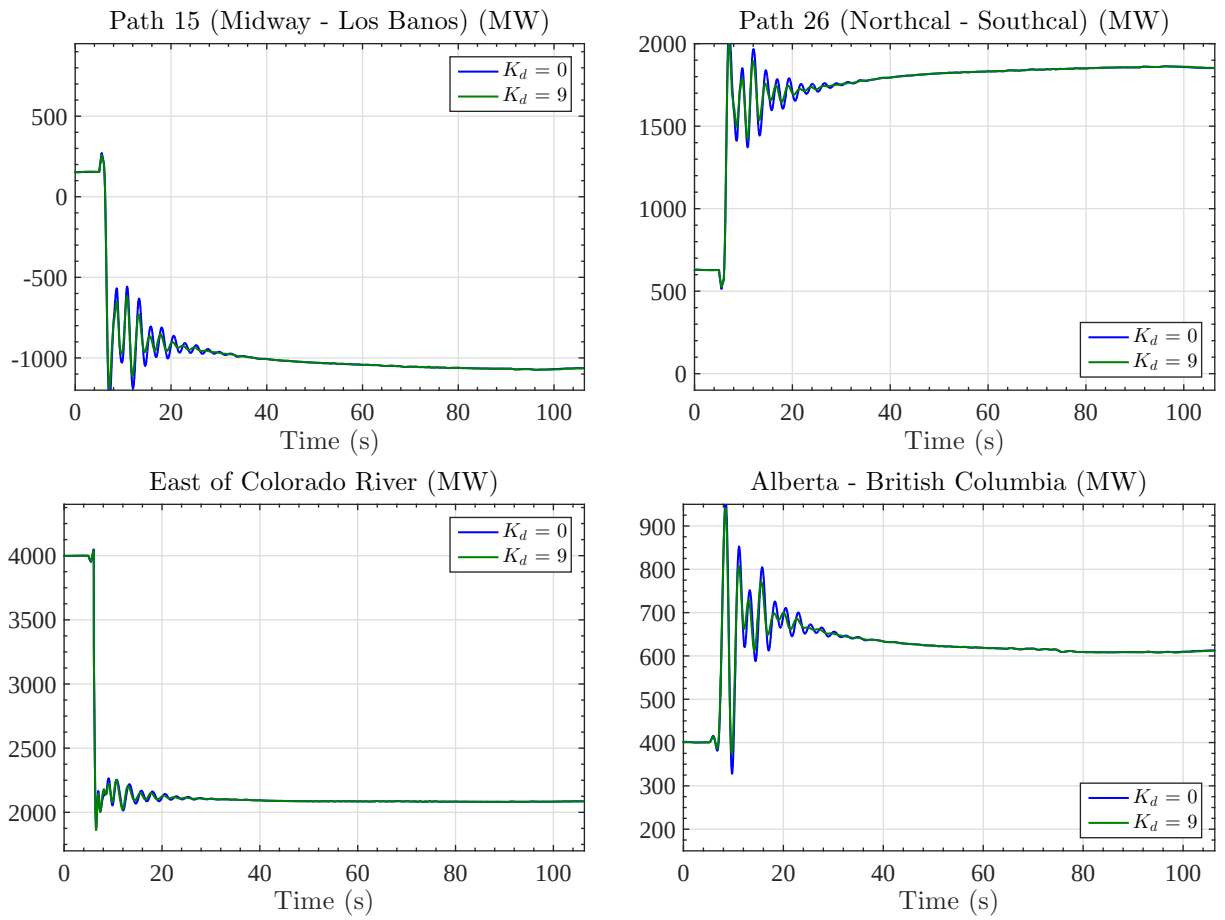


Figure 262. Active power flows. Event: 200 MW pulses followed by double Palo Verde outage.

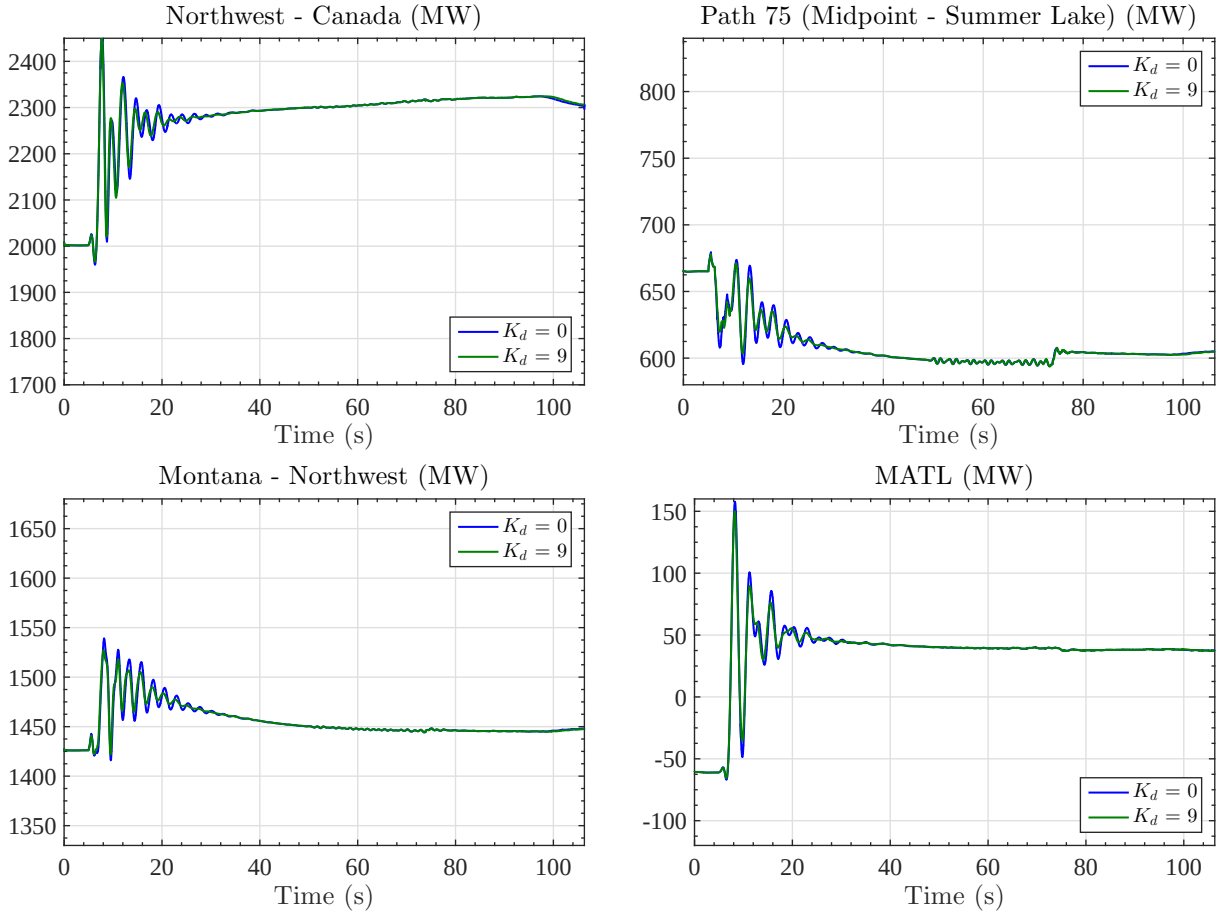


Figure 263. Active power flows. Event: 200 MW pulses followed by double Palo Verde outage.

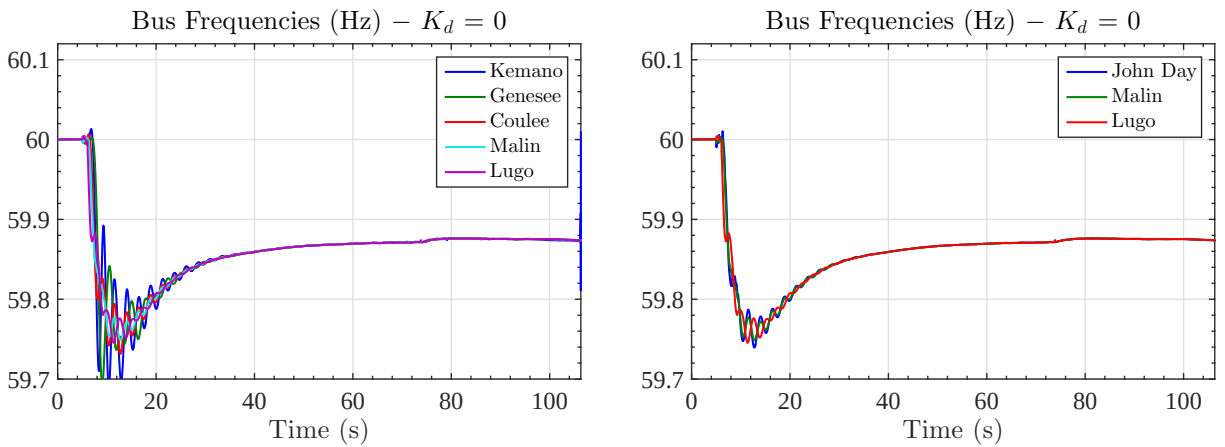


Figure 264. Bus frequencies. Event: 200 MW pulses followed by double Palo Verde outage.

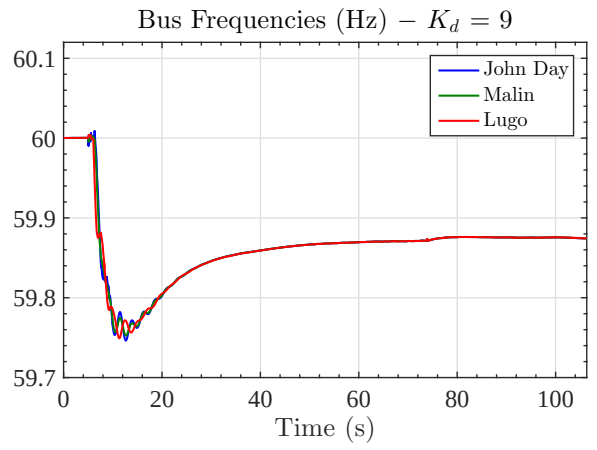
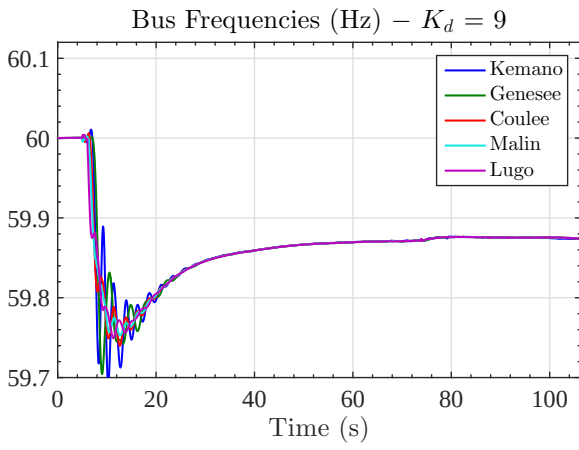


Figure 265. Bus frequencies. Event: 200 MW pulses followed by double Palo Verde outage.

4.1.6. Test System: Light Summer 2016. Event: 200 MW pulses followed by CGS outage

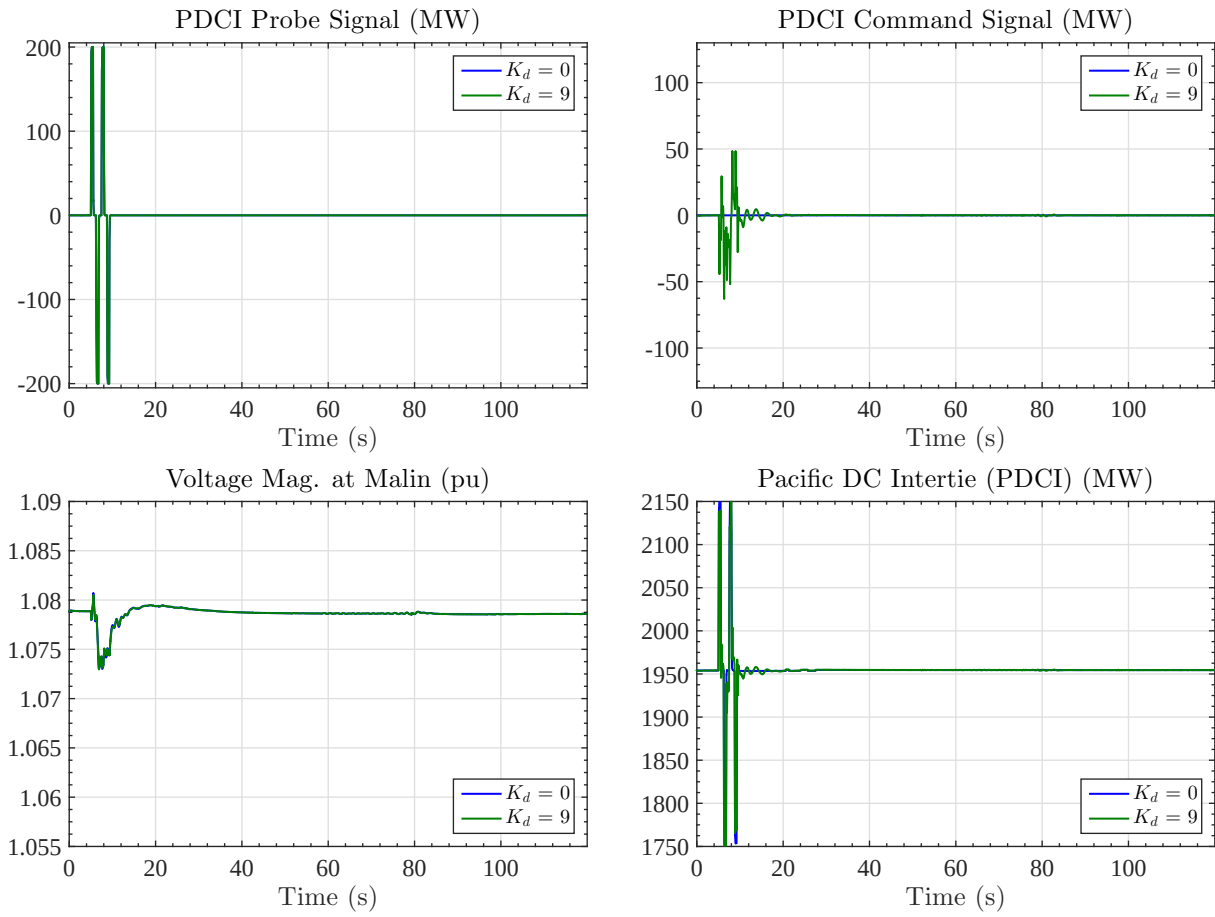


Figure 266. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses followed by CGS outage.

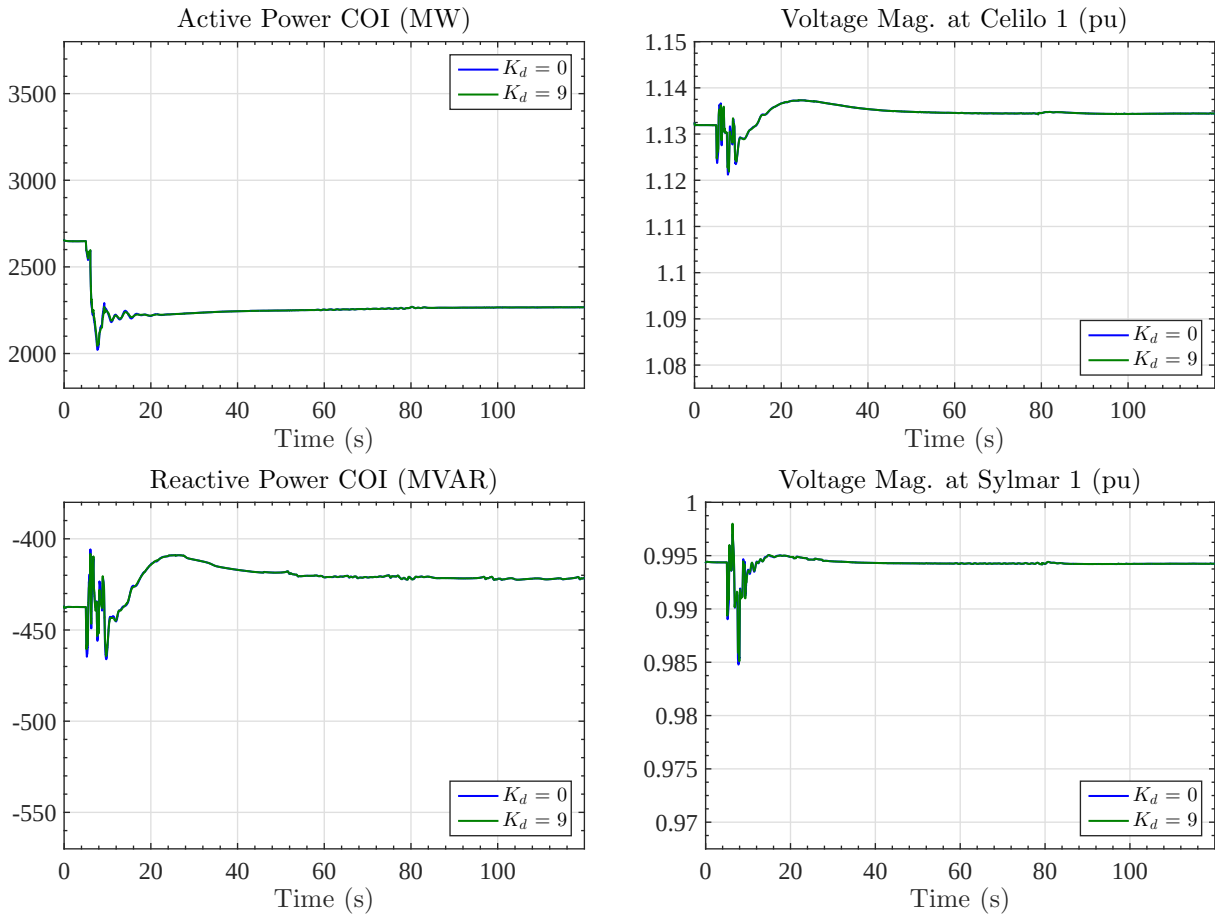


Figure 267. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses followed by CGS outage.

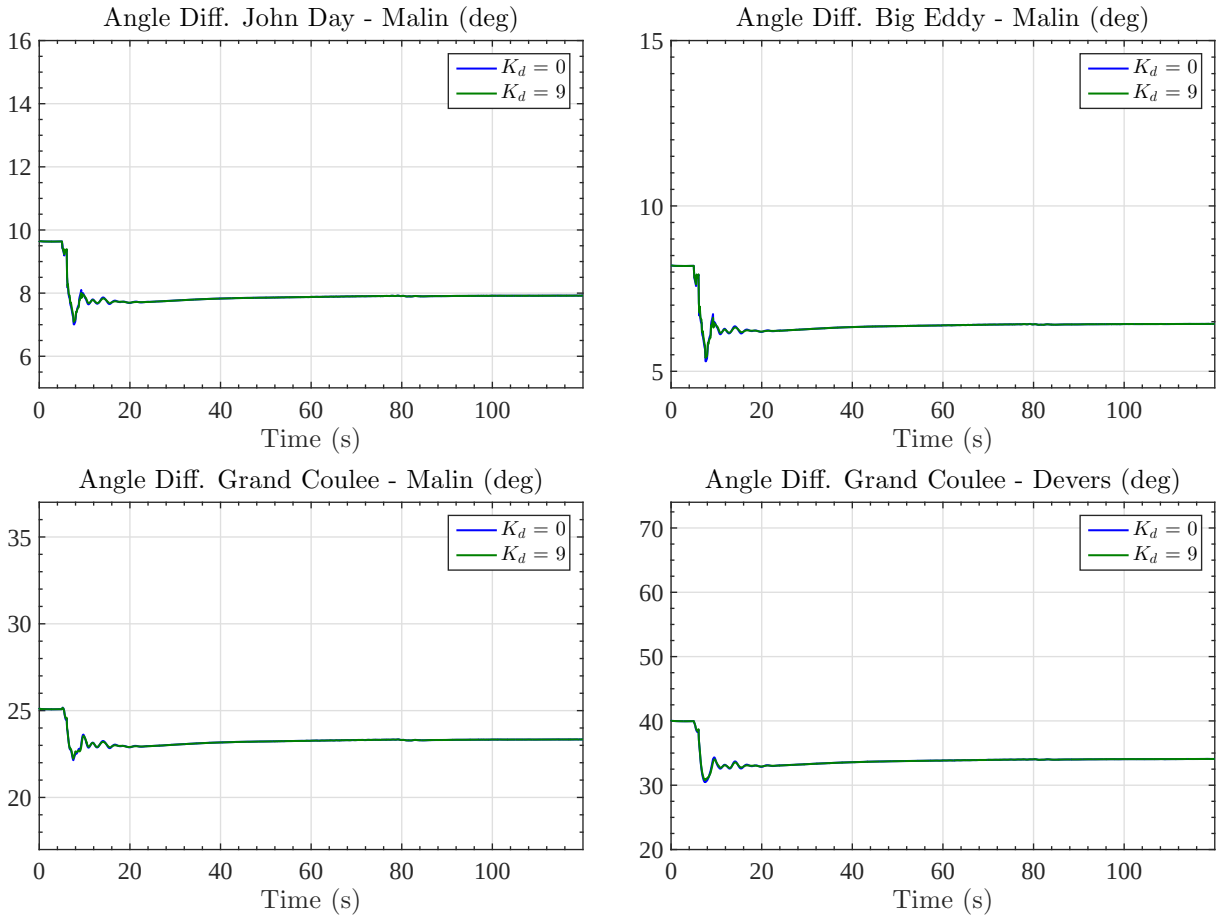


Figure 268. Angle differences. Event: 200 MW pulses followed by CGS outage.

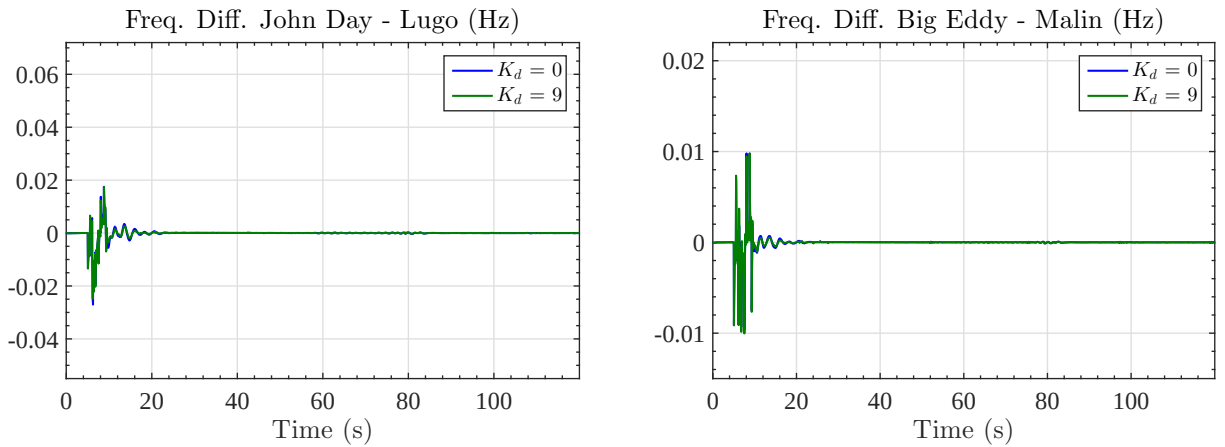


Figure 269. Frequency differences. Event: 200 MW pulses followed by CGS outage.

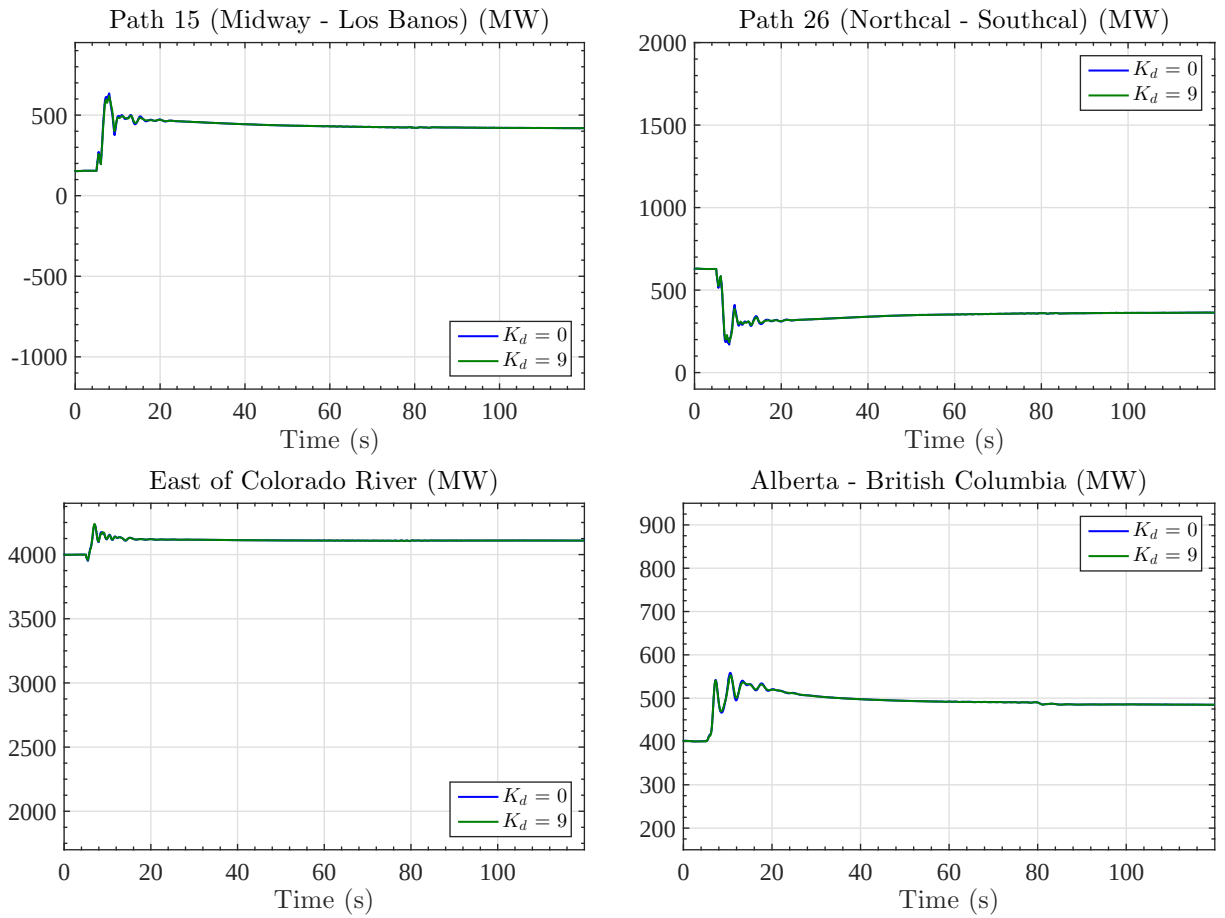


Figure 270. Active power flows. Event: 200 MW pulses followed by CGS outage.

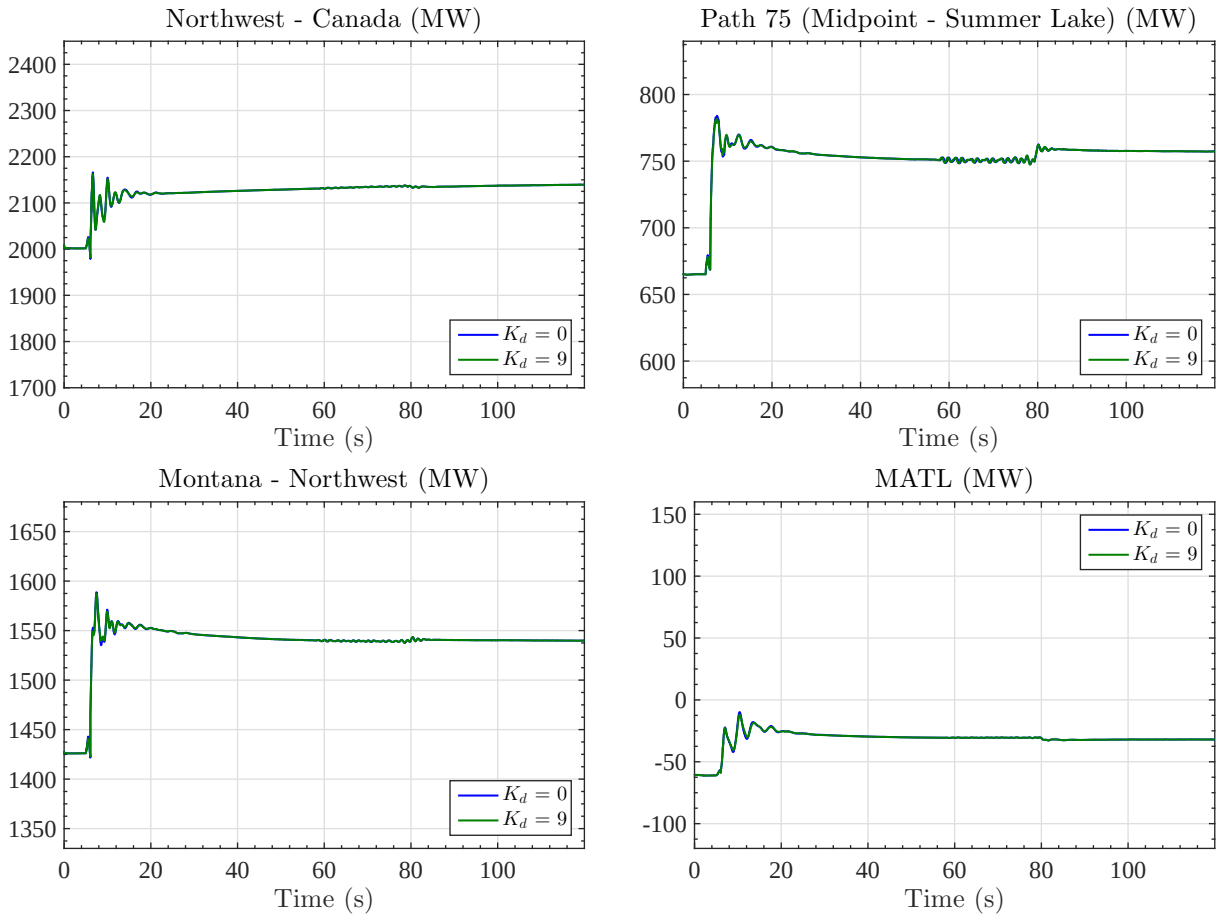


Figure 271. Active power flows. Event: 200 MW pulses followed by CGS outage.

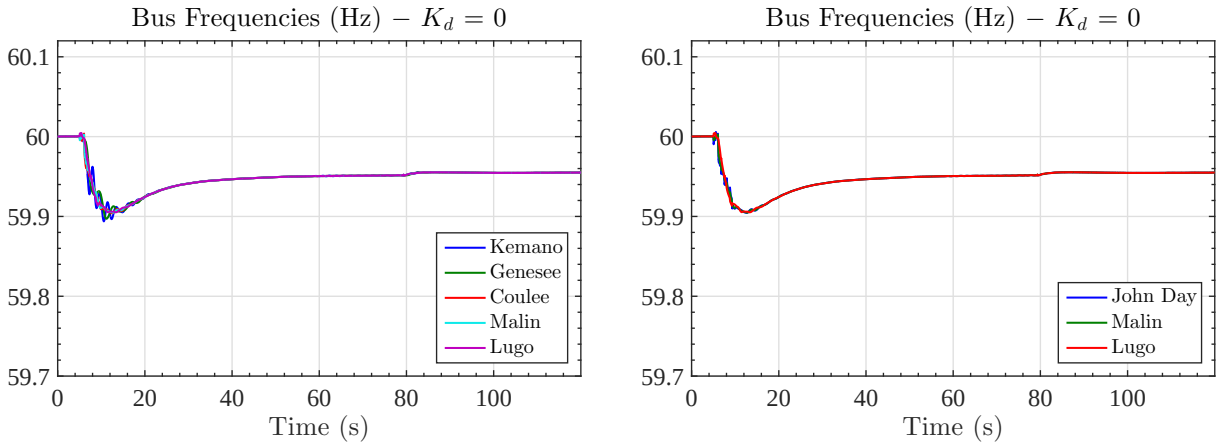


Figure 272. Bus frequencies. Event: 200 MW pulses followed by CGS outage.

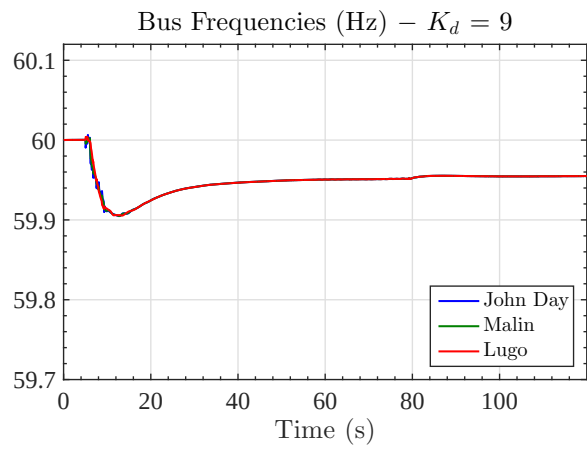
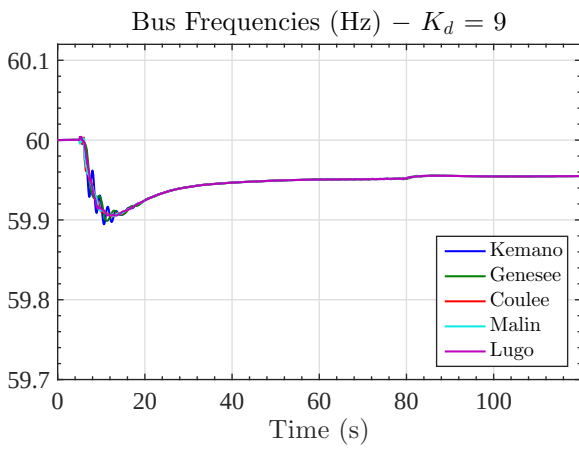


Figure 273. Bus frequencies. Event: 200 MW pulses followed by CGS outage.

4.1.7. Test System: Light Summer 2016. Event: MSF 20 MW followed by forced oscillation

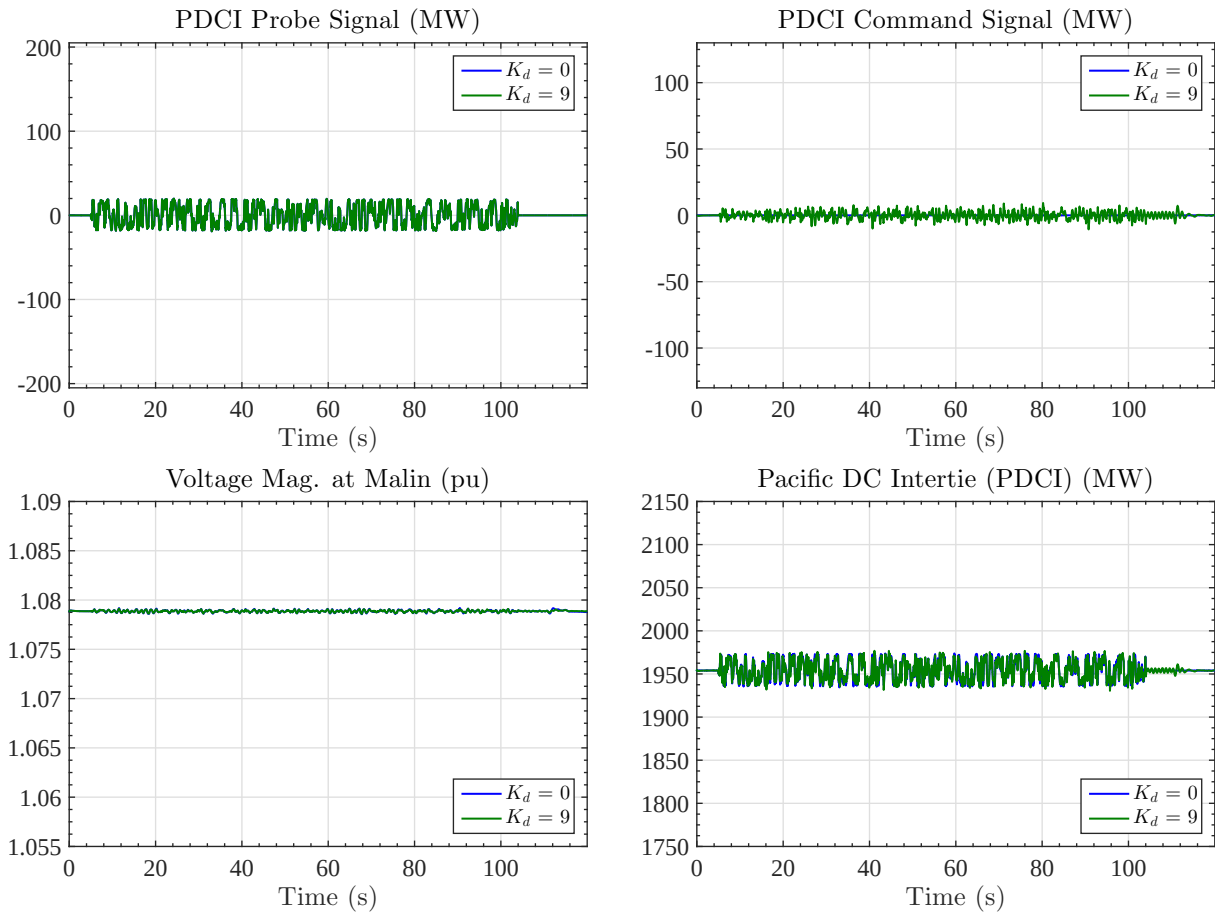


Figure 274. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 20 MW followed by forced oscillation.

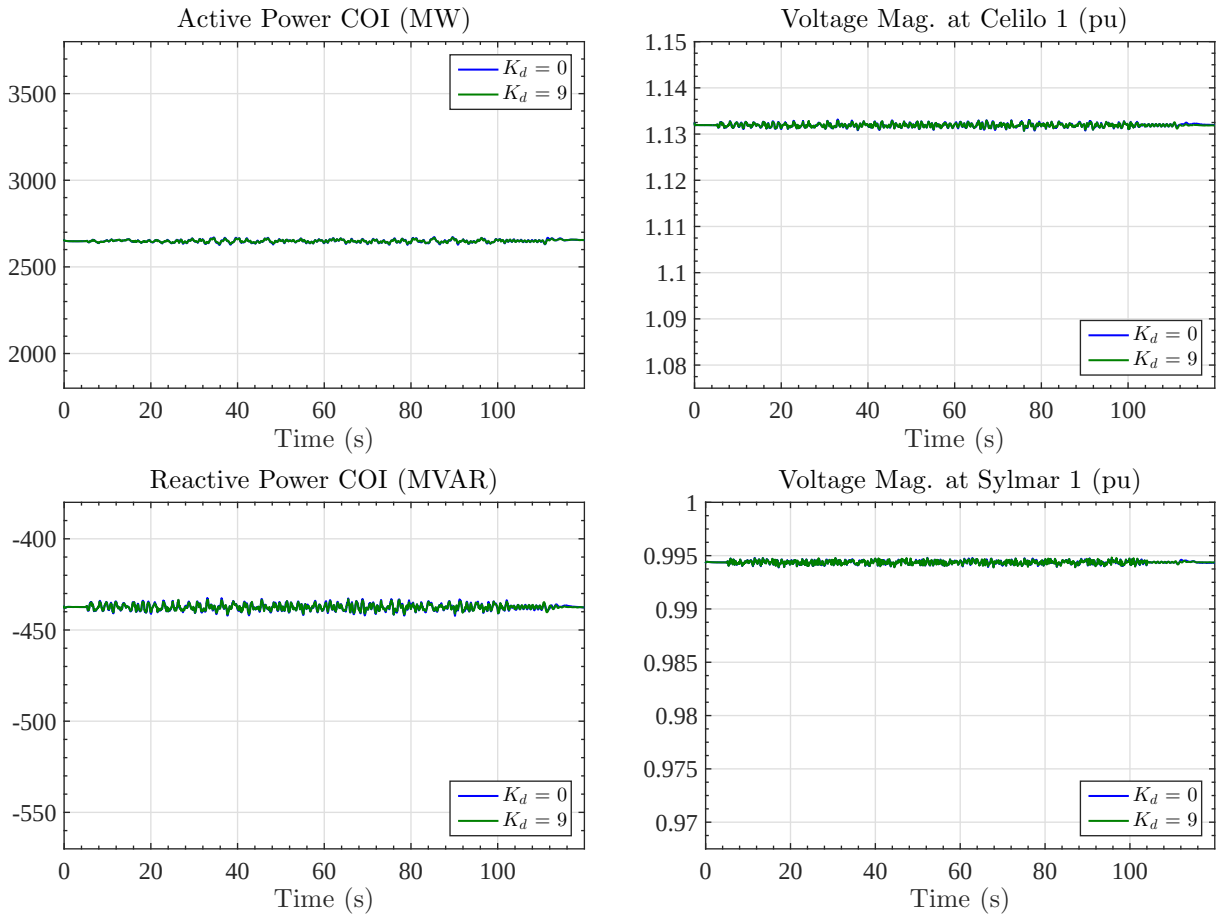


Figure 275. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 20 MW followed by forced oscillation.

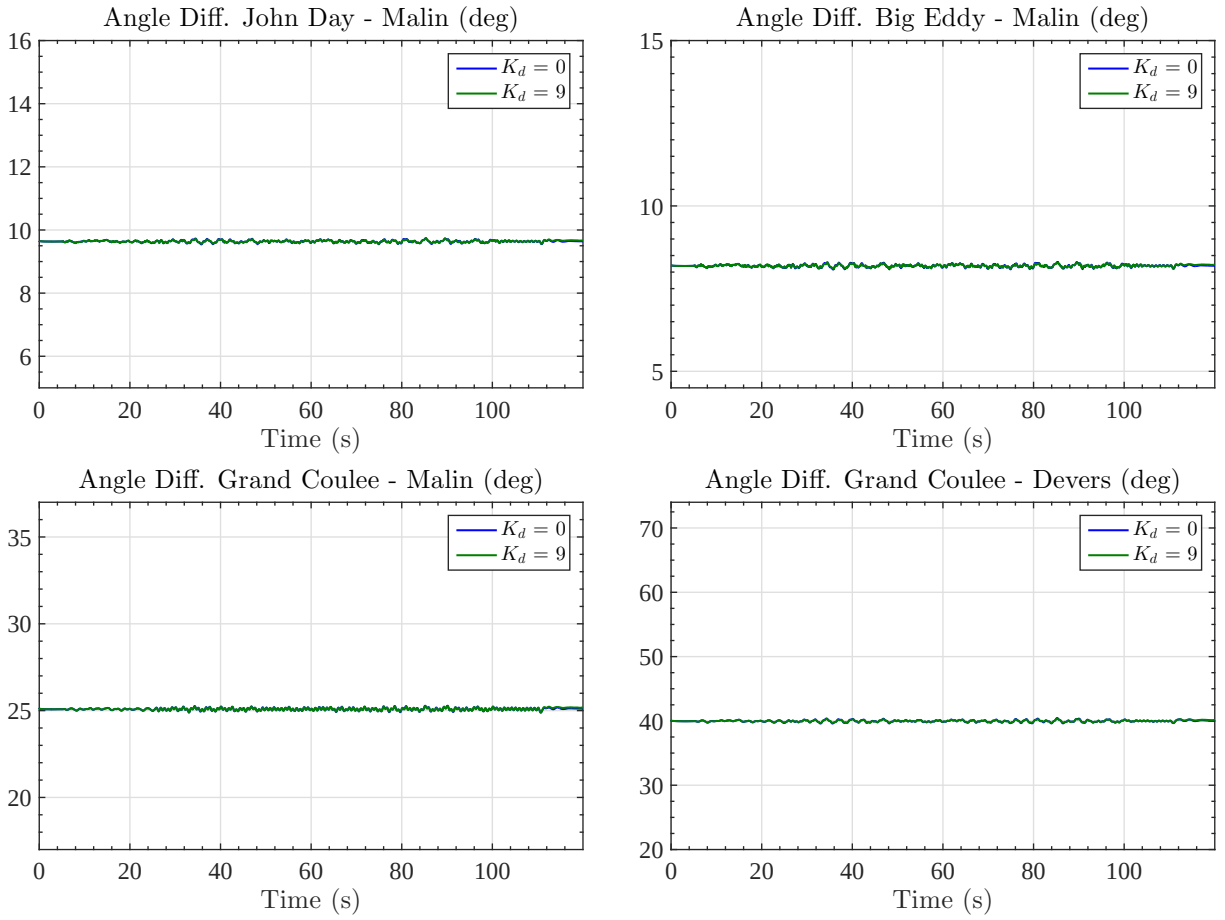


Figure 276. Angle differences. Event: MSF 20 MW followed by forced oscillation.

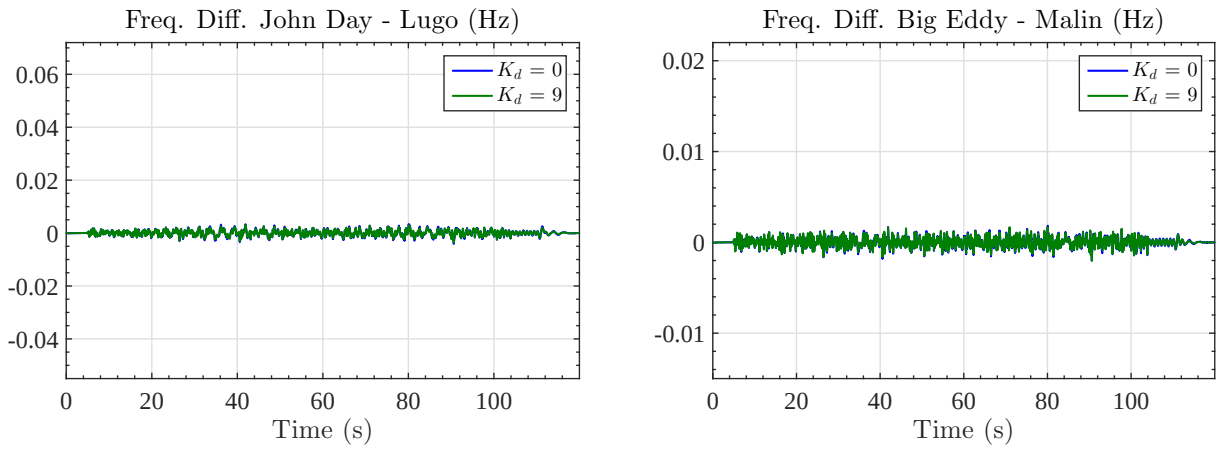


Figure 277. Frequency differences. Event: MSF 20 MW followed by forced oscillation.

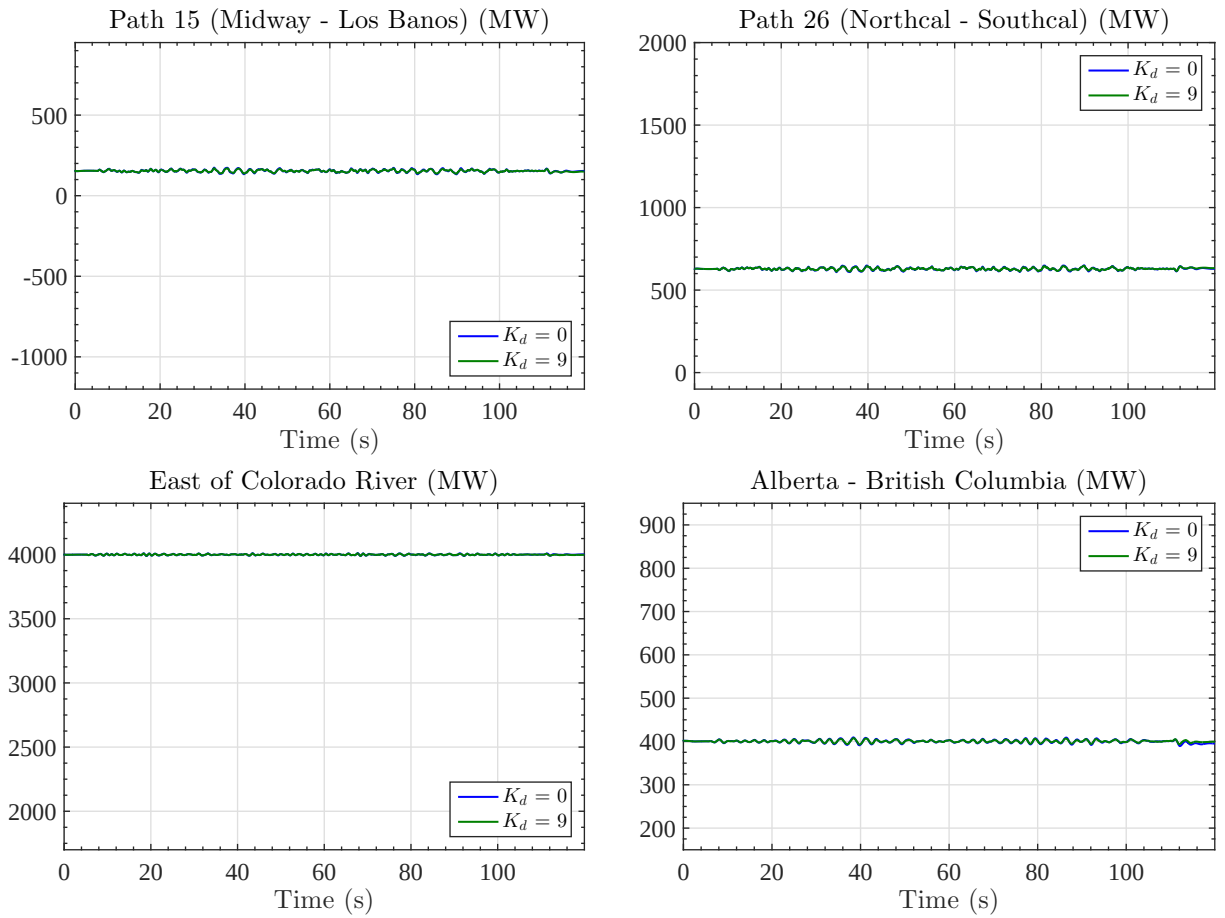


Figure 278. Active power flows. Event: MSF 20 MW followed by forced oscillation.

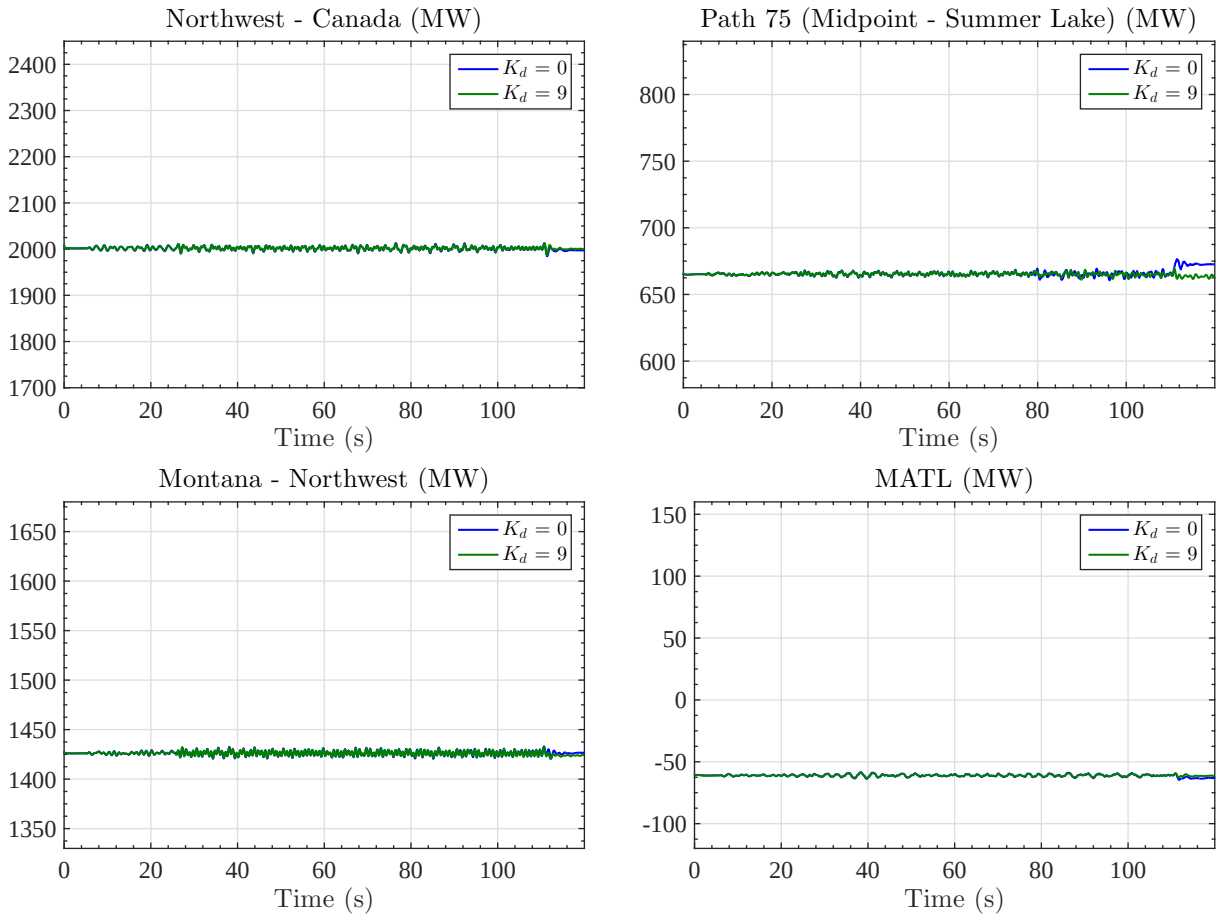


Figure 279. Active power flows. Event: MSF 20 MW followed by forced oscillation.

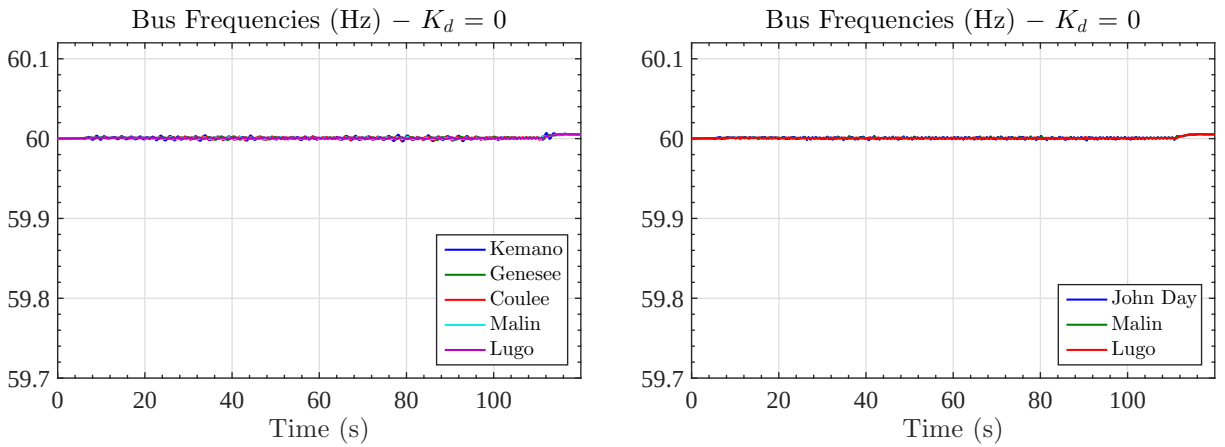


Figure 280. Bus frequencies. Event: MSF 20 MW followed by forced oscillation.

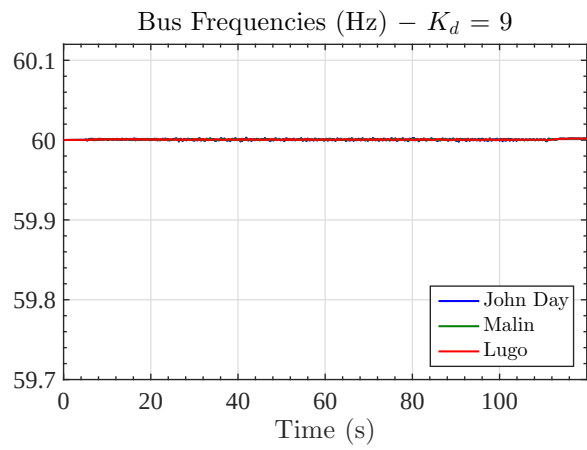
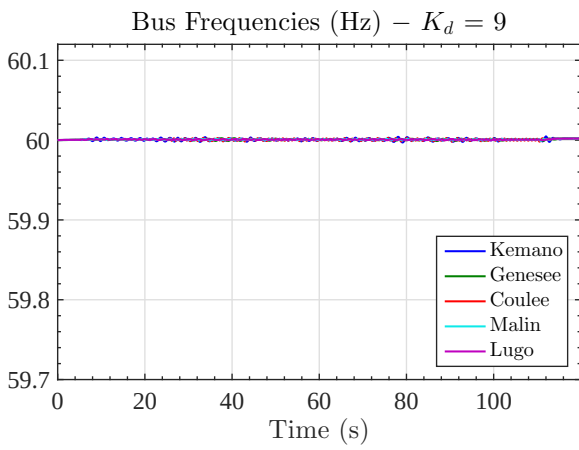


Figure 281. Bus frequencies. Event: MSF 20 MW followed by forced oscillation.

4.1.8. Test System: Light Summer 2016. Event: MSF 20 MW followed by double Palo Verde outage

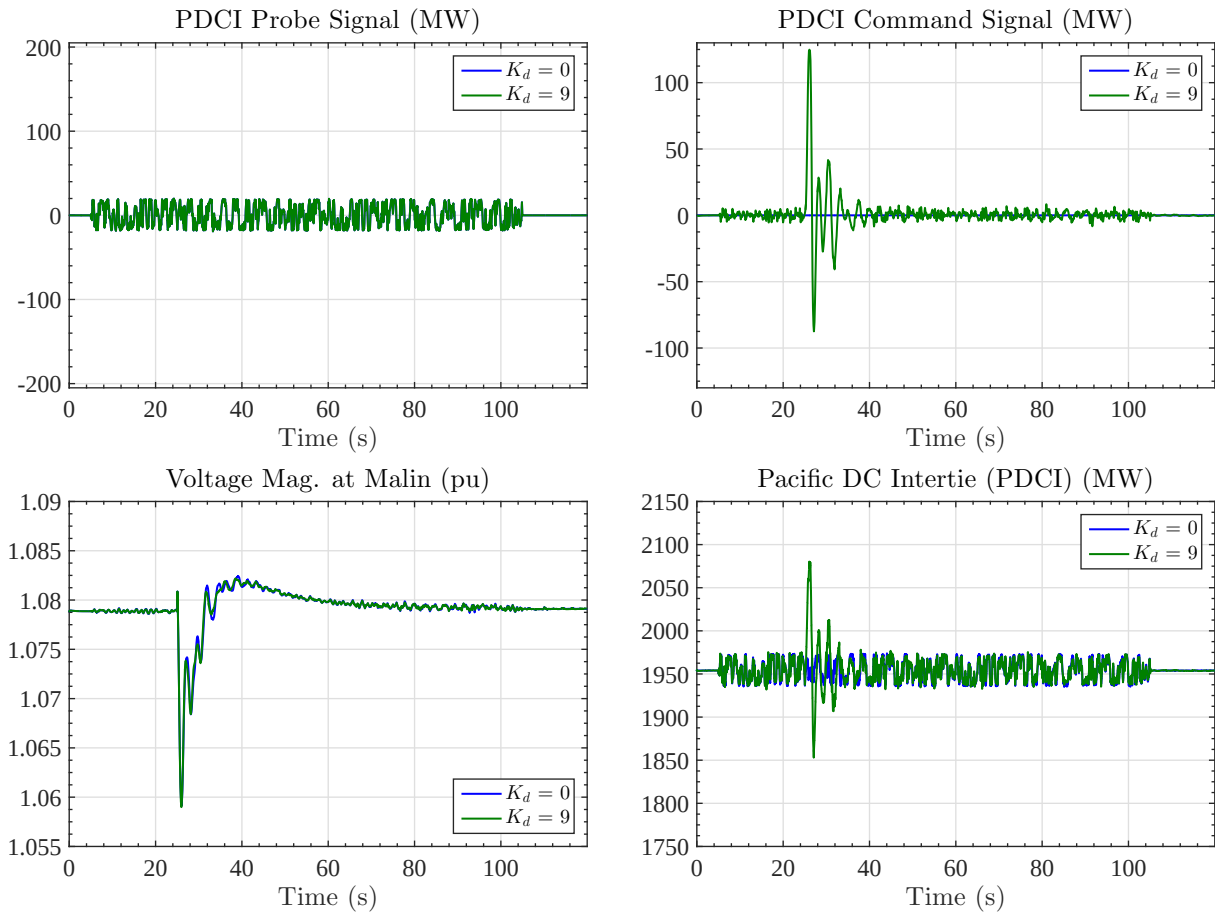


Figure 282. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 20 MW followed by double Palo Verde outage.

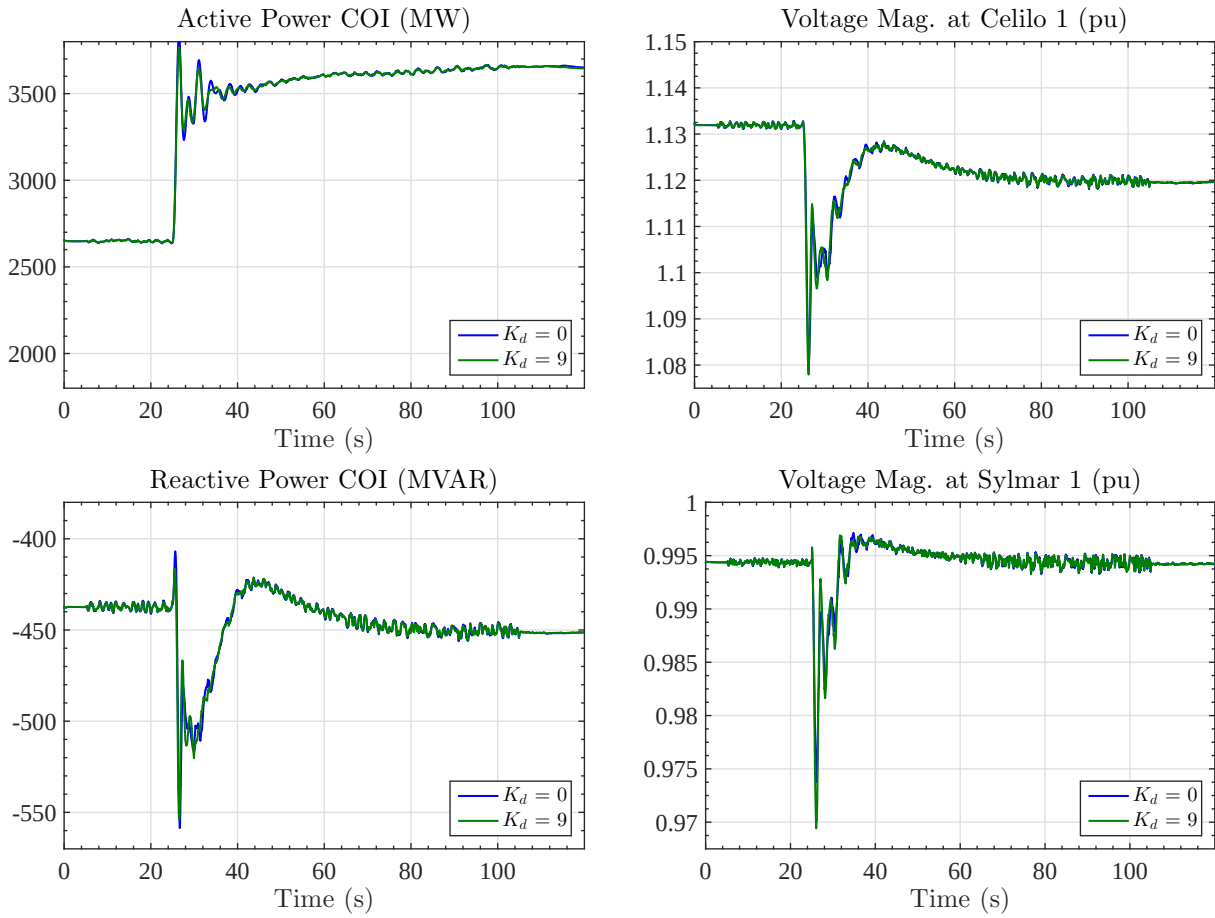


Figure 283. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 20 MW followed by double Palo Verde outage.

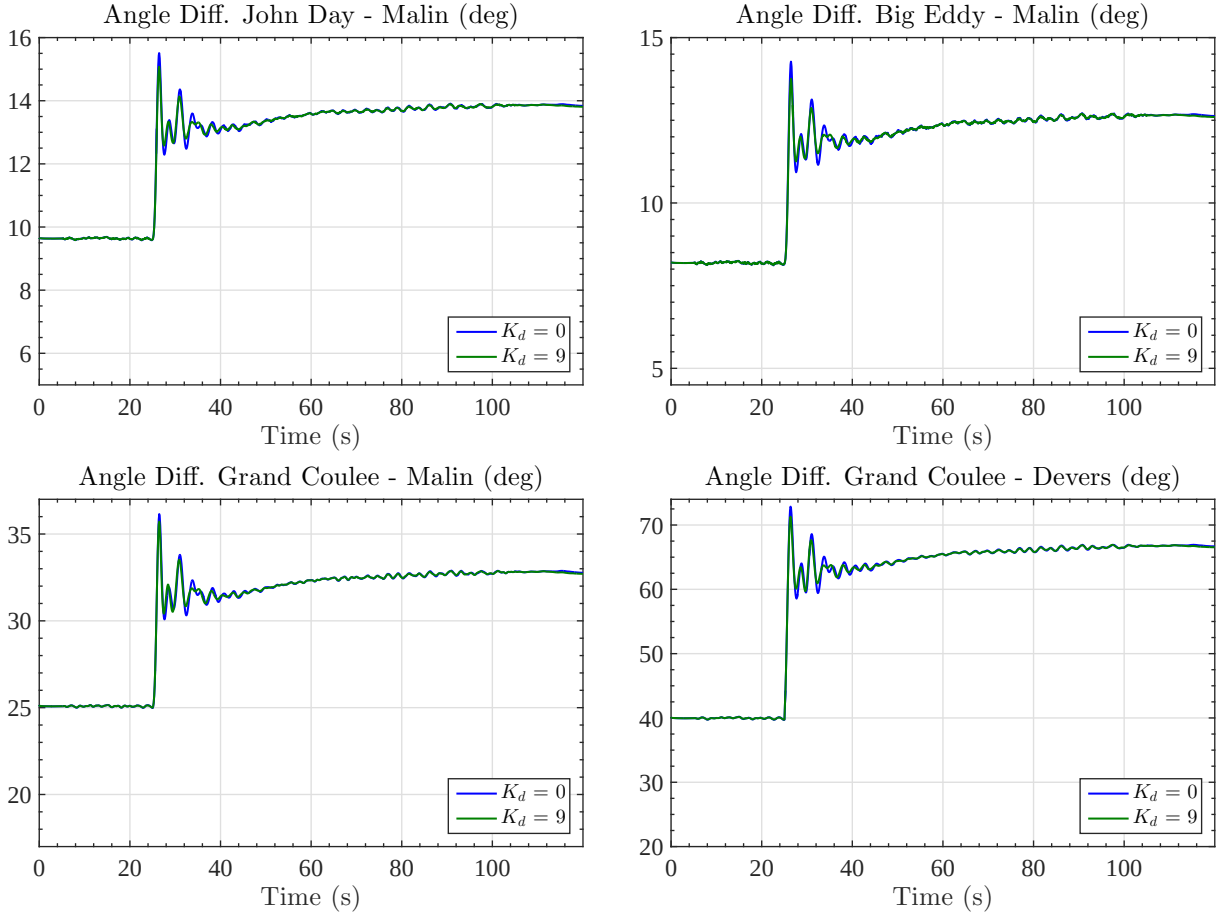


Figure 284. Angle differences. Event: MSF 20 MW followed by double Palo Verde outage.

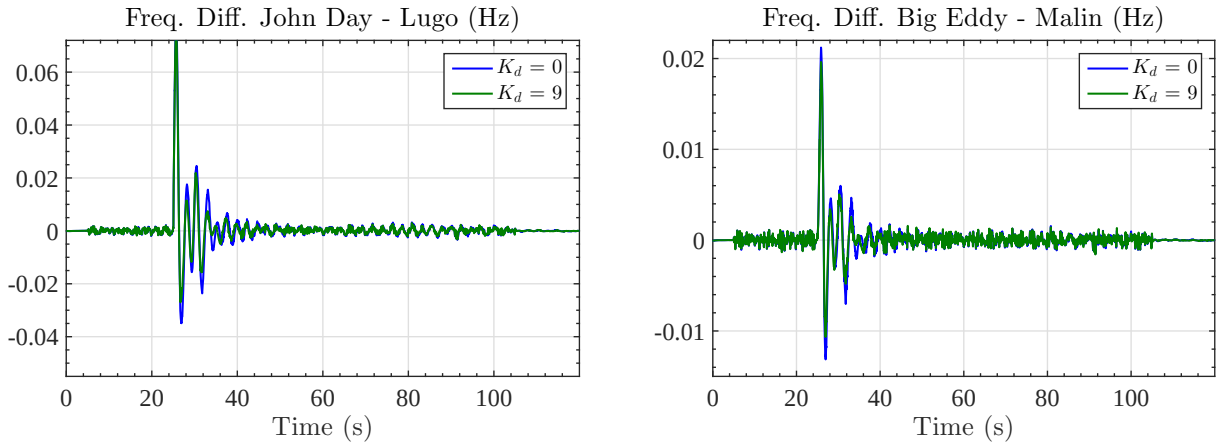


Figure 285. Frequency differences. Event: MSF 20 MW followed by double Palo Verde outage.

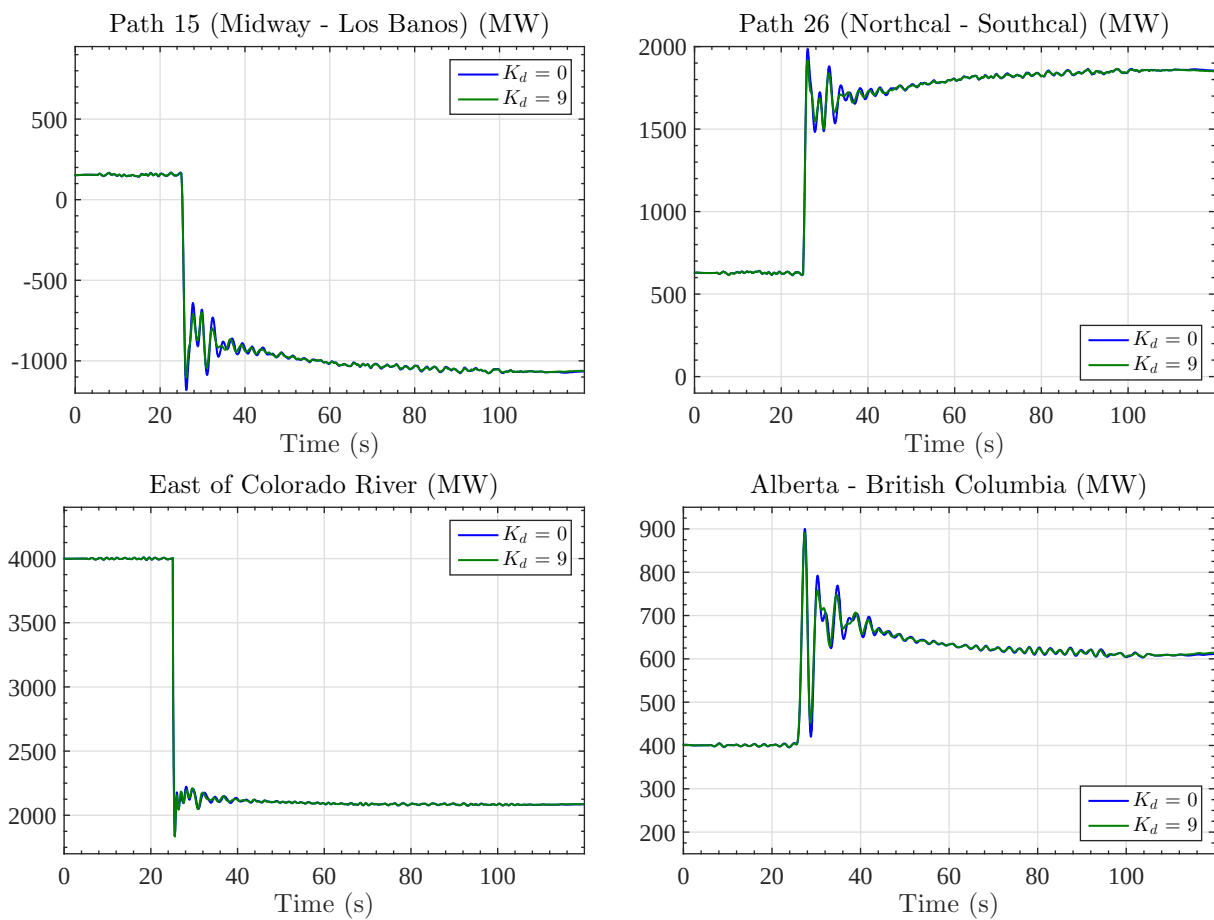


Figure 286. Active power flows. Event: MSF 20 MW followed by double Palo Verde outage.

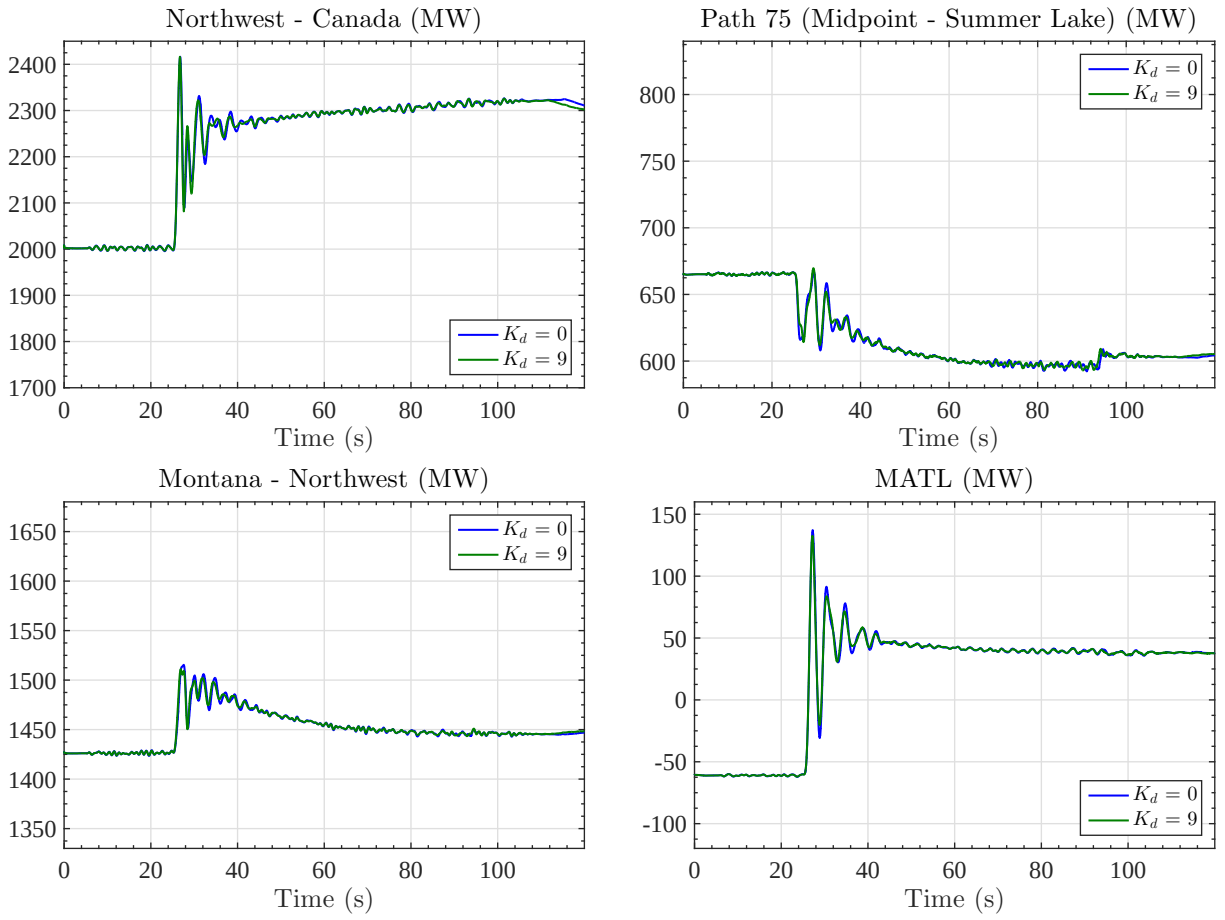


Figure 287. Active power flows. Event: MSF 20 MW followed by double Palo Verde outage.

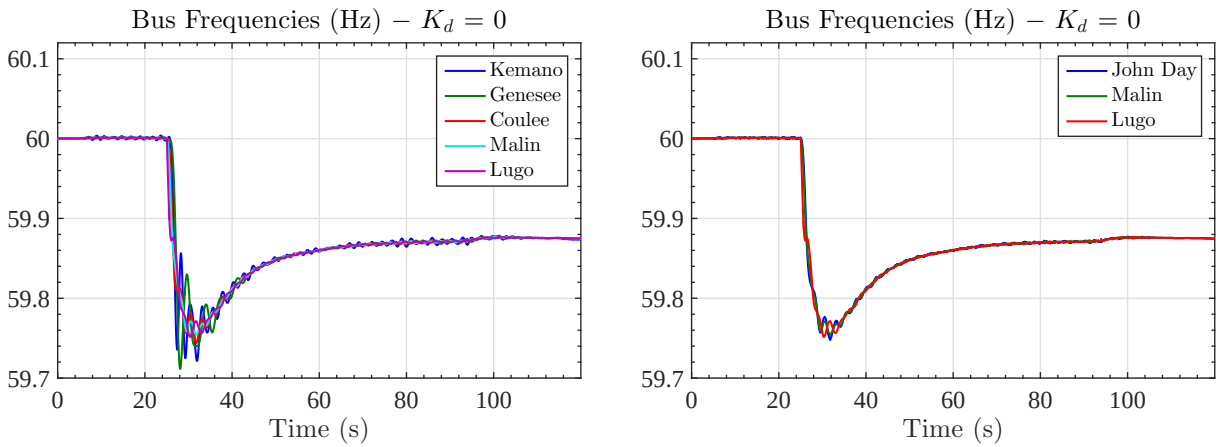


Figure 288. Bus frequencies. Event: MSF 20 MW followed by double Palo Verde outage.

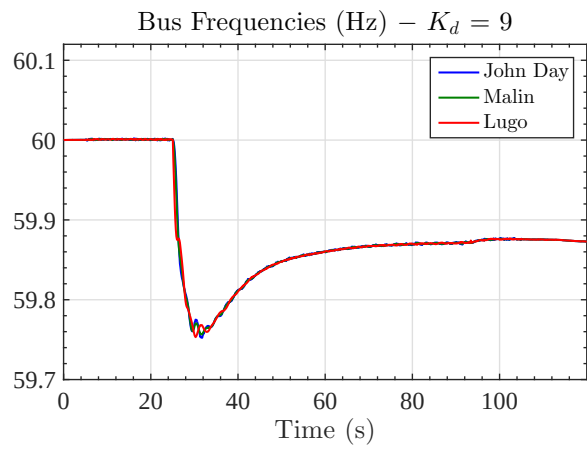
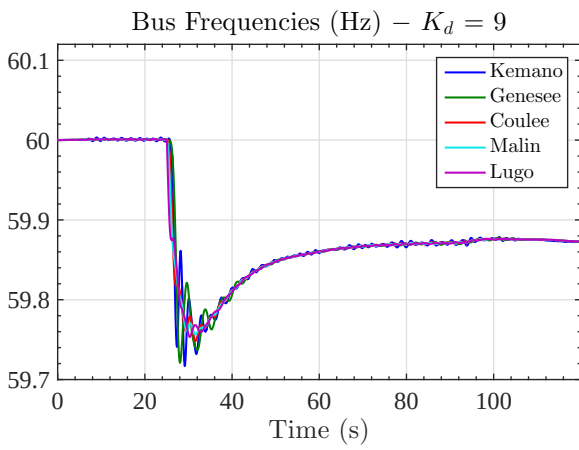


Figure 289. Bus frequencies. Event: MSF 20 MW followed by double Palo Verde outage.

4.1.9. Test System: Light Summer 2016. Event: MSF 20 MW followed by CGS outage

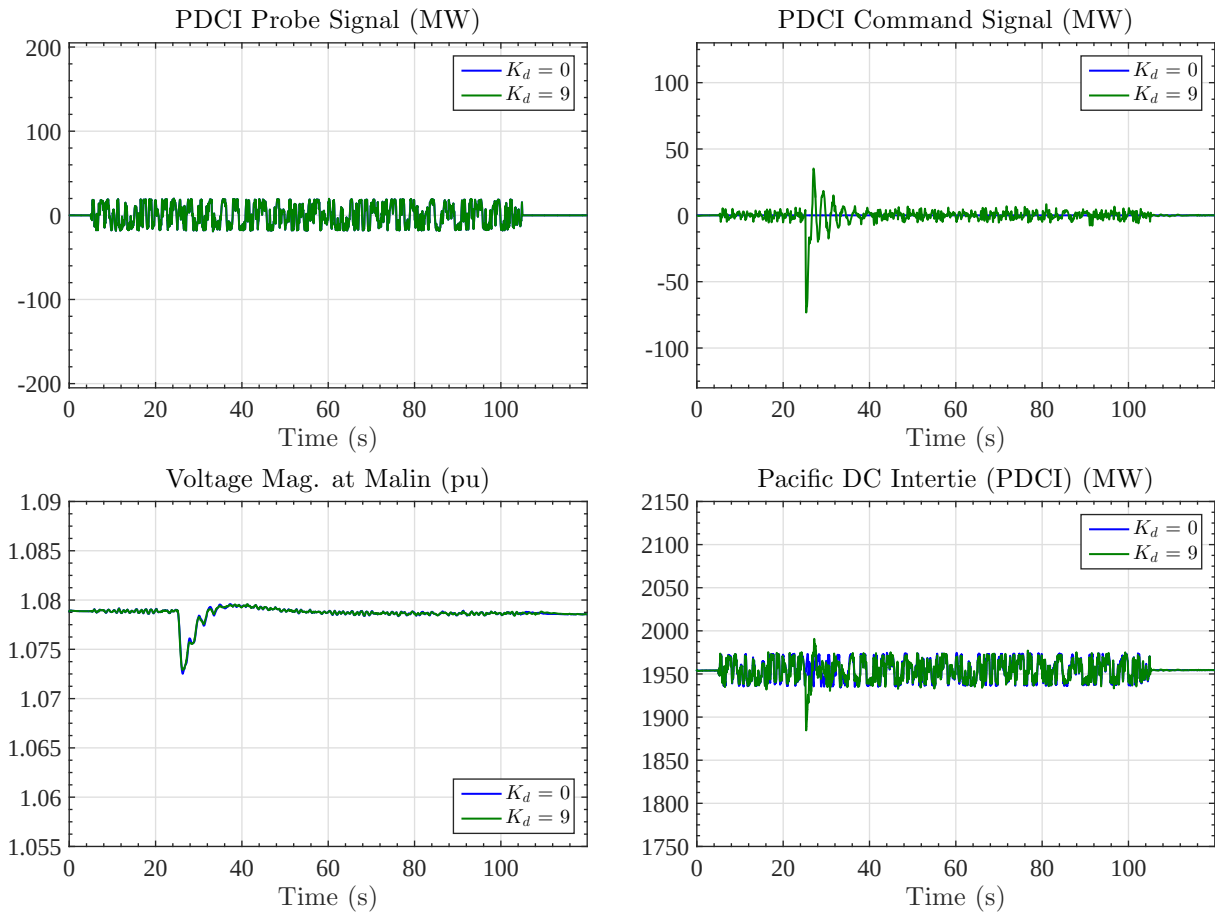


Figure 290. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 20 MW followed by CGS outage.

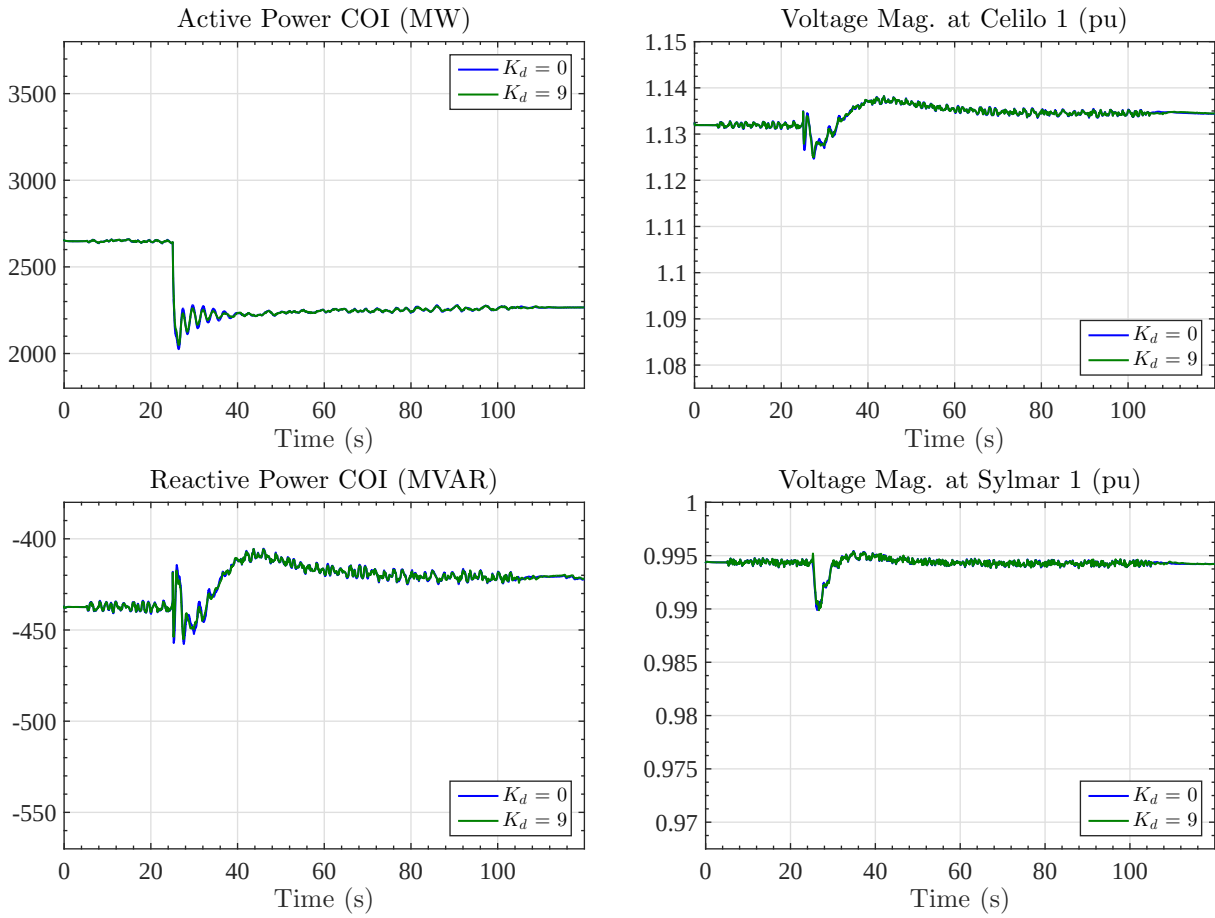


Figure 291. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 20 MW followed by CGS outage.

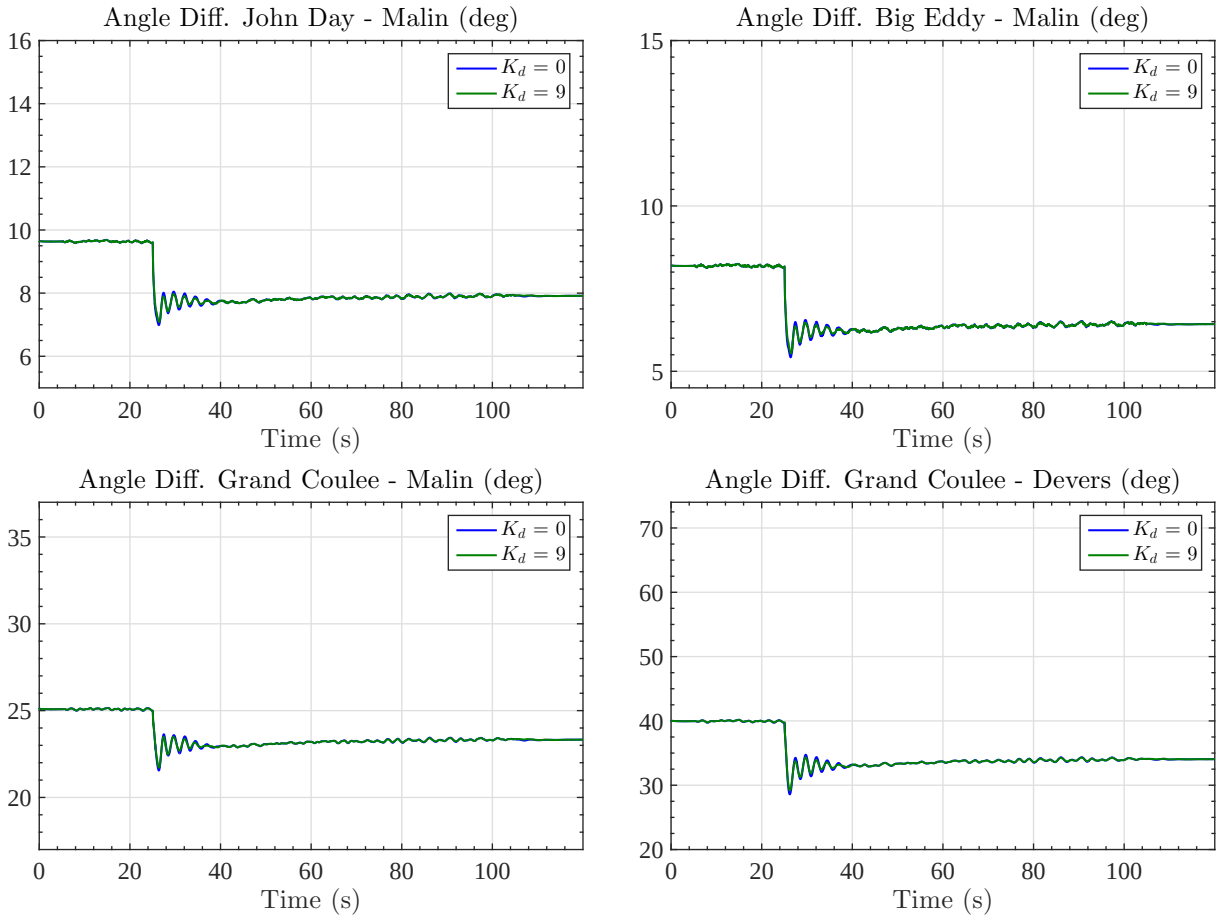


Figure 292. Angle differences. Event: MSF 20 MW followed by CGS outage.

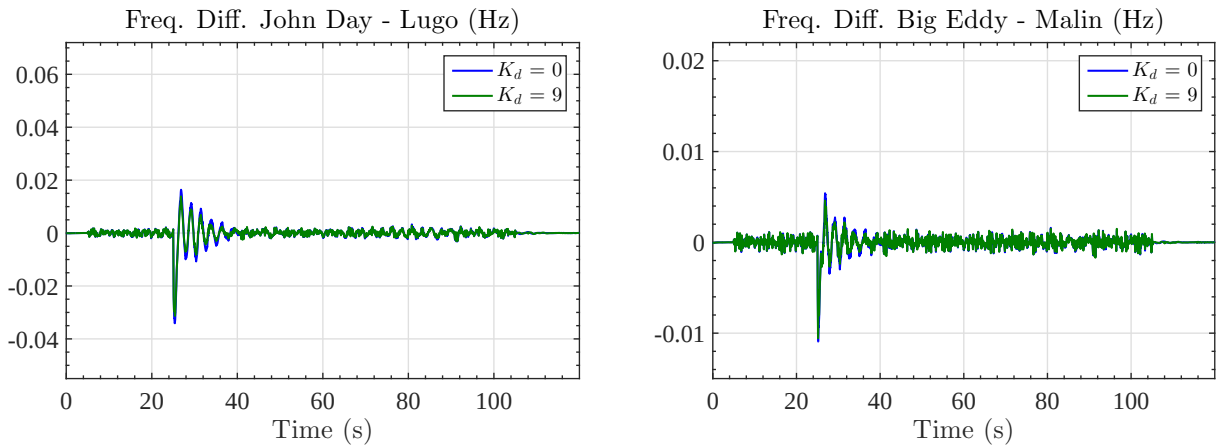


Figure 293. Frequency differences. Event: MSF 20 MW followed by CGS outage.

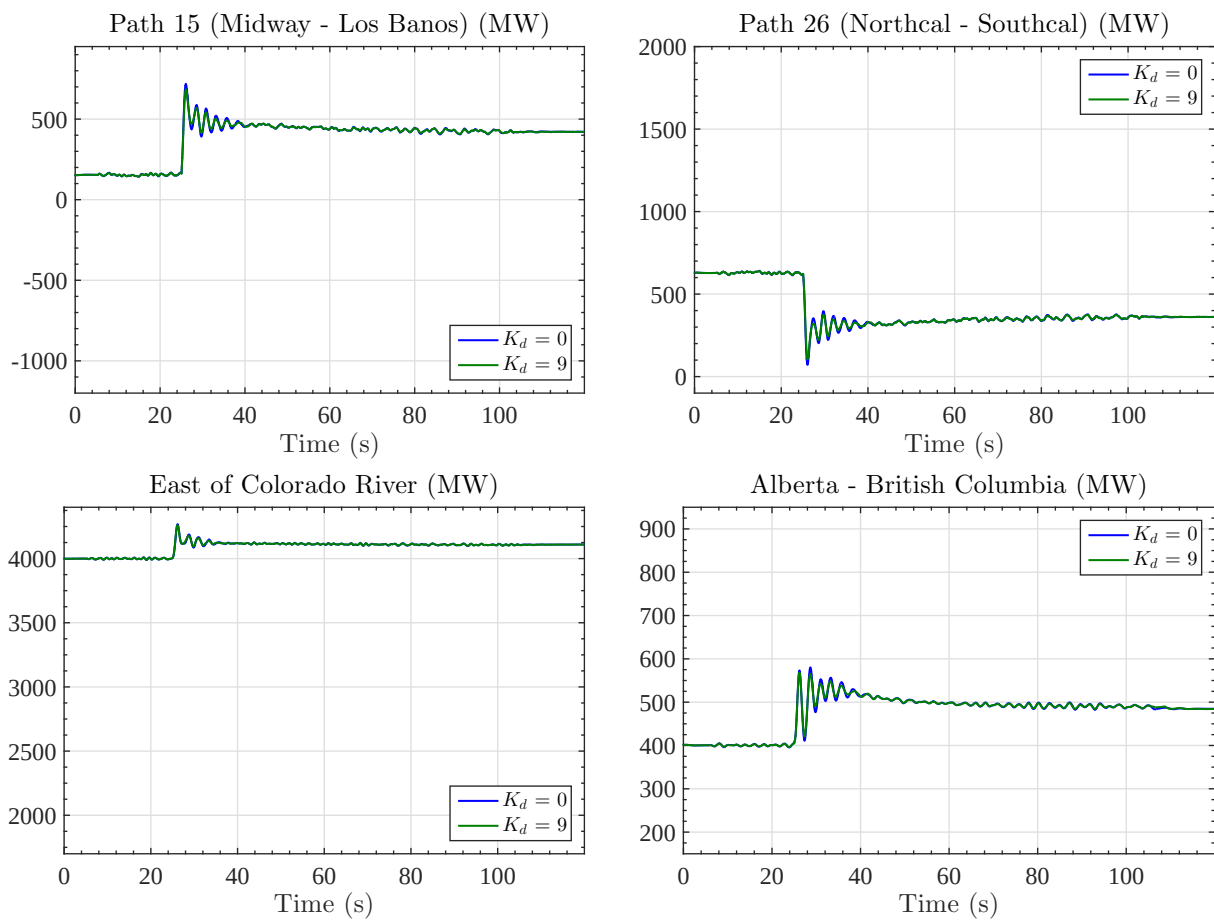


Figure 294. Active power flows. Event: MSF 20 MW followed by CGS outage.

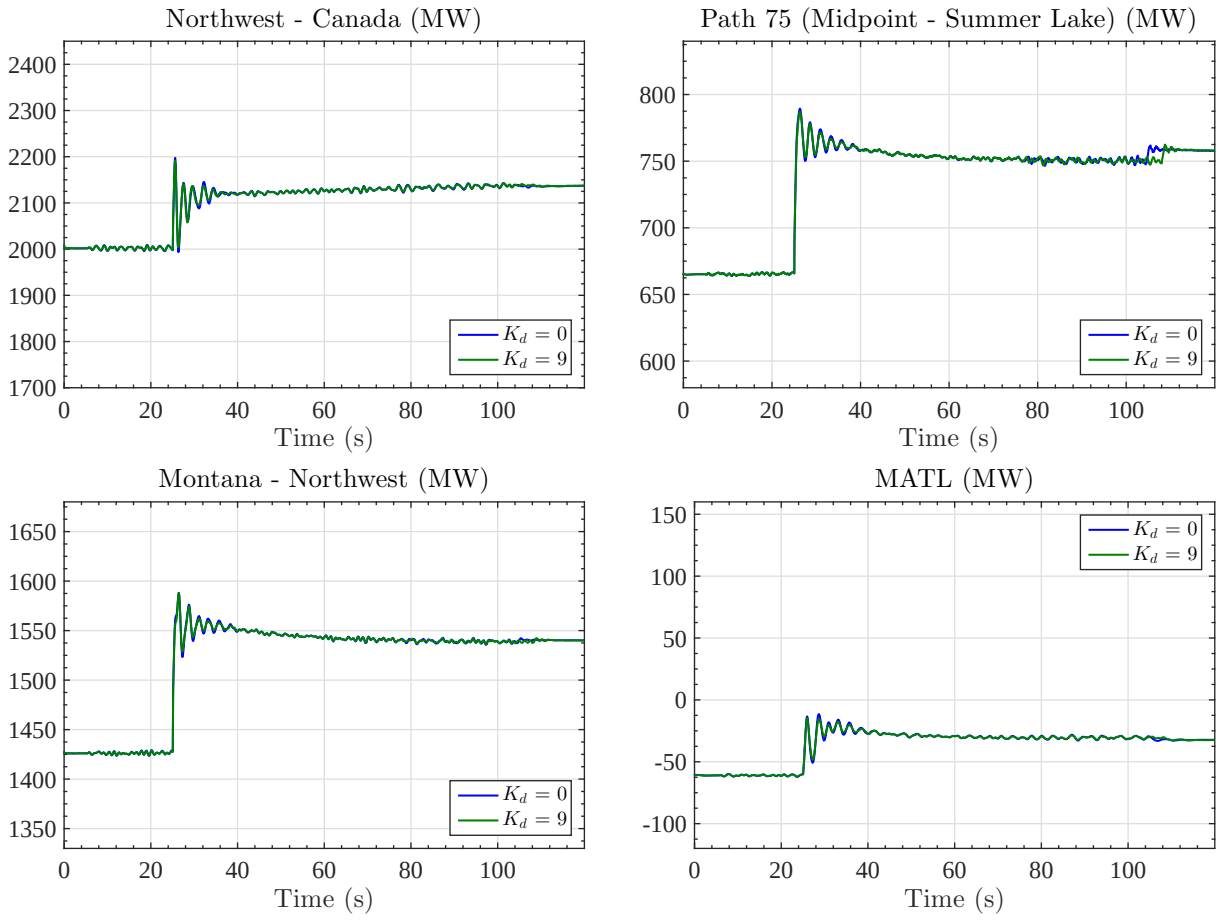


Figure 295. Active power flows. Event: MSF 20 MW followed by CGS outage.

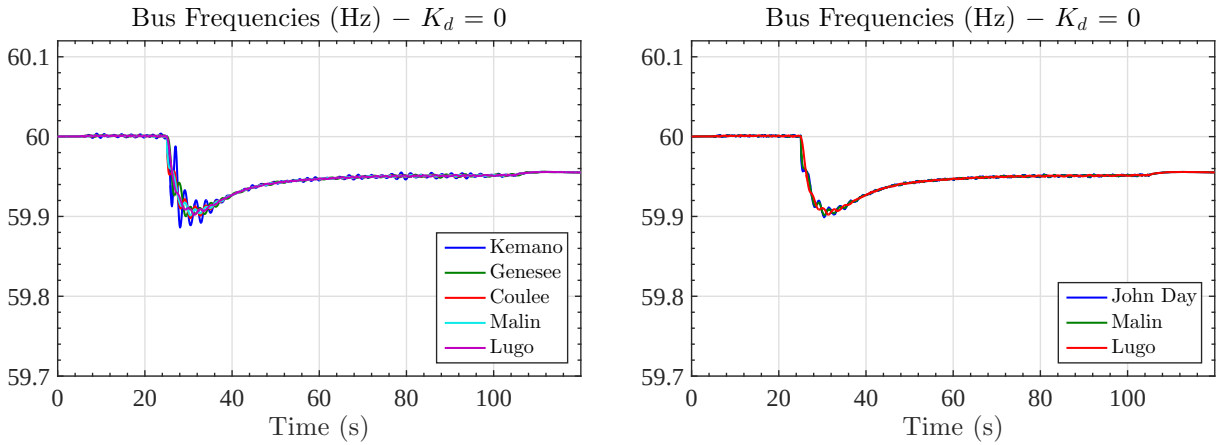


Figure 296. Bus frequencies. Event: MSF 20 MW followed by CGS outage.

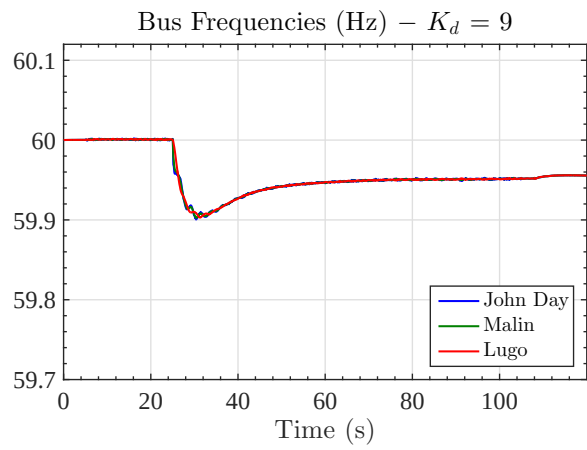
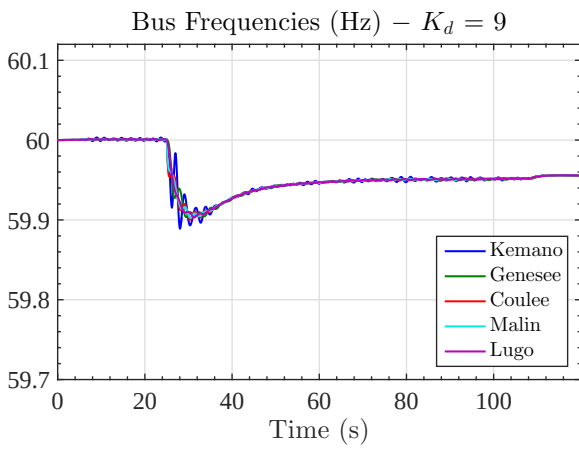


Figure 297. Bus frequencies. Event: MSF 20 MW followed by CGS outage.

5. CASE STUDY: HEAVY SUMMER 2016 - LARGE EVENTS WHILE TESTING

5.1. Closed Loop Testing

5.1.1. Test System: Heavy Summer 2016. Event: Chief Joe Brake followed by forced oscillation

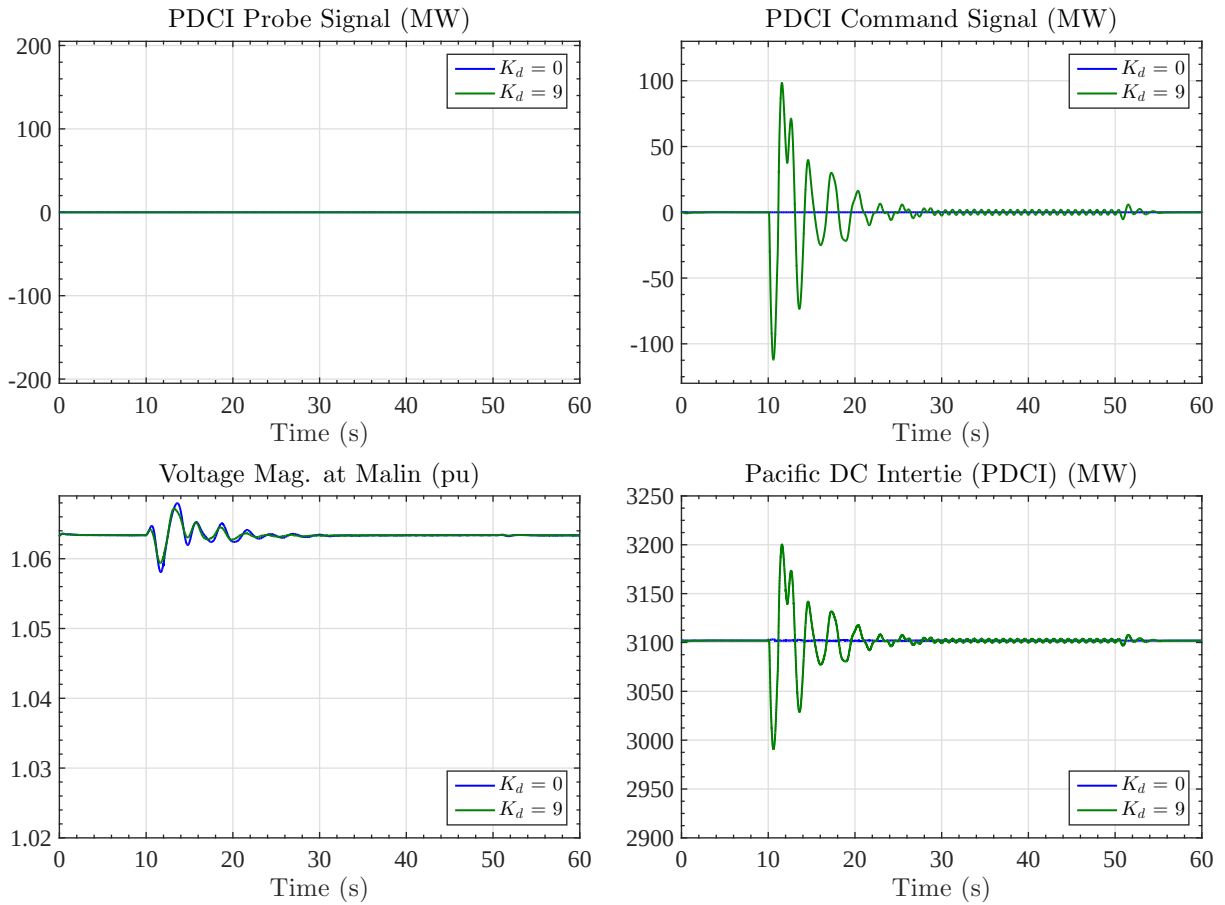


Figure 298. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake followed by forced oscillation.

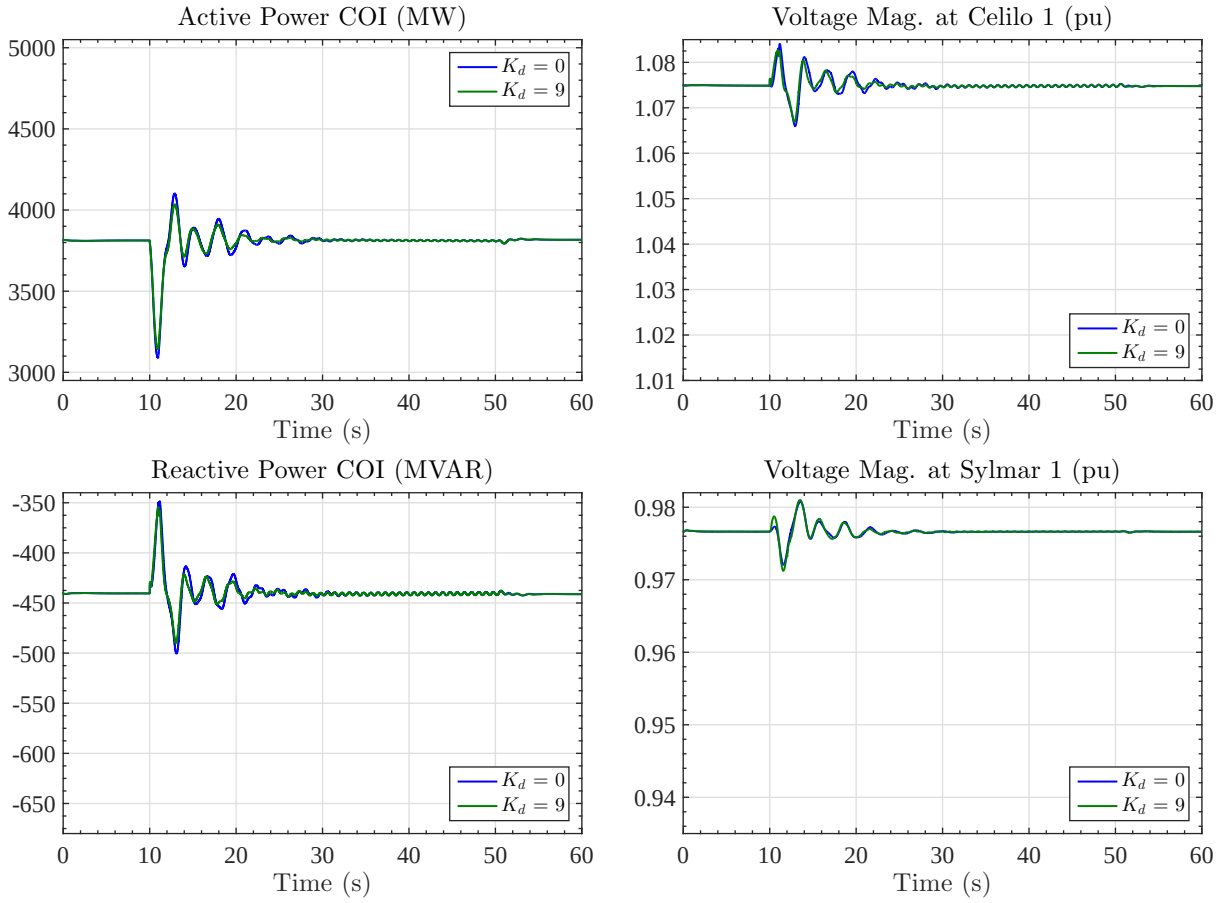


Figure 299. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake followed by forced oscillation.

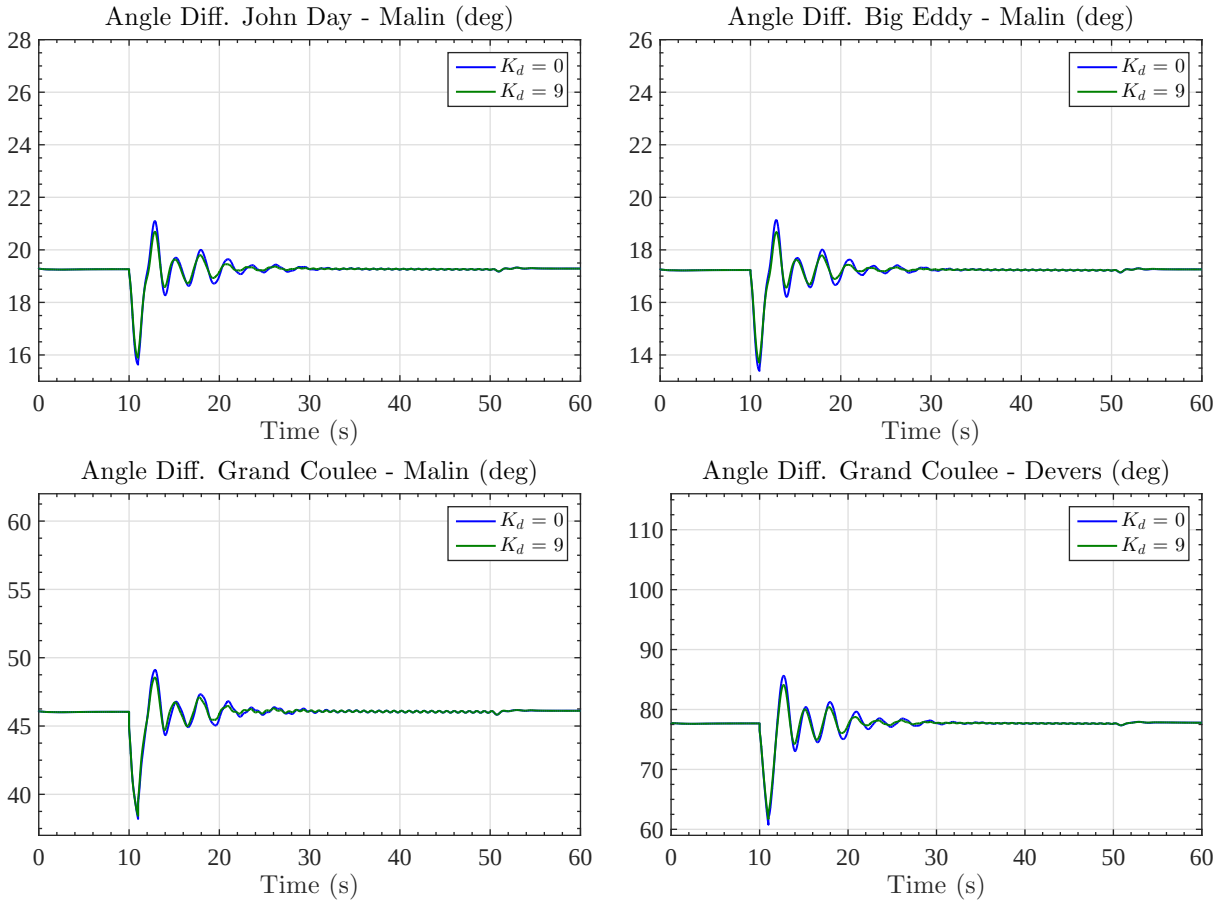


Figure 300. Angle differences. Event: Chief Joe Brake followed by forced oscillation.

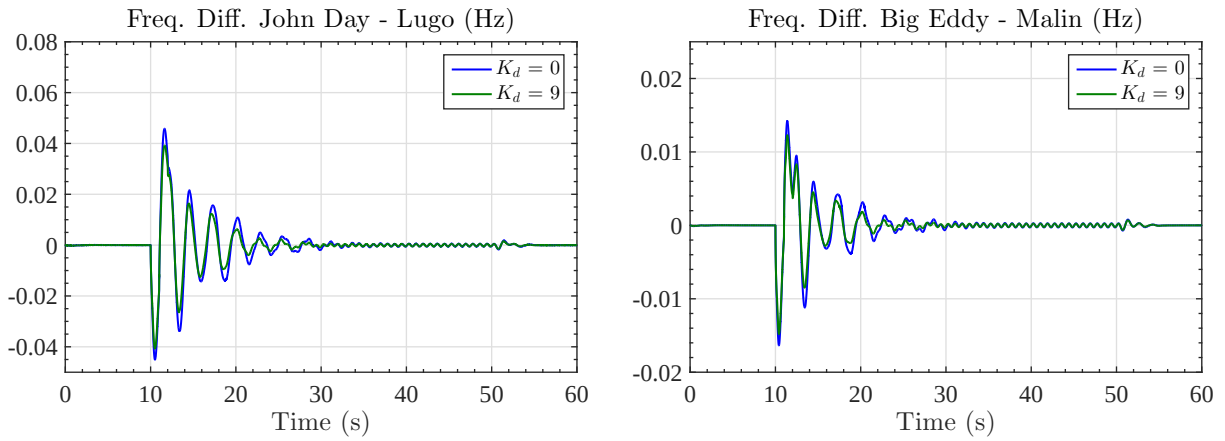


Figure 301. Frequency differences. Event: Chief Joe Brake followed by forced oscillation.

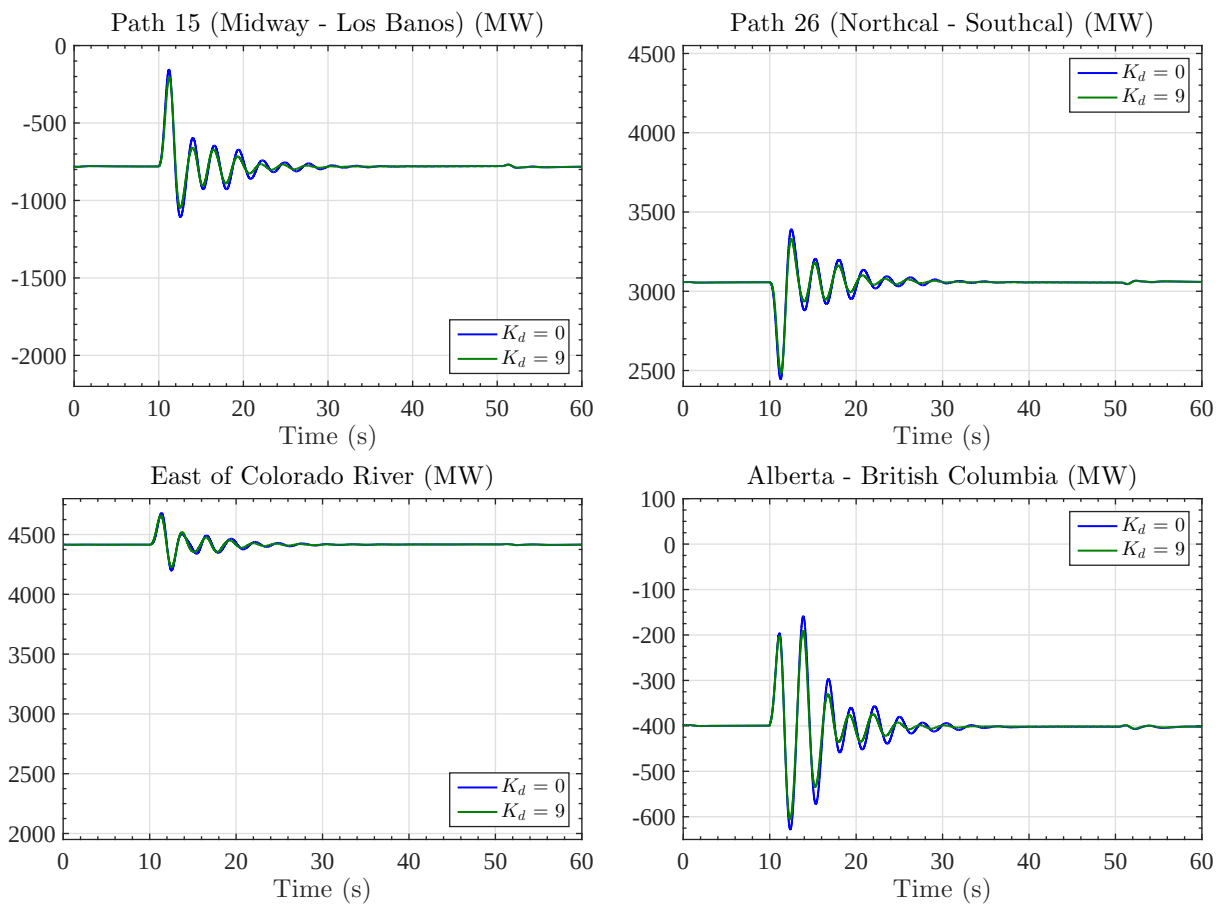


Figure 302. Active power flows. Event: Chief Joe Brake followed by forced oscillation.

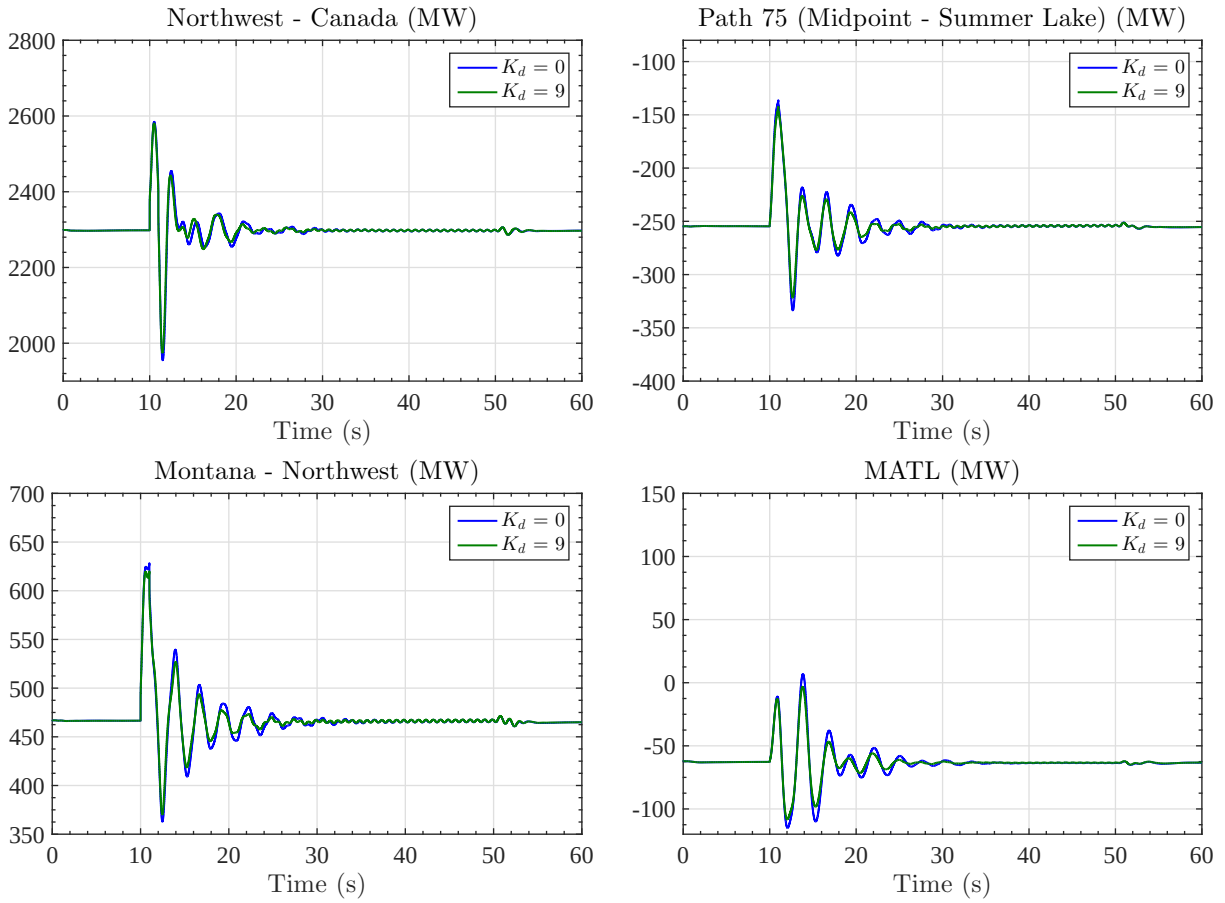


Figure 303. Active power flows. Event: Chief Joe Brake followed by forced oscillation.

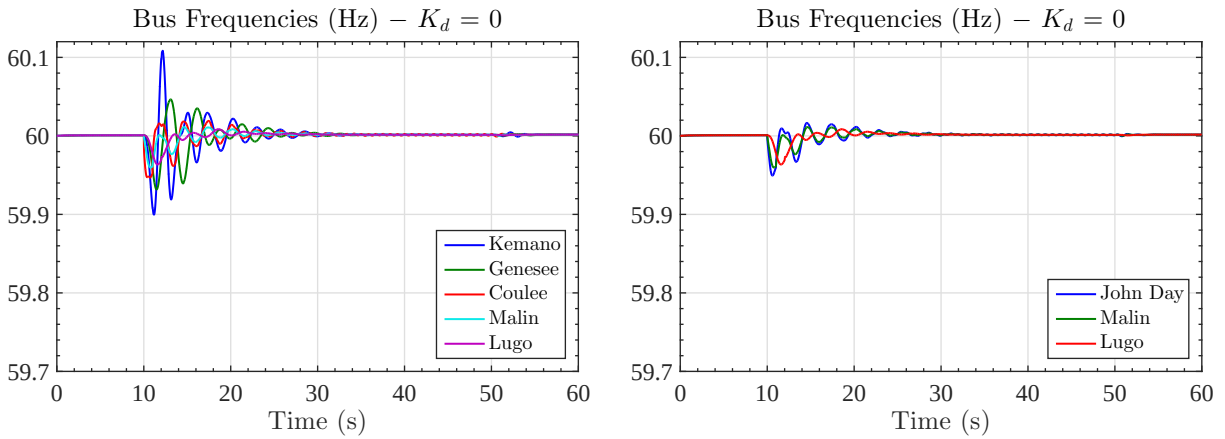


Figure 304. Bus frequencies. Event: Chief Joe Brake followed by forced oscillation.

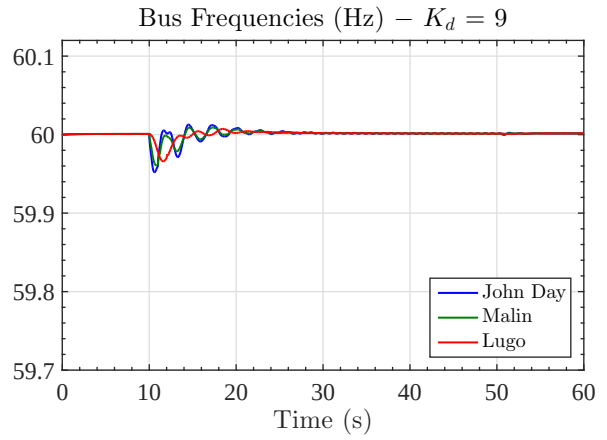
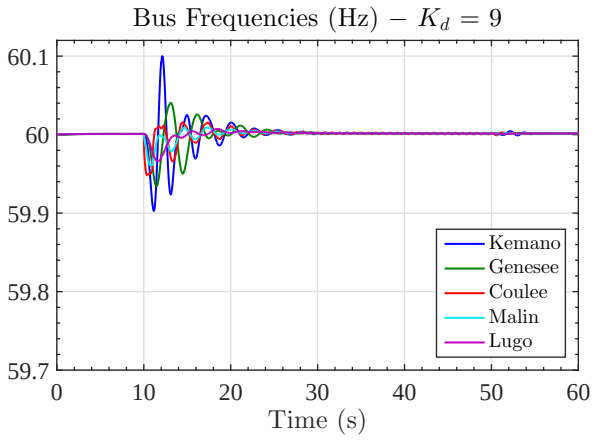


Figure 305. Bus frequencies. Event: Chief Joe Brake followed by forced oscillation.

5.1.2. Test System: Heavy Summer 2016. Event: Chief Joe Brake followed by double Palo Verde outage

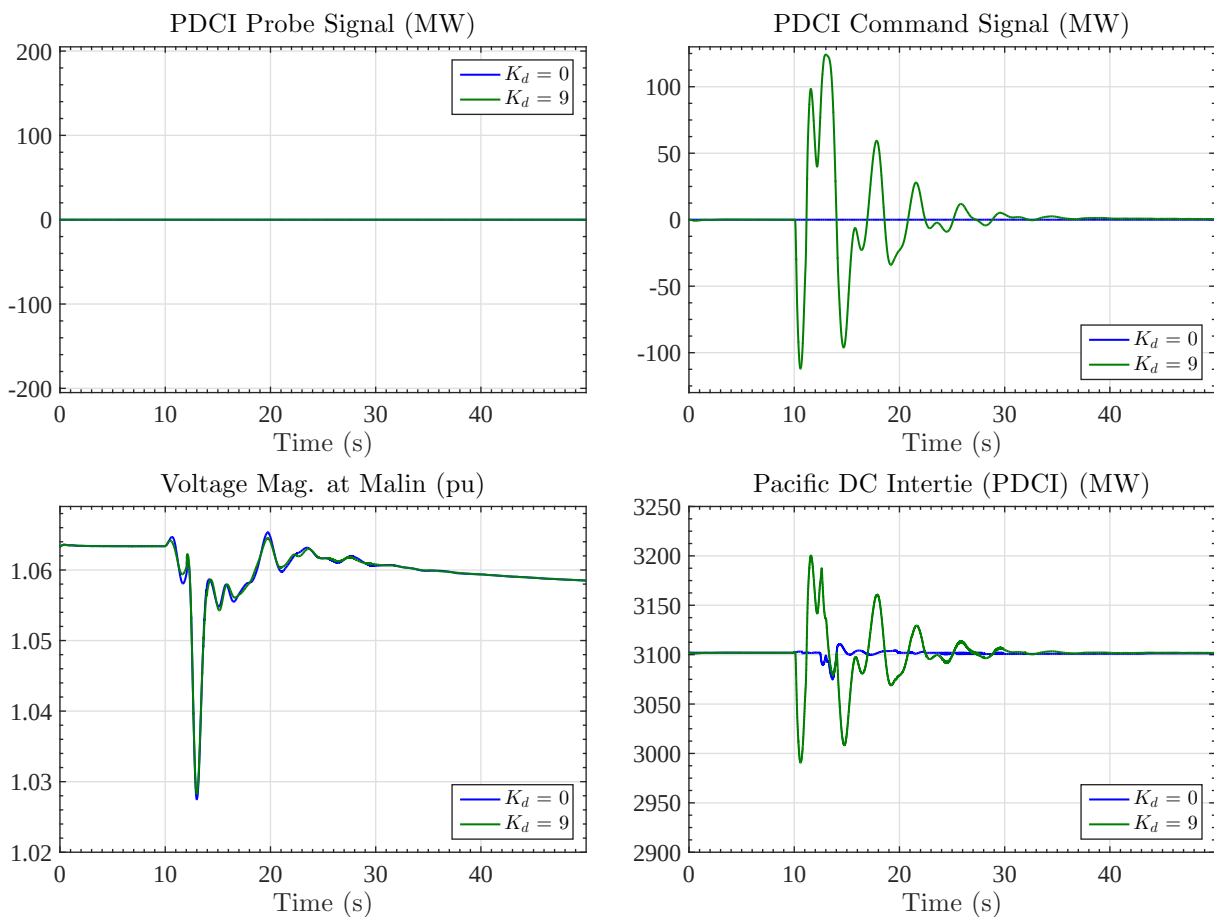


Figure 306. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake followed by double Palo Verde outage.

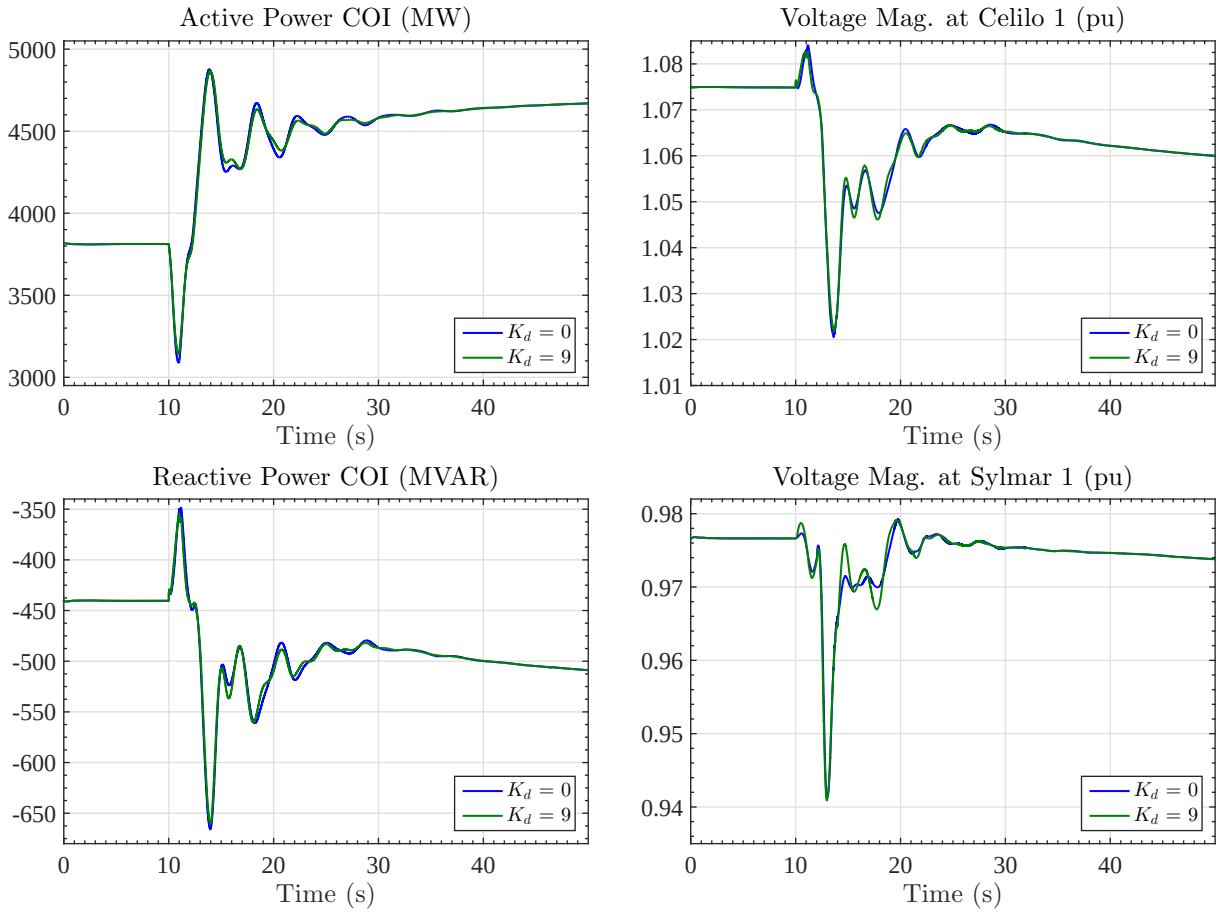


Figure 307. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake followed by double Palo Verde outage.

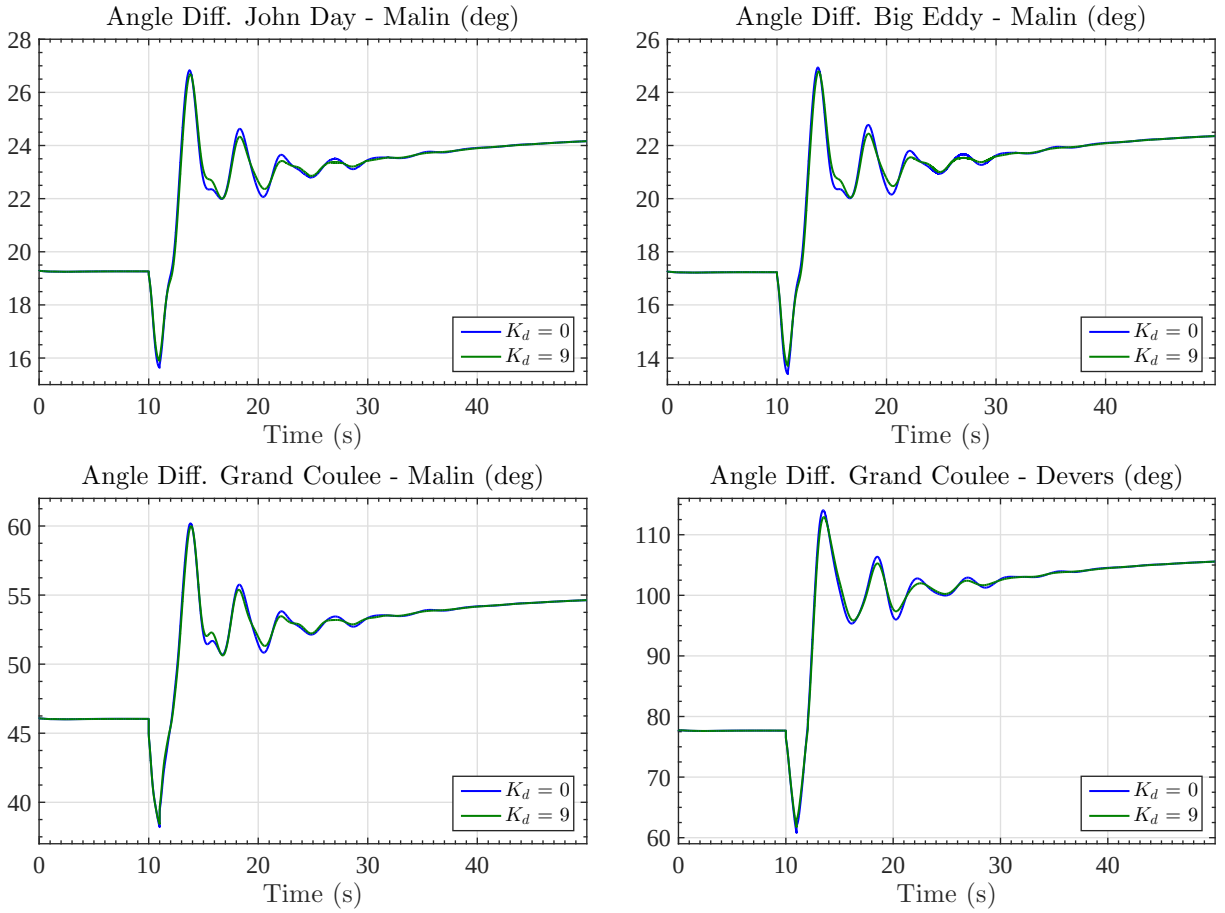


Figure 308. Angle differences. Event: Chief Joe Brake followed by double Palo Verde outage.

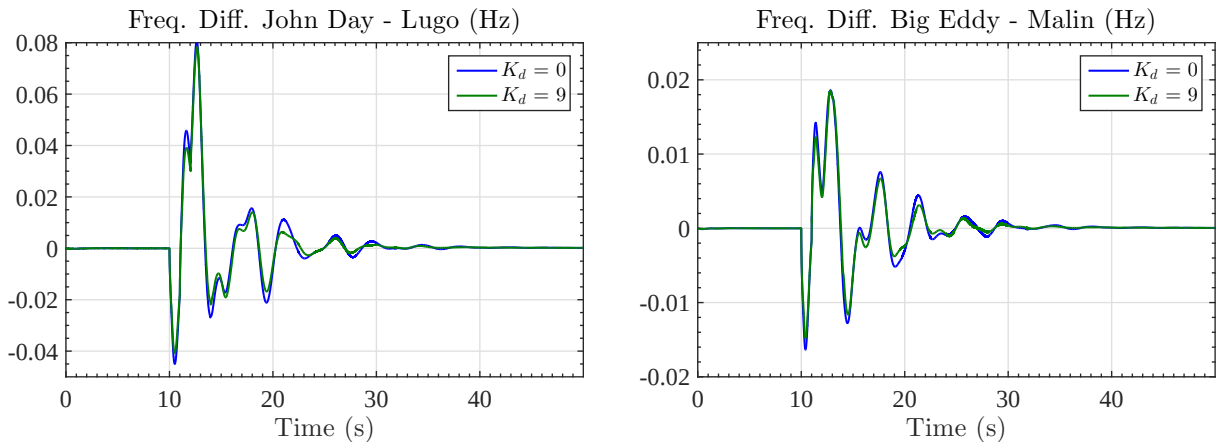


Figure 309. Frequency differences. Event: Chief Joe Brake followed by double Palo Verde outage.

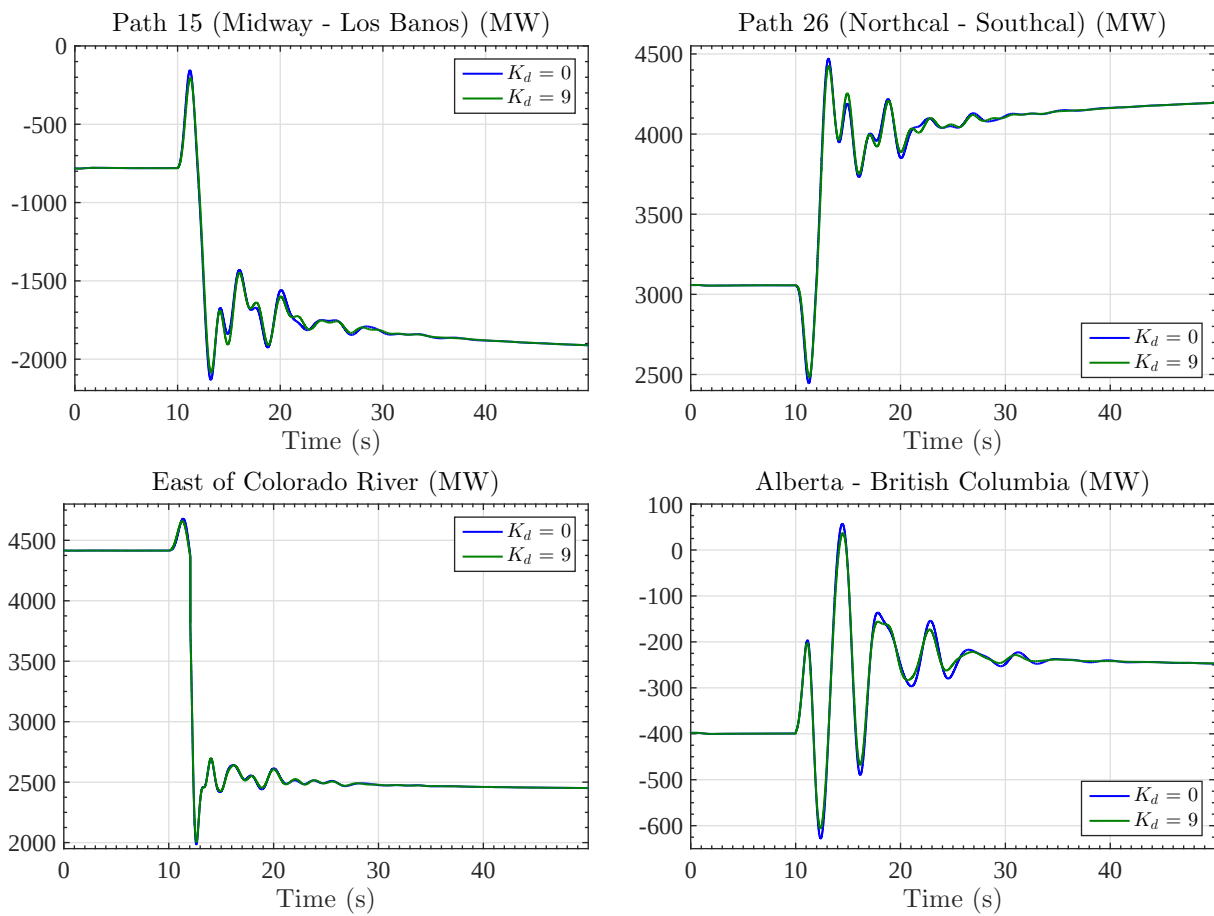


Figure 310. Active power flows. Event: Chief Joe Brake followed by double Palo Verde outage.

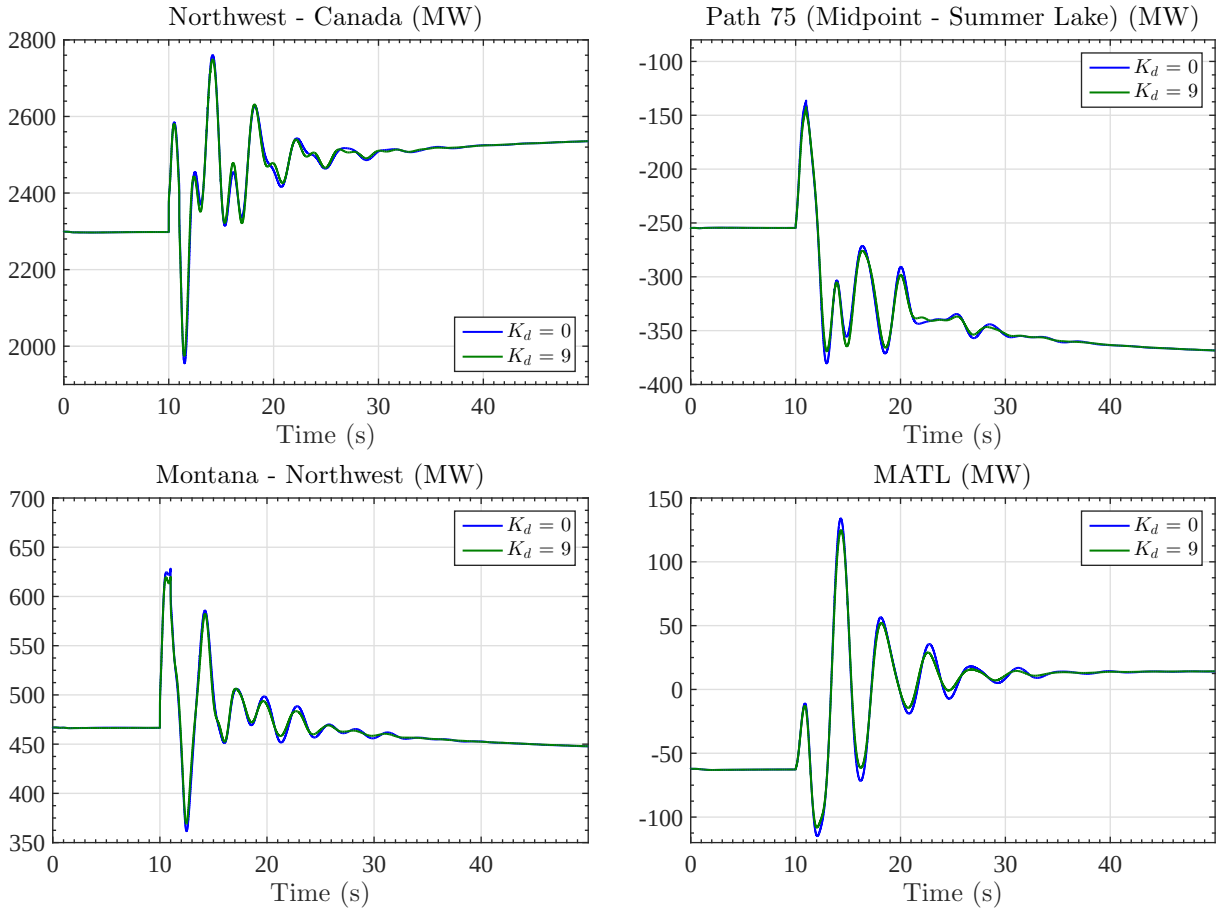


Figure 311. Active power flows. Event: Chief Joe Brake followed by double Palo Verde outage.

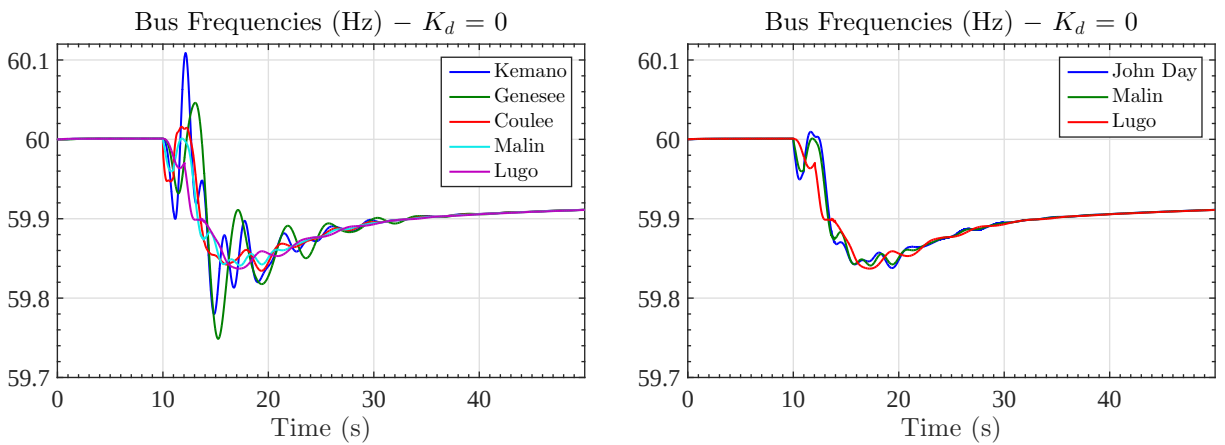


Figure 312. Bus frequencies. Event: Chief Joe Brake followed by double Palo Verde outage.

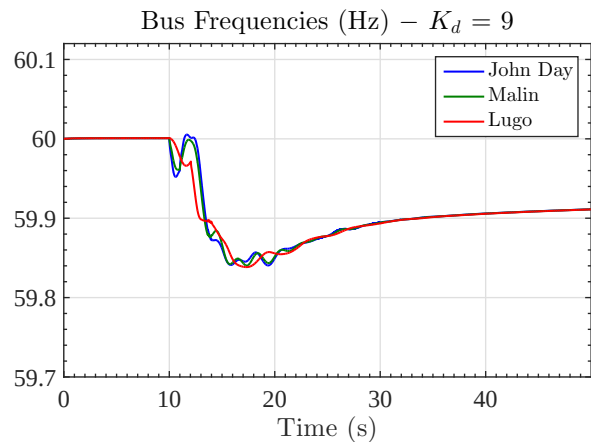
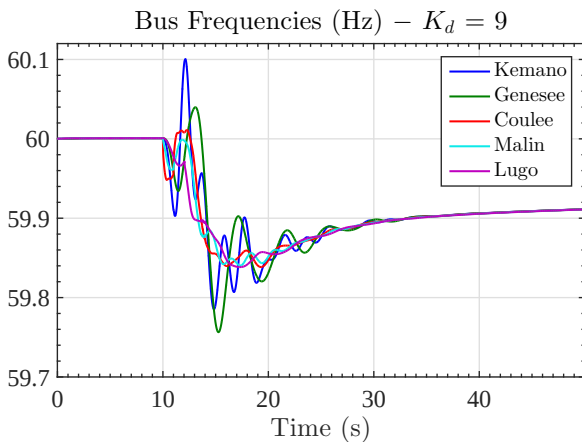


Figure 313. Bus frequencies. Event: Chief Joe Brake followed by double Palo Verde outage.

5.1.3. Test System: Heavy Summer 2016. Event: Chief Joe Brake followed by CGS outage

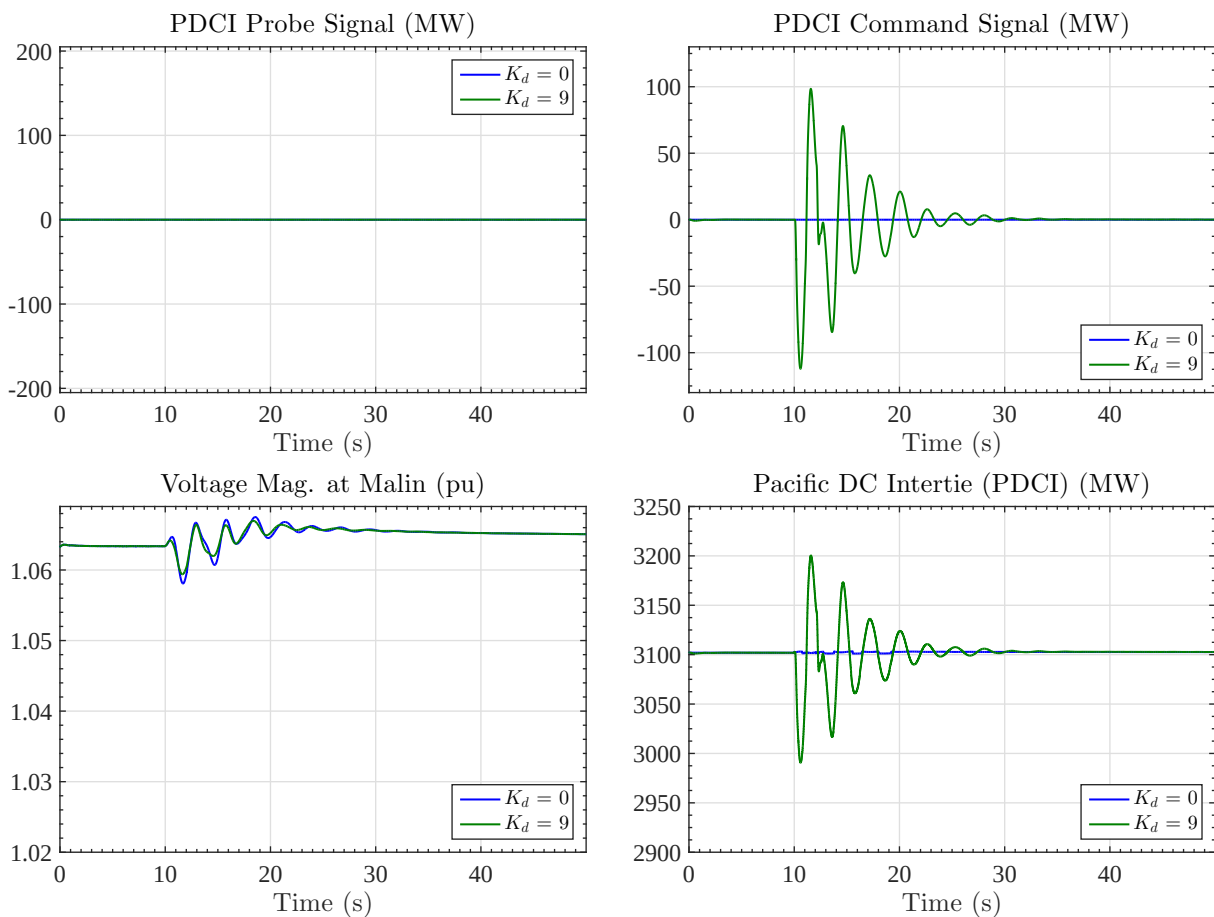


Figure 314. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake followed by CGS outage.

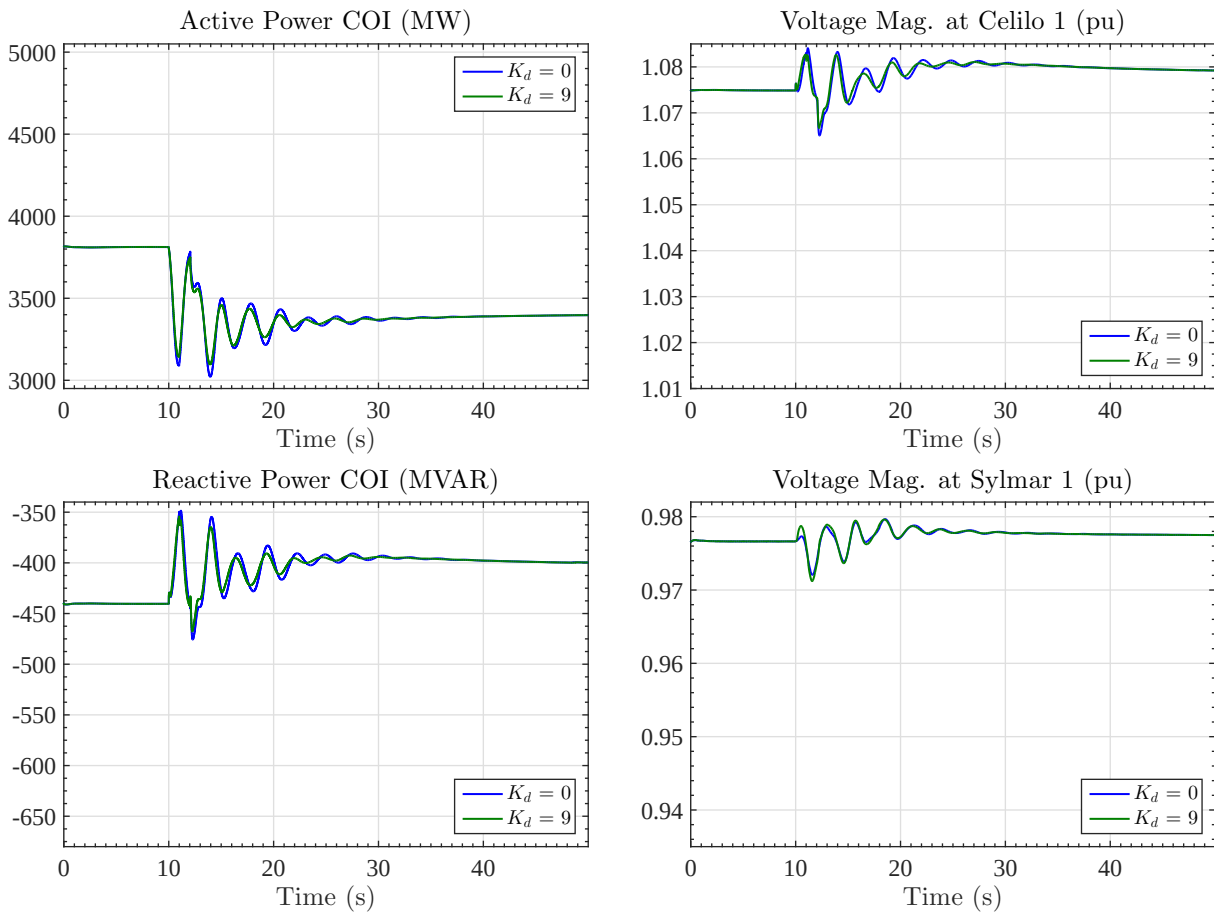


Figure 315. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake followed by CGS outage.

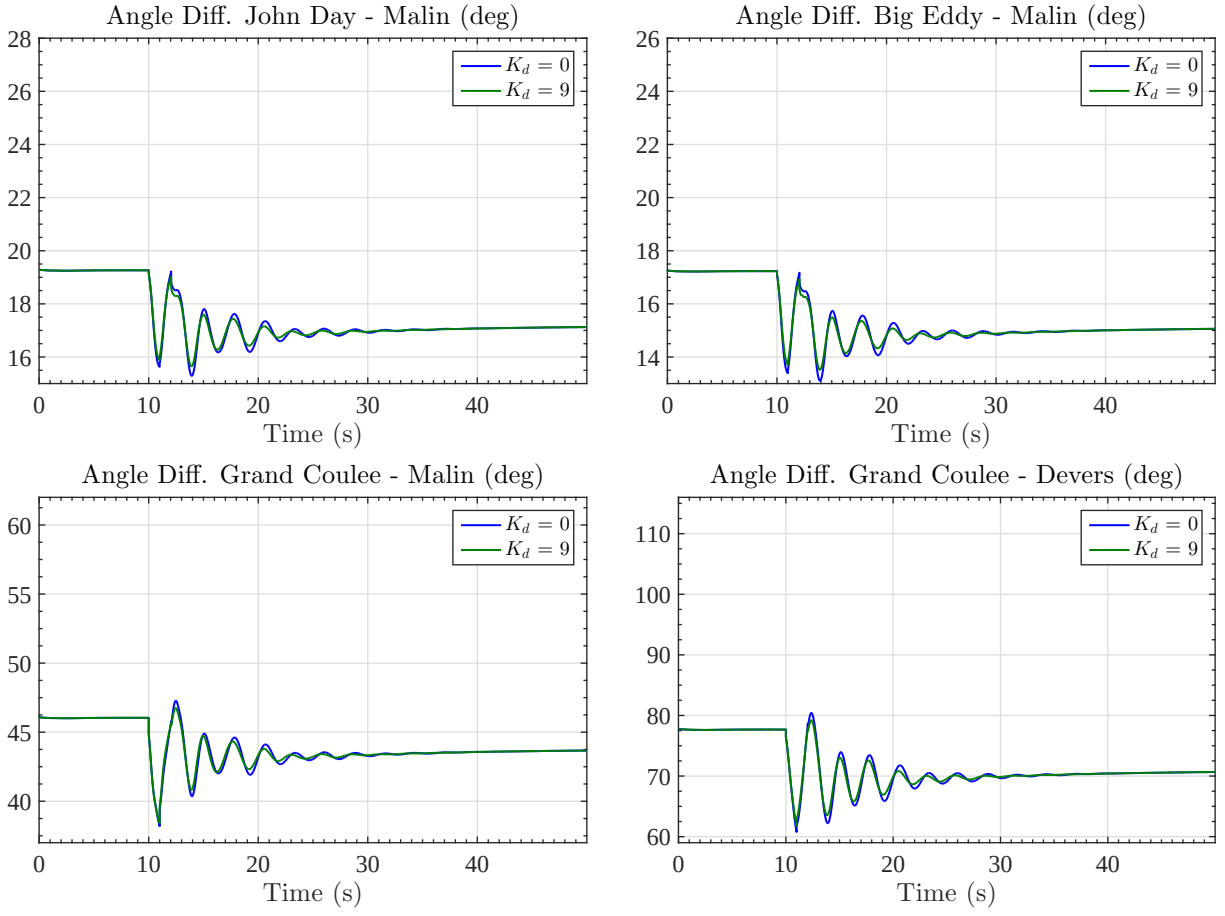


Figure 316. Angle differences. Event: Chief Joe Brake followed by CGS outage.

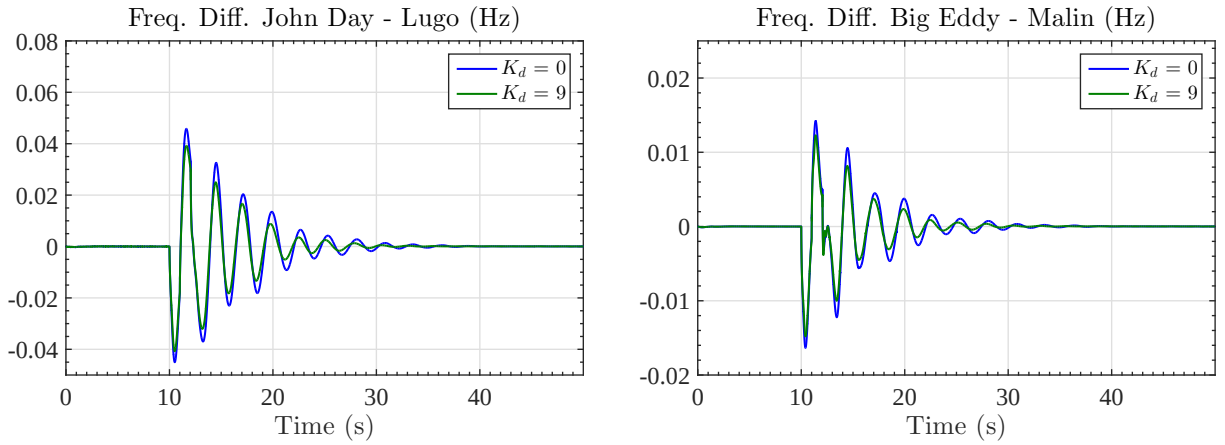


Figure 317. Frequency differences. Event: Chief Joe Brake followed by CGS outage.

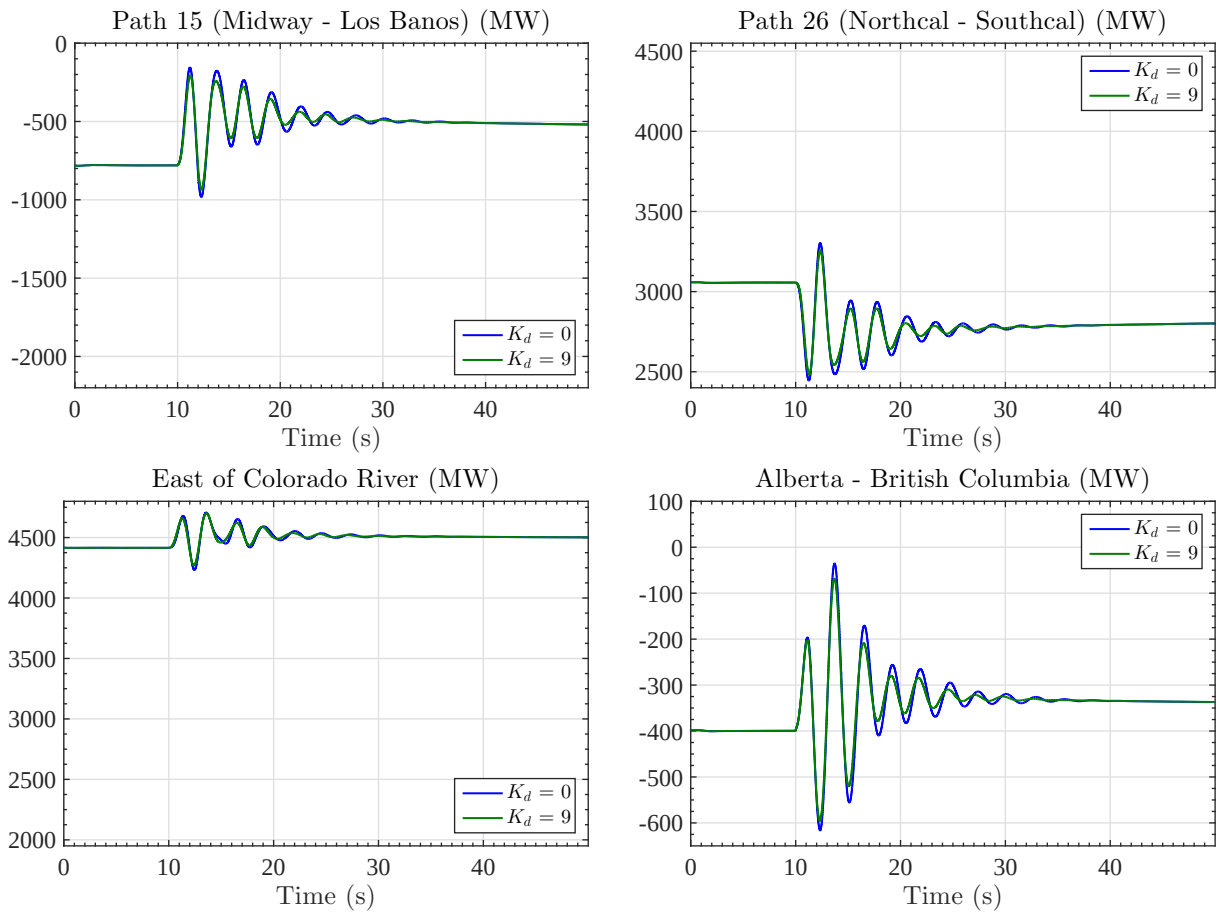


Figure 318. Active power flows. Event: Chief Joe Brake followed by CGS outage.

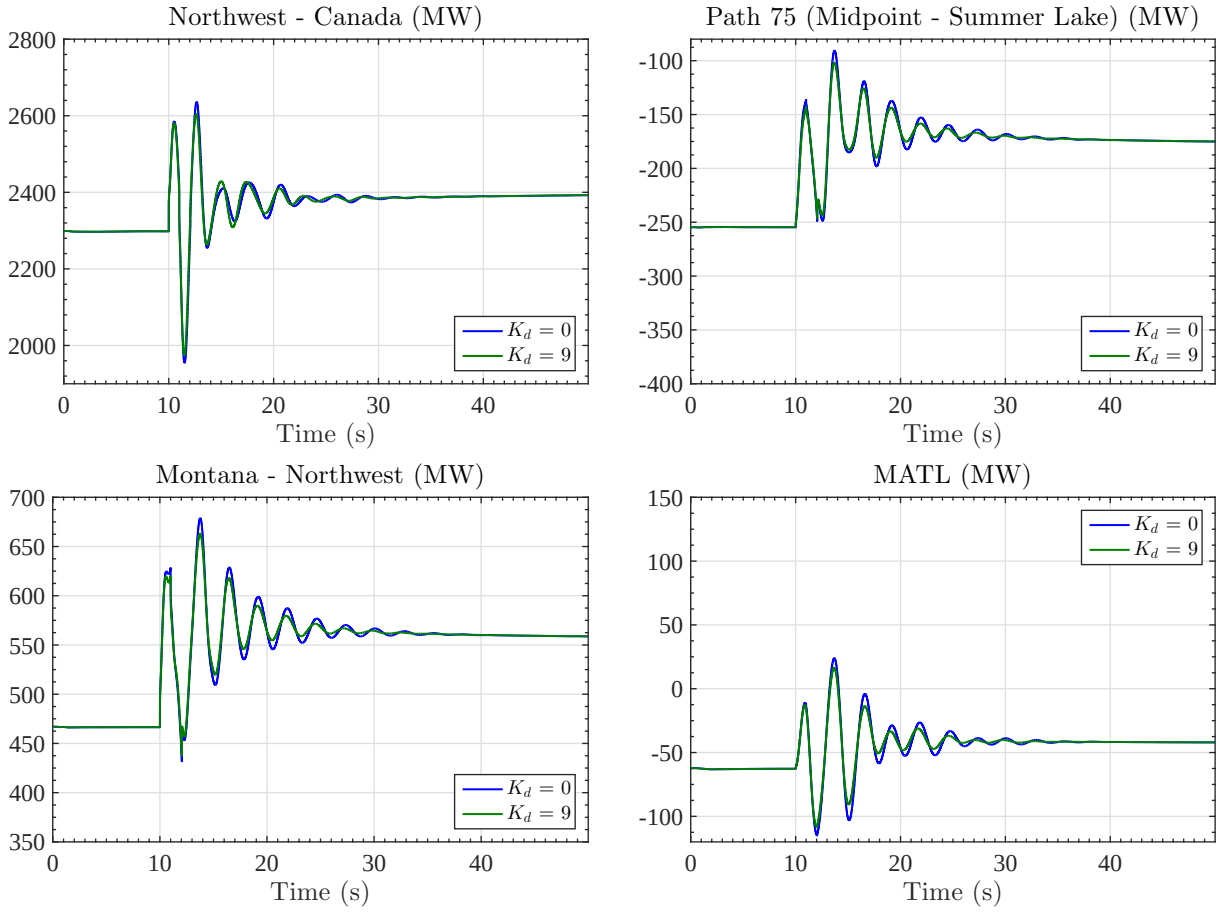


Figure 319. Active power flows. Event: Chief Joe Brake followed by CGS outage.

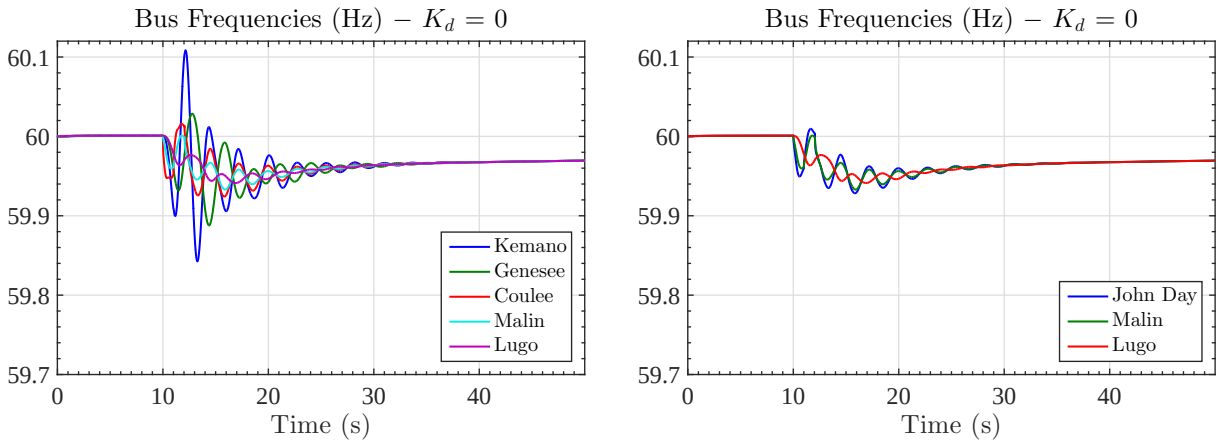


Figure 320. Bus frequencies. Event: Chief Joe Brake followed by CGS outage.

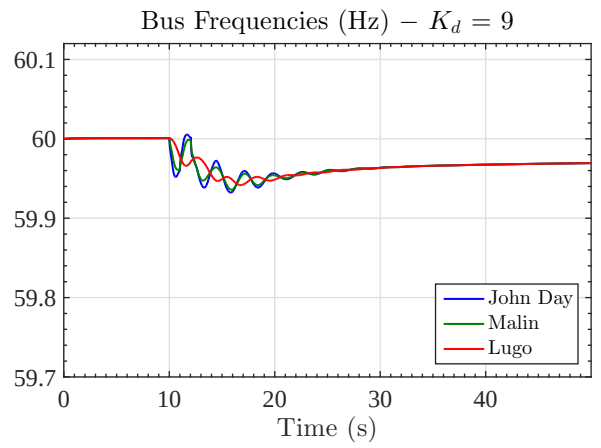
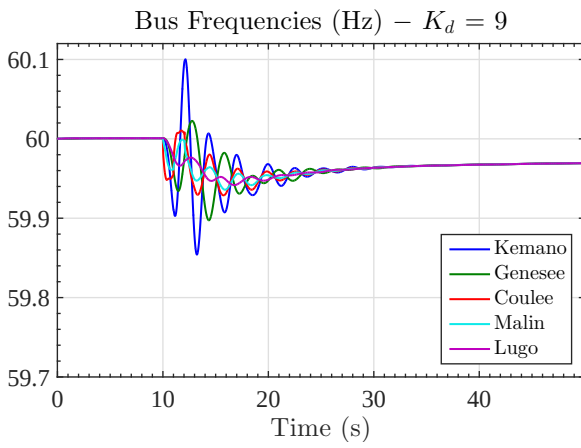


Figure 321. Bus frequencies. Event: Chief Joe Brake followed by CGS outage.

5.1.4. Test System: Heavy Summer 2016. Event: 200 MW pulses followed by forced oscillation

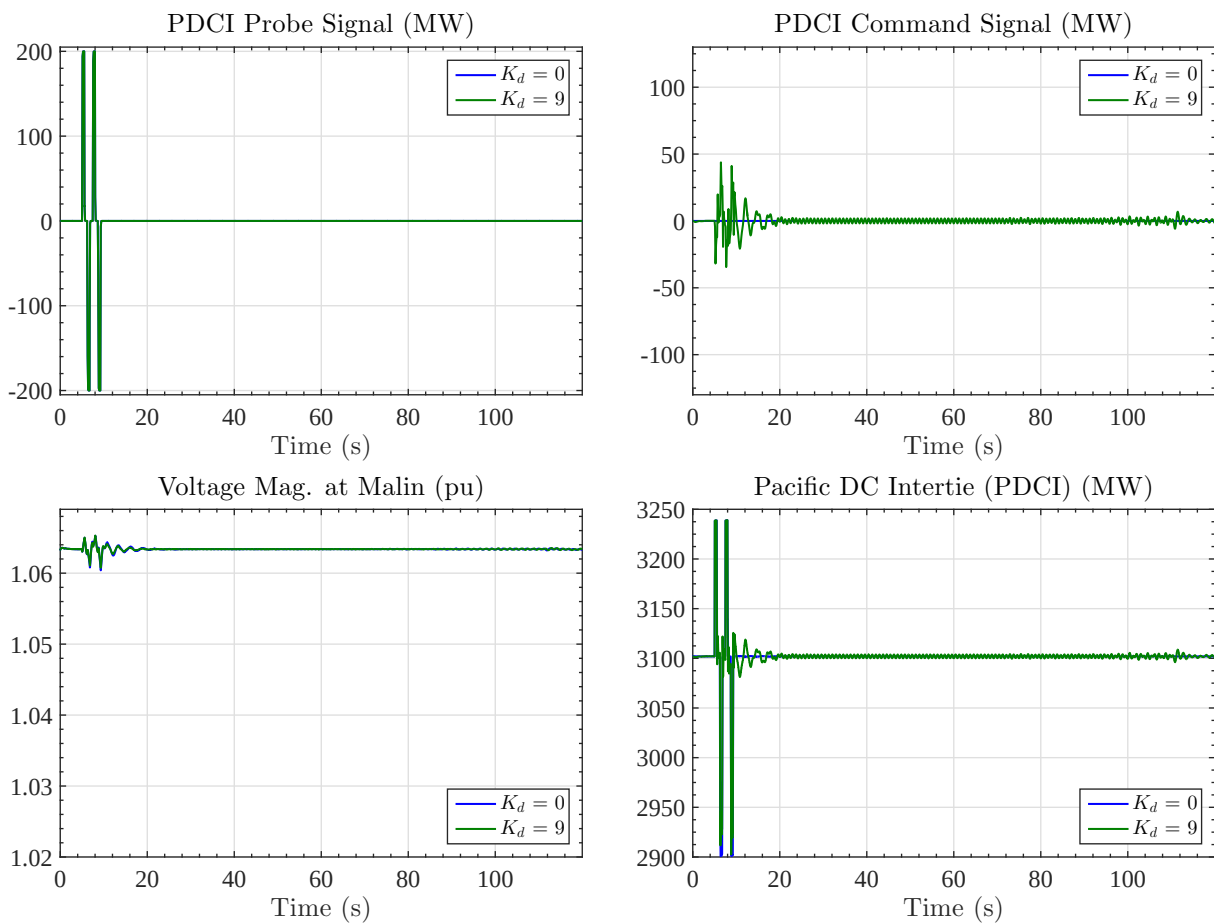


Figure 322. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses followed by forced oscillation.

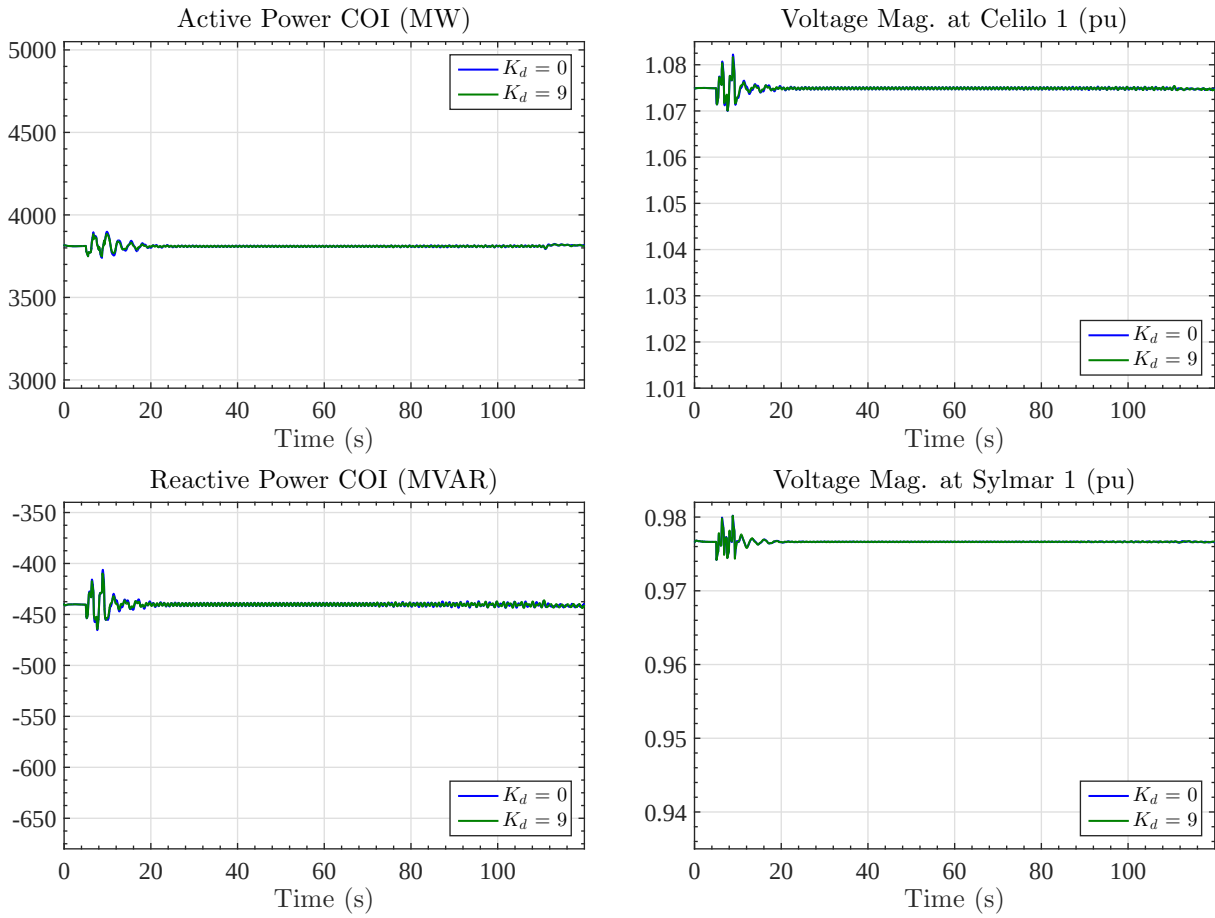


Figure 323. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses followed by forced oscillation.

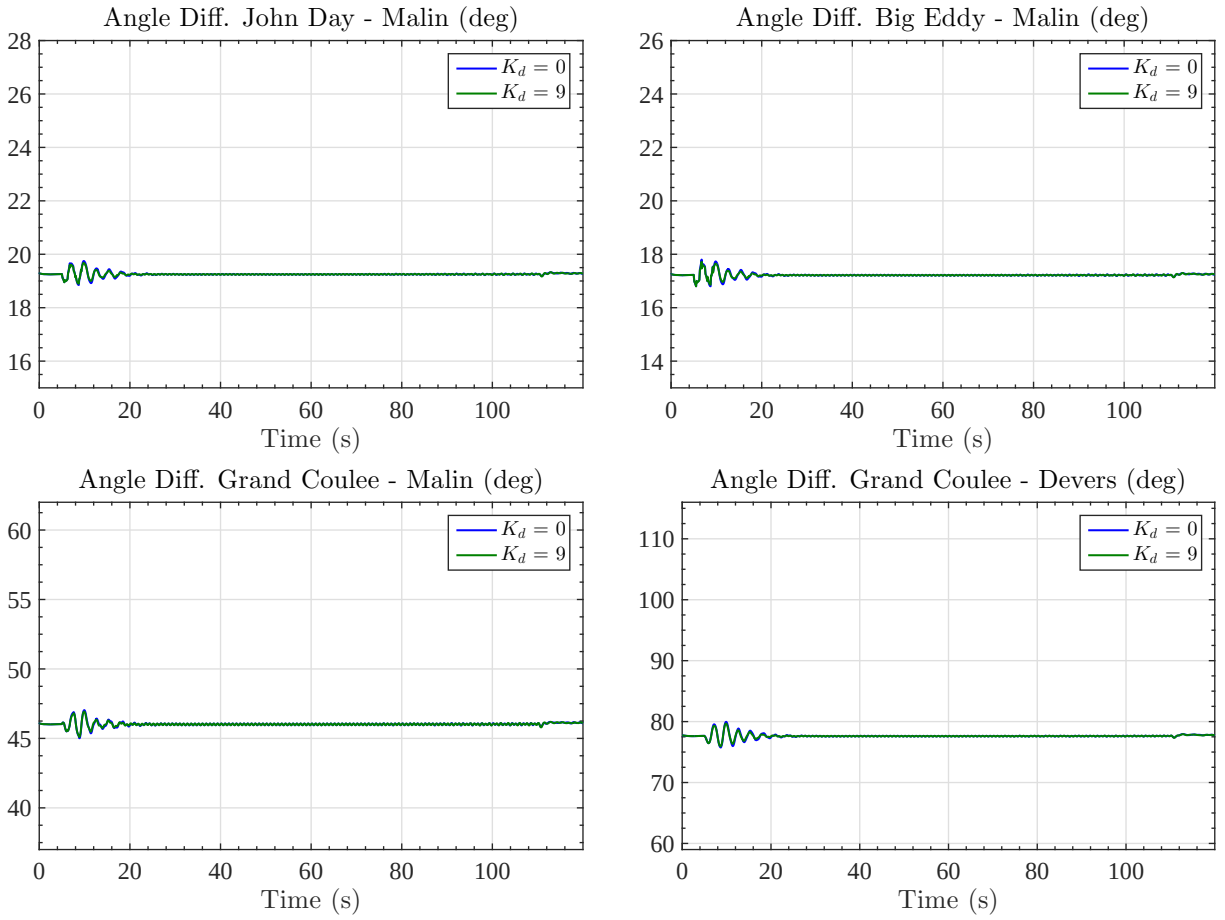


Figure 324. Angle differences. Event: 200 MW pulses followed by forced oscillation.

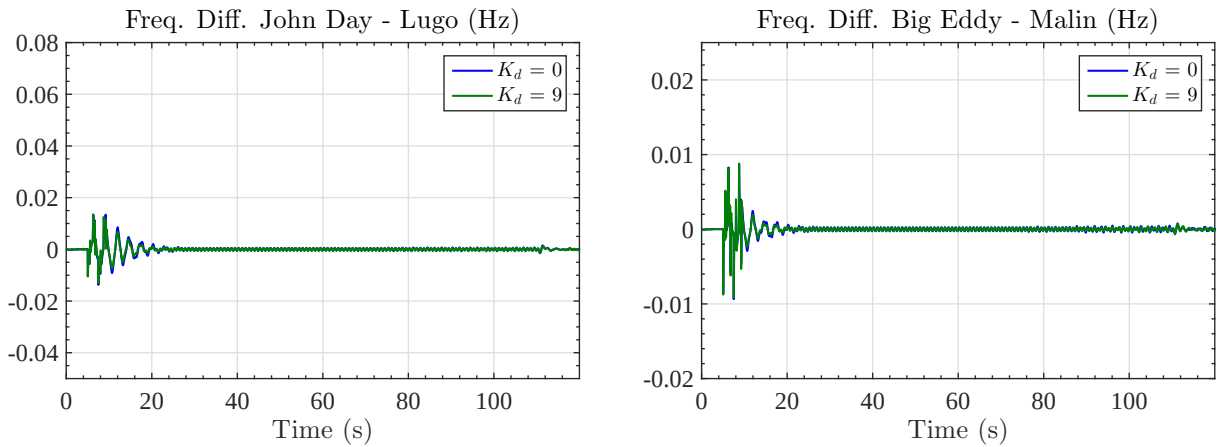


Figure 325. Frequency differences. Event: 200 MW pulses followed by forced oscillation.

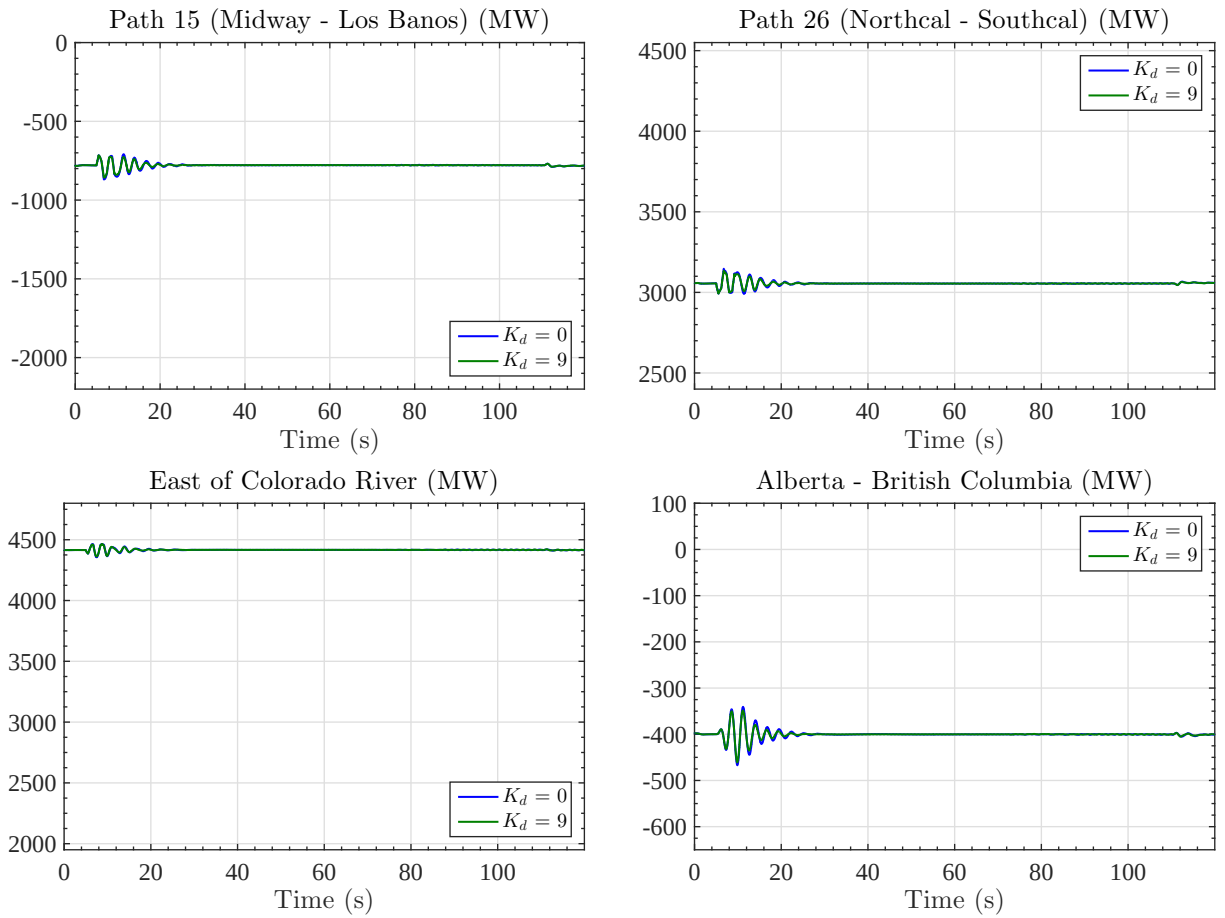


Figure 326. Active power flows. Event: 200 MW pulses followed by forced oscillation.

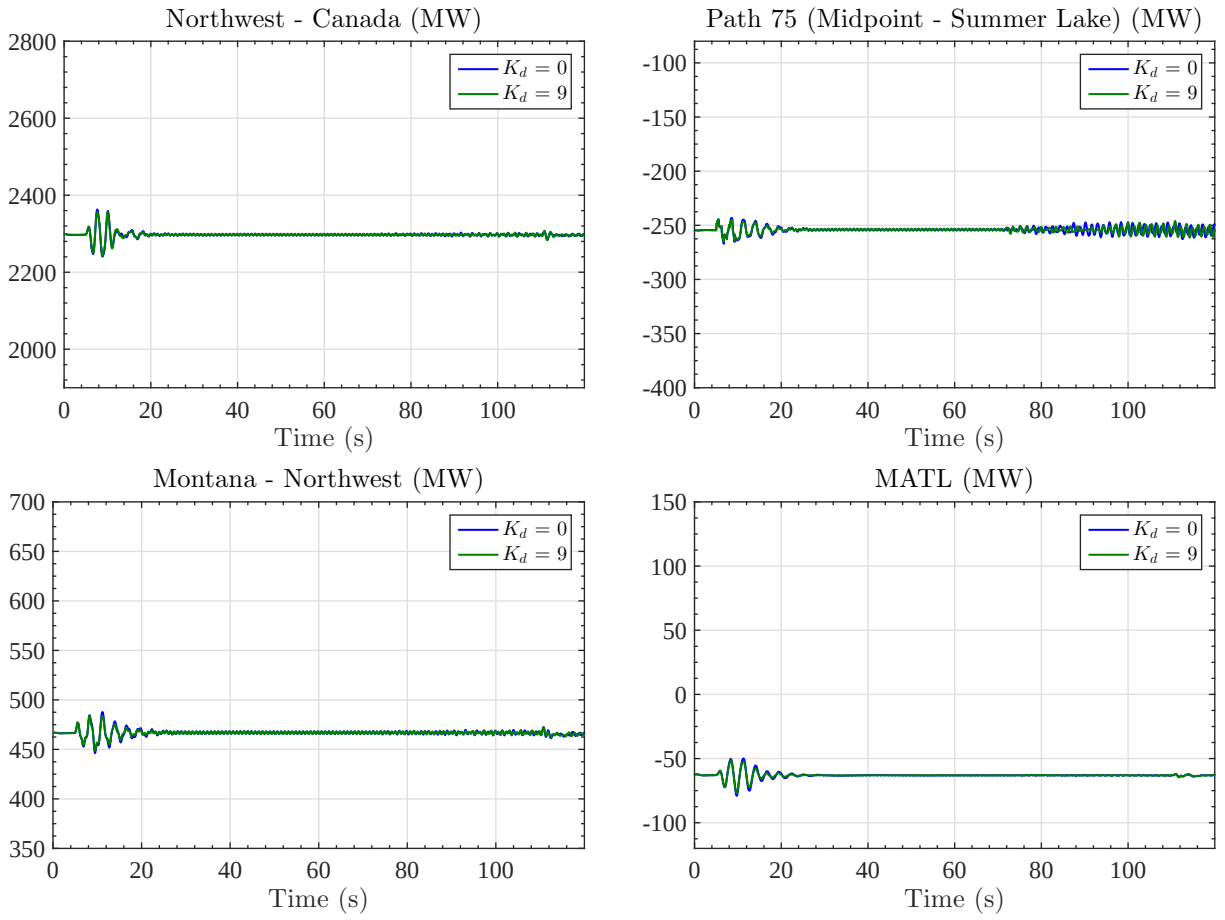


Figure 327. Active power flows. Event: 200 MW pulses followed by forced oscillation.

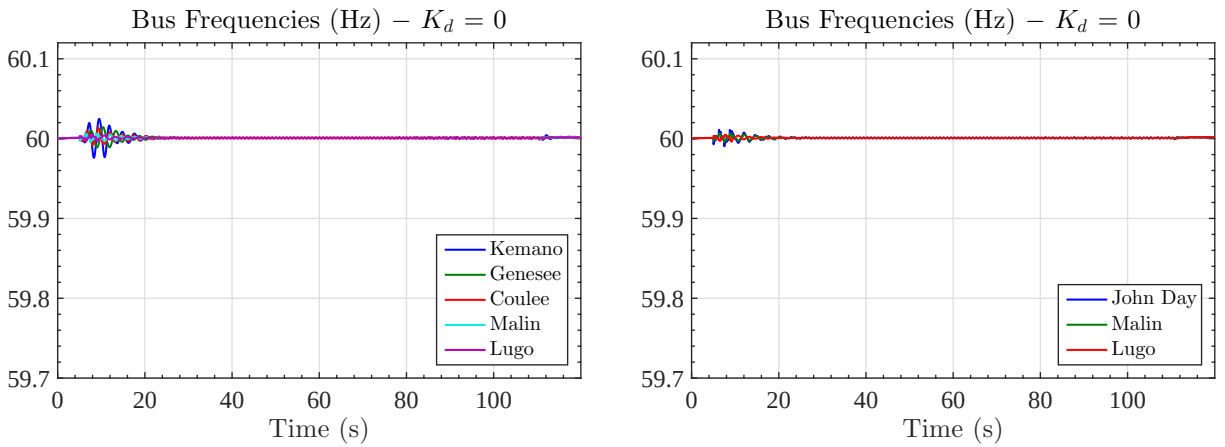


Figure 328. Bus frequencies. Event: 200 MW pulses followed by forced oscillation.

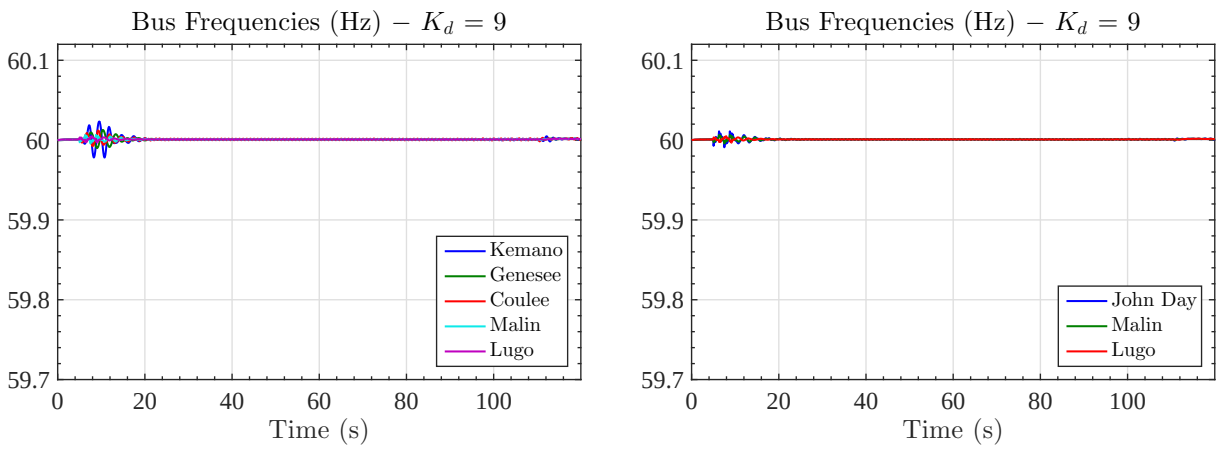


Figure 329. Bus frequencies. Event: 200 MW pulses followed by forced oscillation.

5.1.5. Test System: Heavy Summer 2016. Event: 200 MW pulses followed by double Palo Verde outage

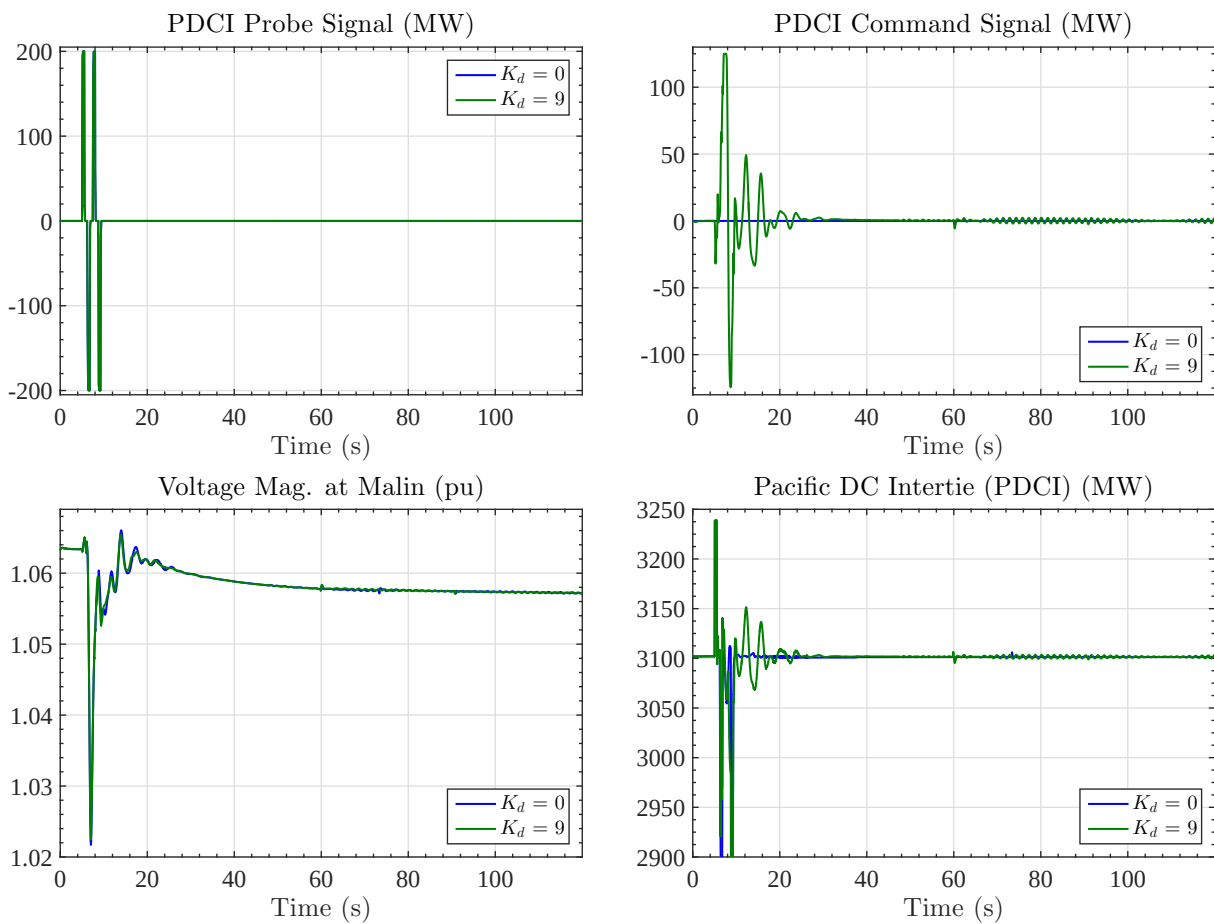


Figure 330. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses followed by double Palo Verde outage.

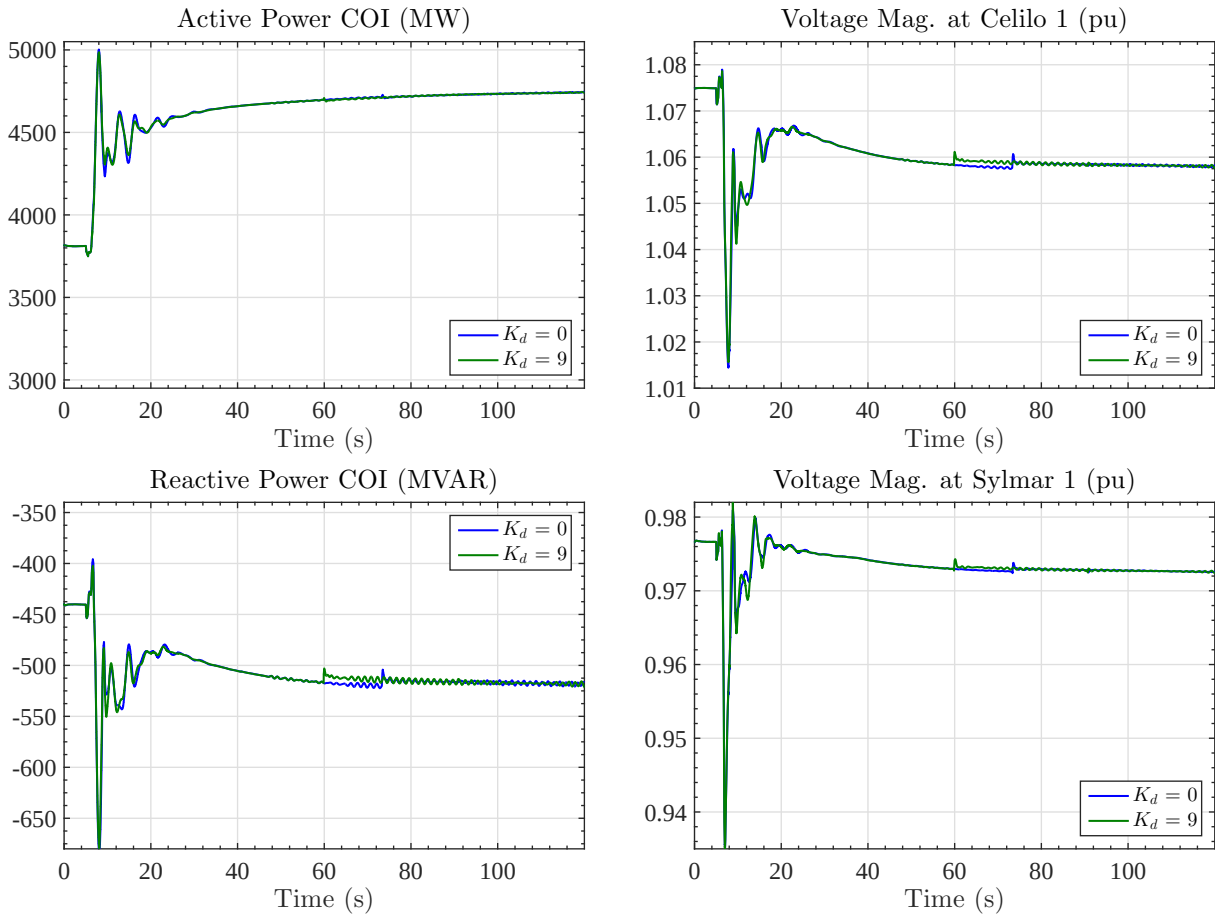


Figure 331. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses followed by double Palo Verde outage.

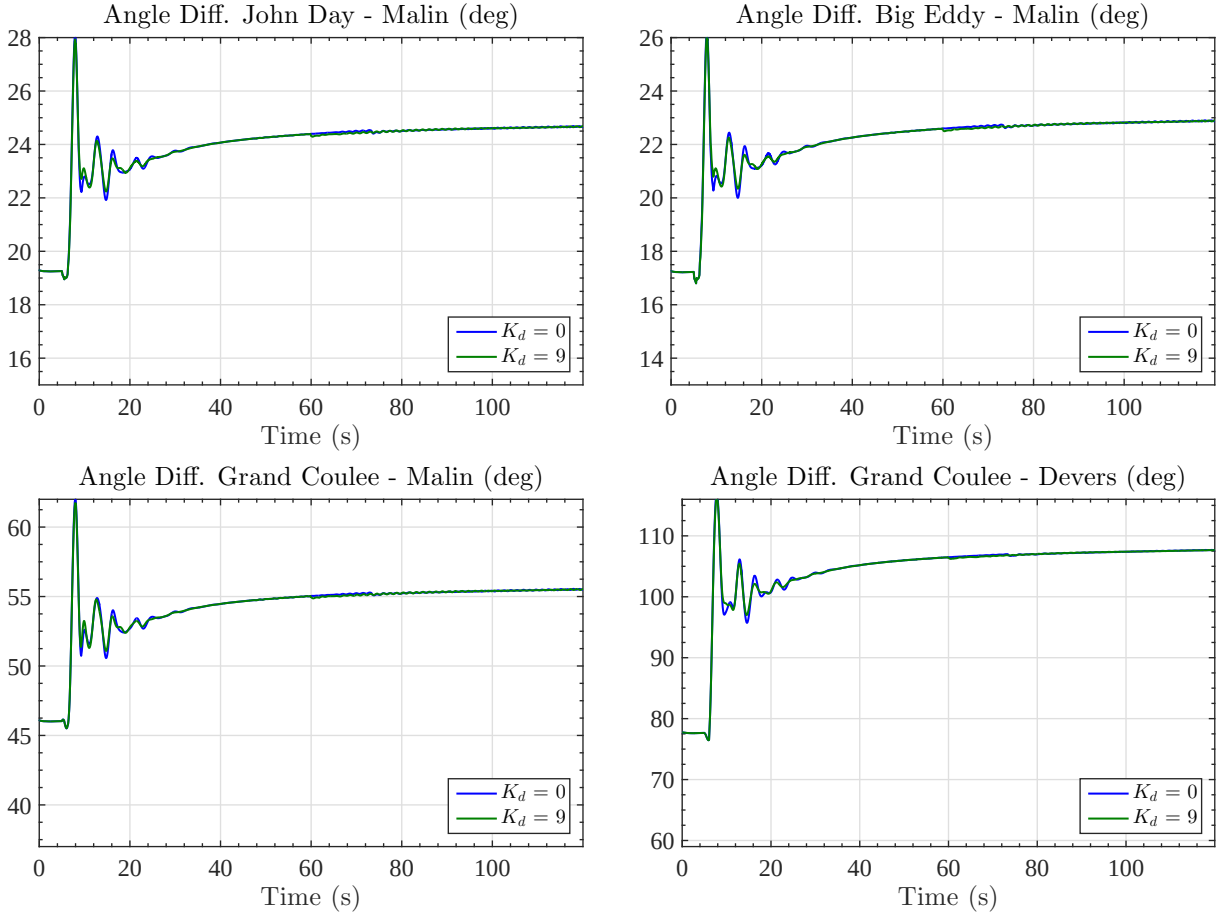


Figure 332. Angle differences. Event: 200 MW pulses followed by double Palo Verde outage.

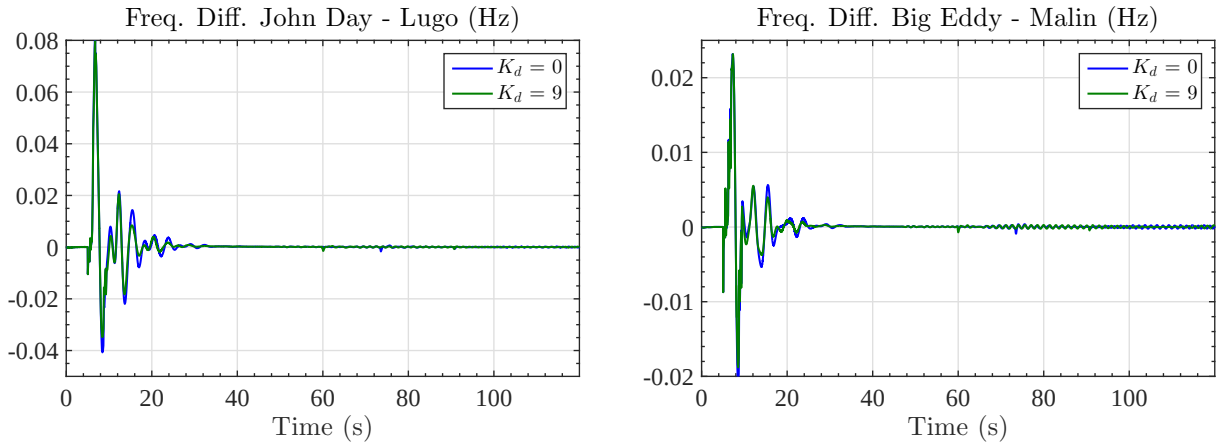


Figure 333. Frequency differences. Event: 200 MW pulses followed by double Palo Verde outage.

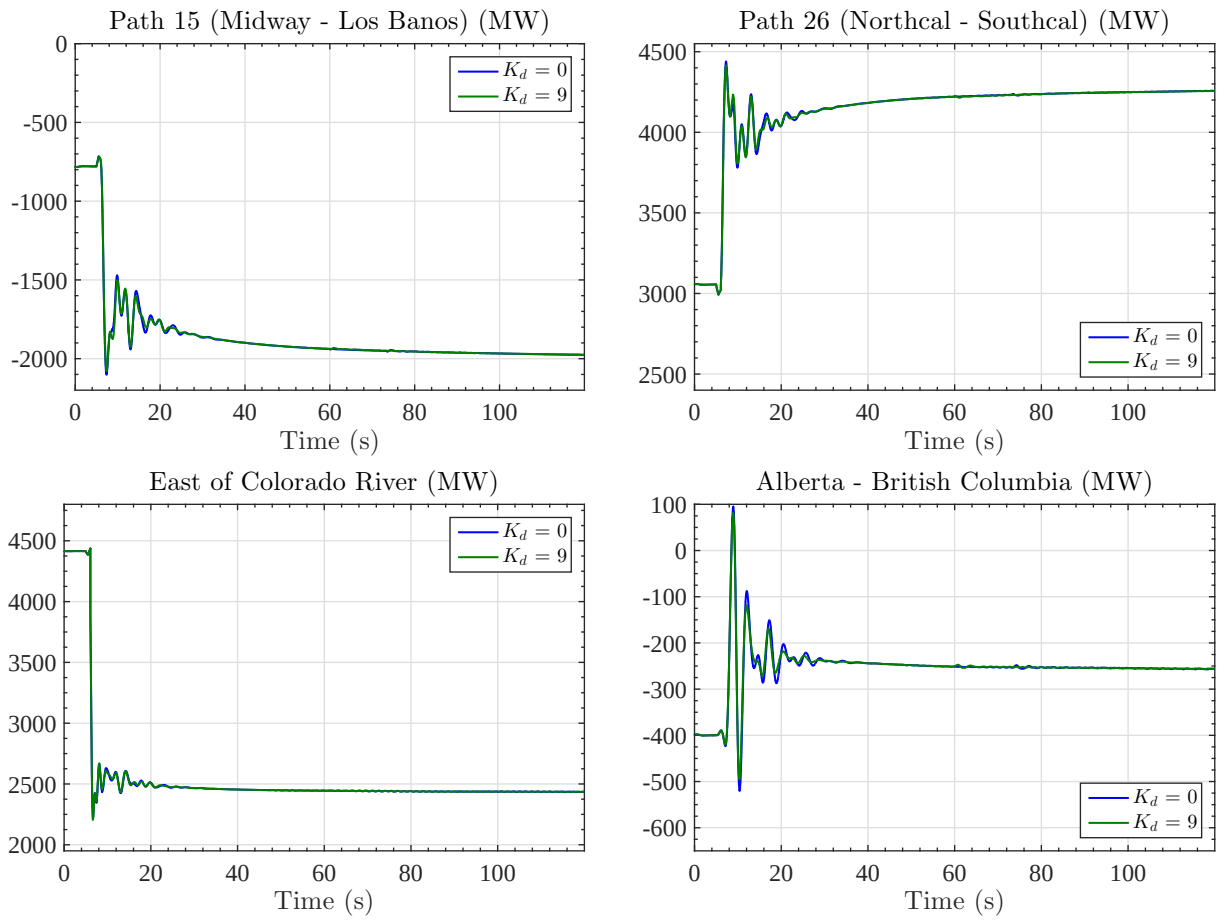


Figure 334. Active power flows. Event: 200 MW pulses followed by double Palo Verde outage.

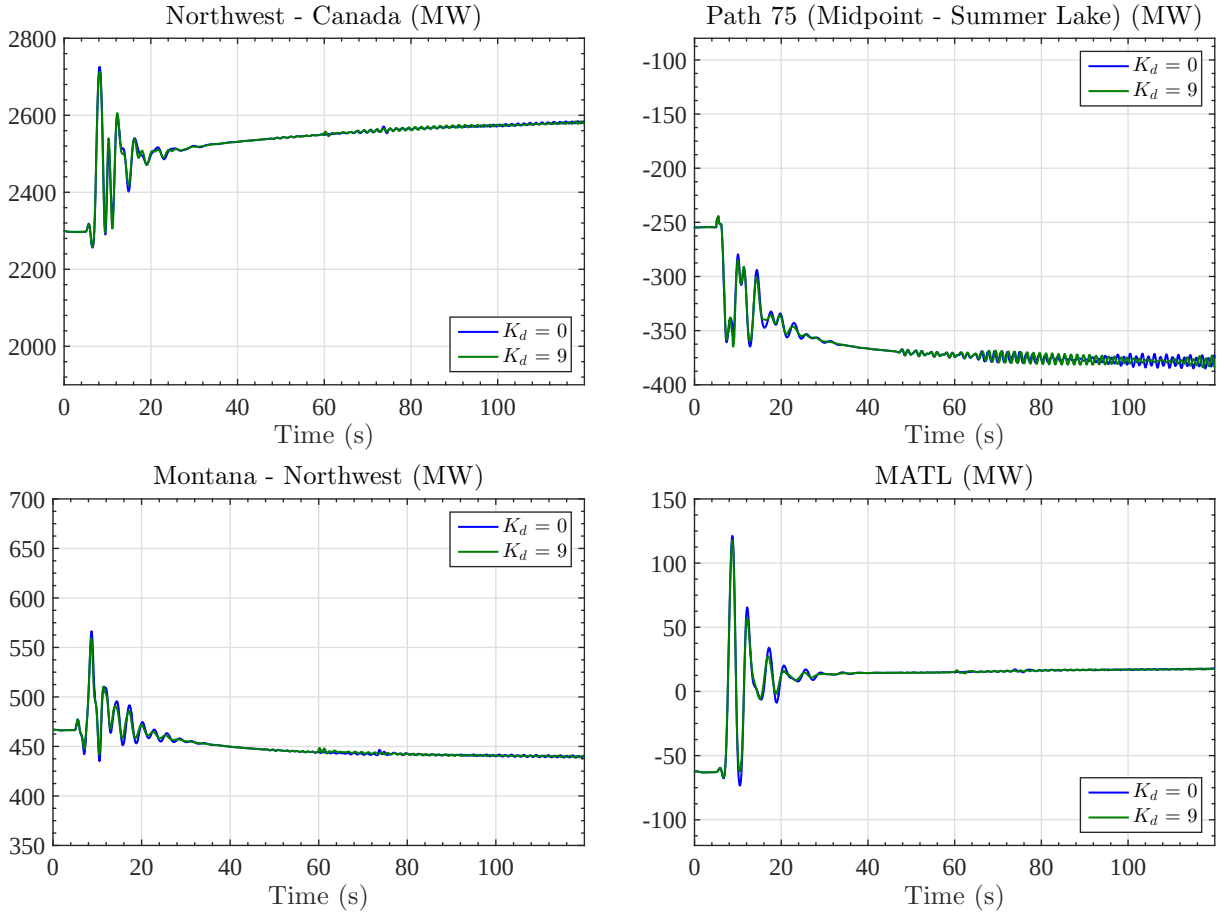


Figure 335. Active power flows. Event: 200 MW pulses followed by double Palo Verde outage.

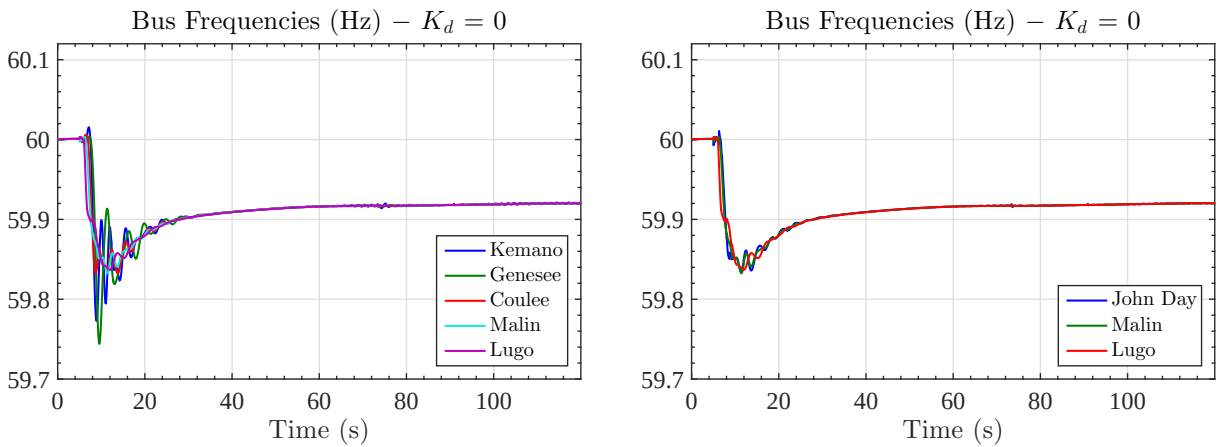


Figure 336. Bus frequencies. Event: 200 MW pulses followed by double Palo Verde outage.

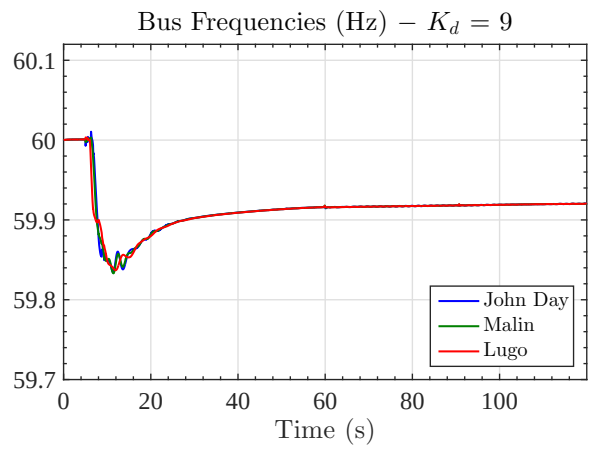
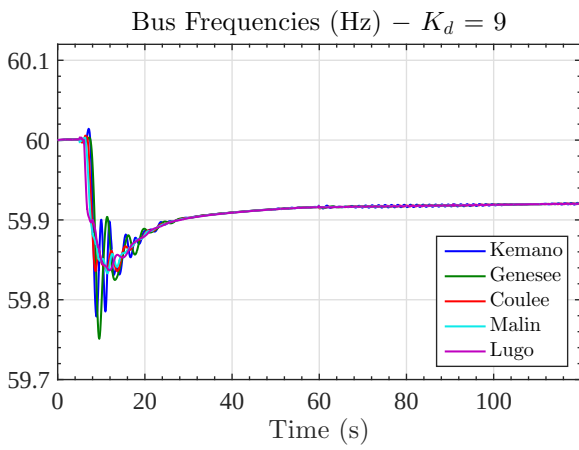


Figure 337. Bus frequencies. Event: 200 MW pulses followed by double Palo Verde outage.

5.1.6. Test System: Heavy Summer 2016. Event: 200 MW pulses followed by CGS outage

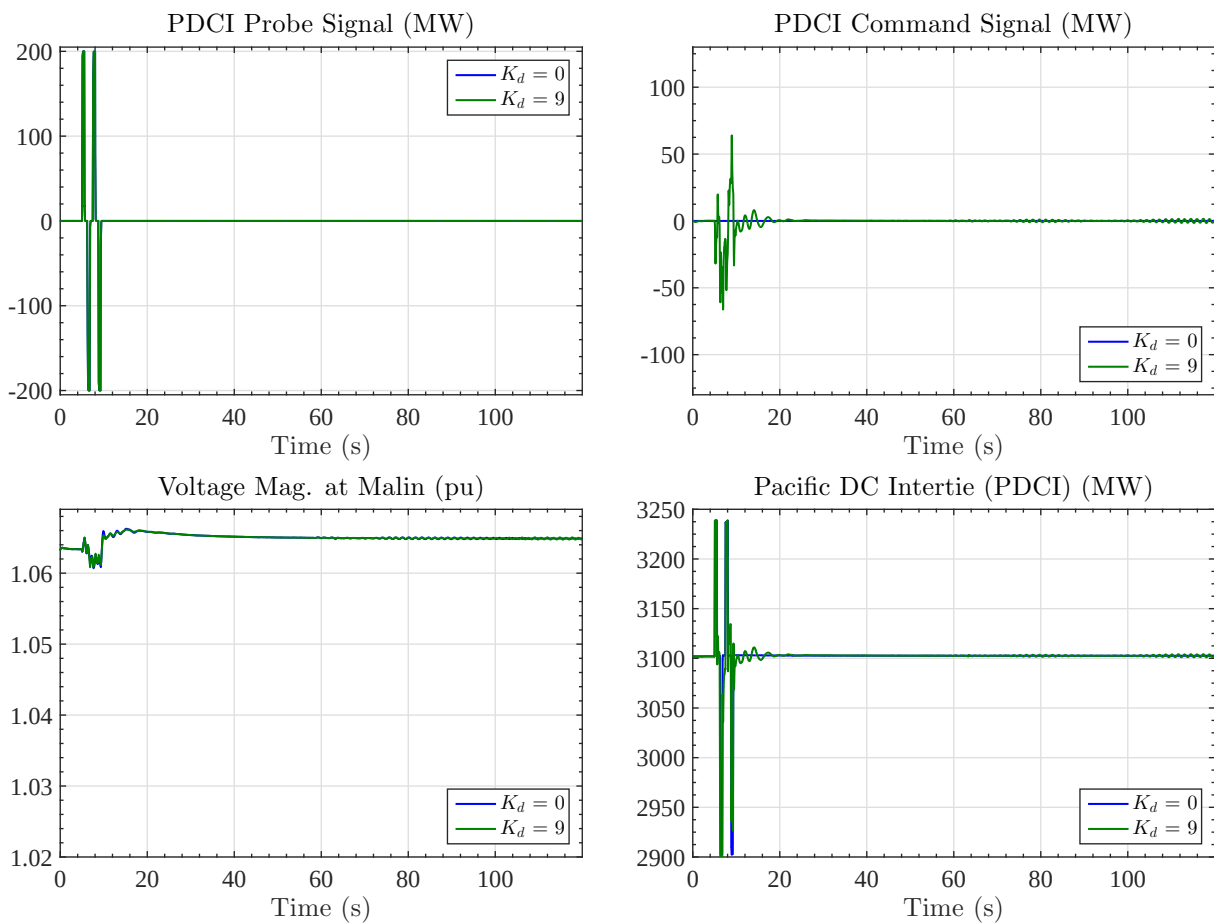


Figure 338. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: 200 MW pulses followed by CGS outage.

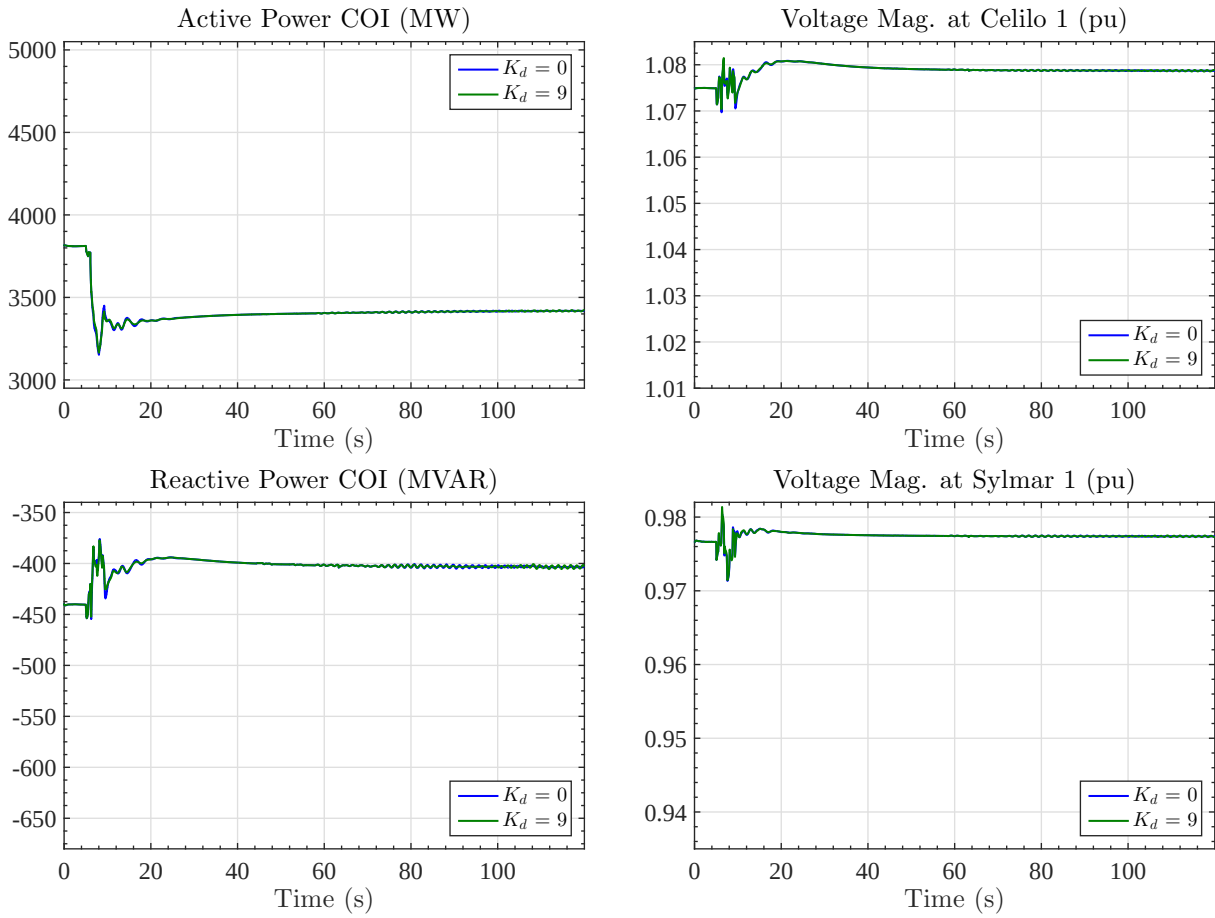


Figure 339. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: 200 MW pulses followed by CGS outage.

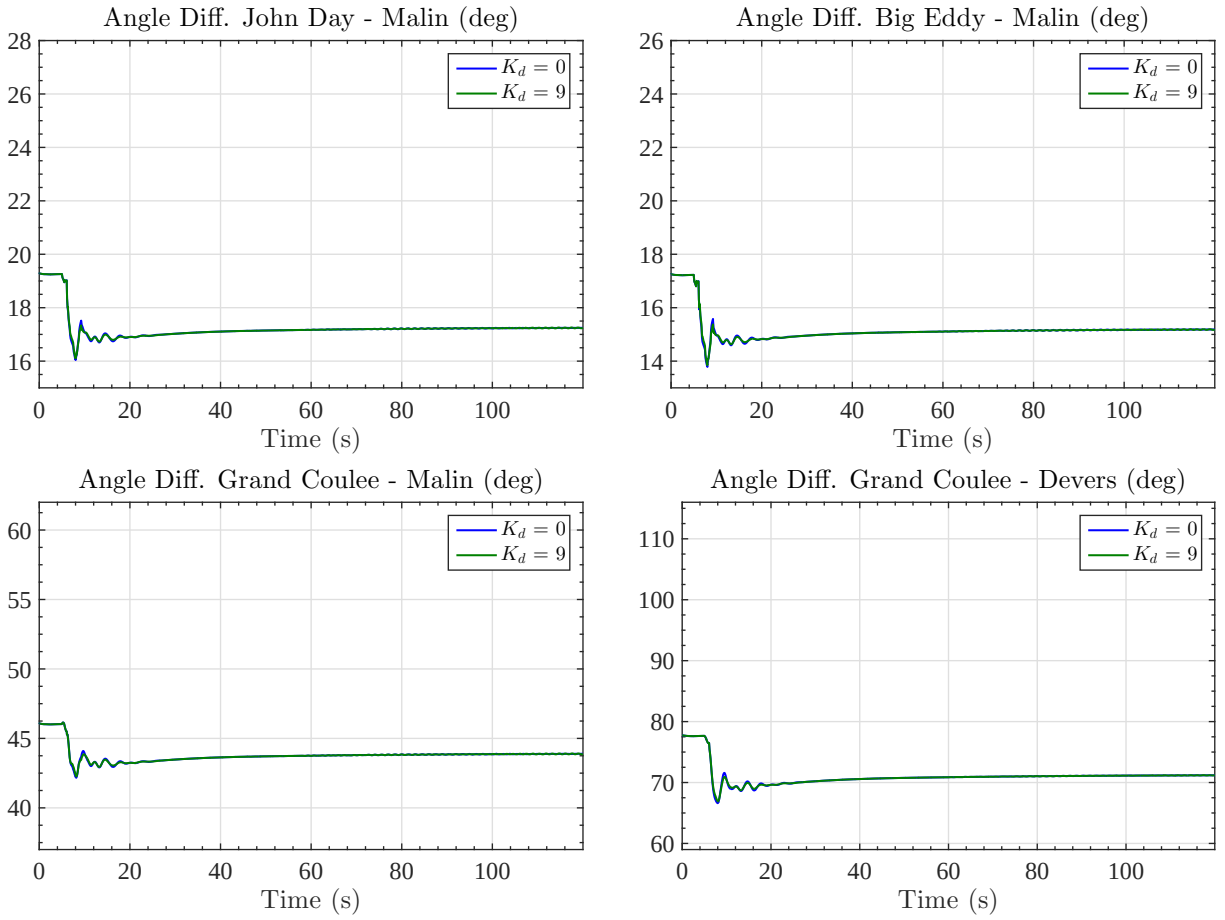


Figure 340. Angle differences. Event: 200 MW pulses followed by CGS outage.

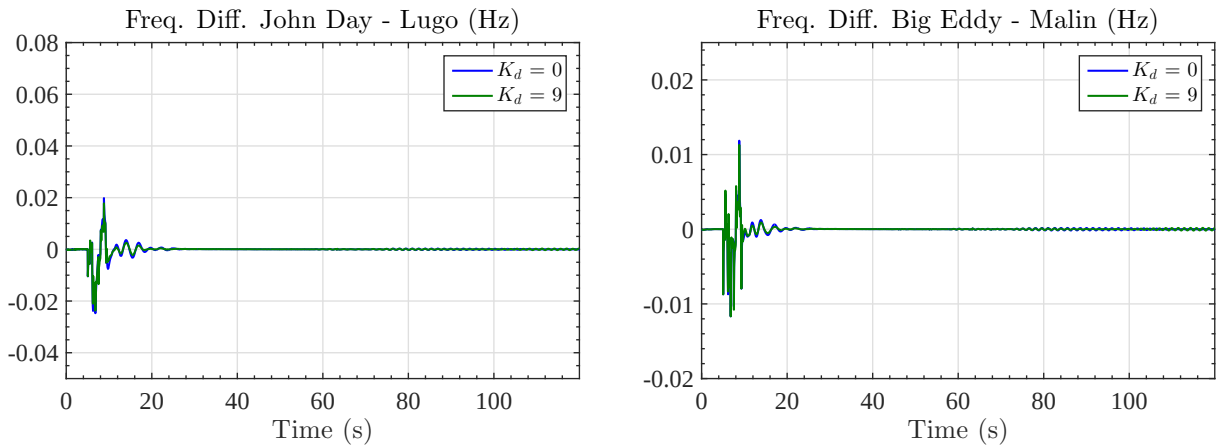


Figure 341. Frequency differences. Event: 200 MW pulses followed by CGS outage.

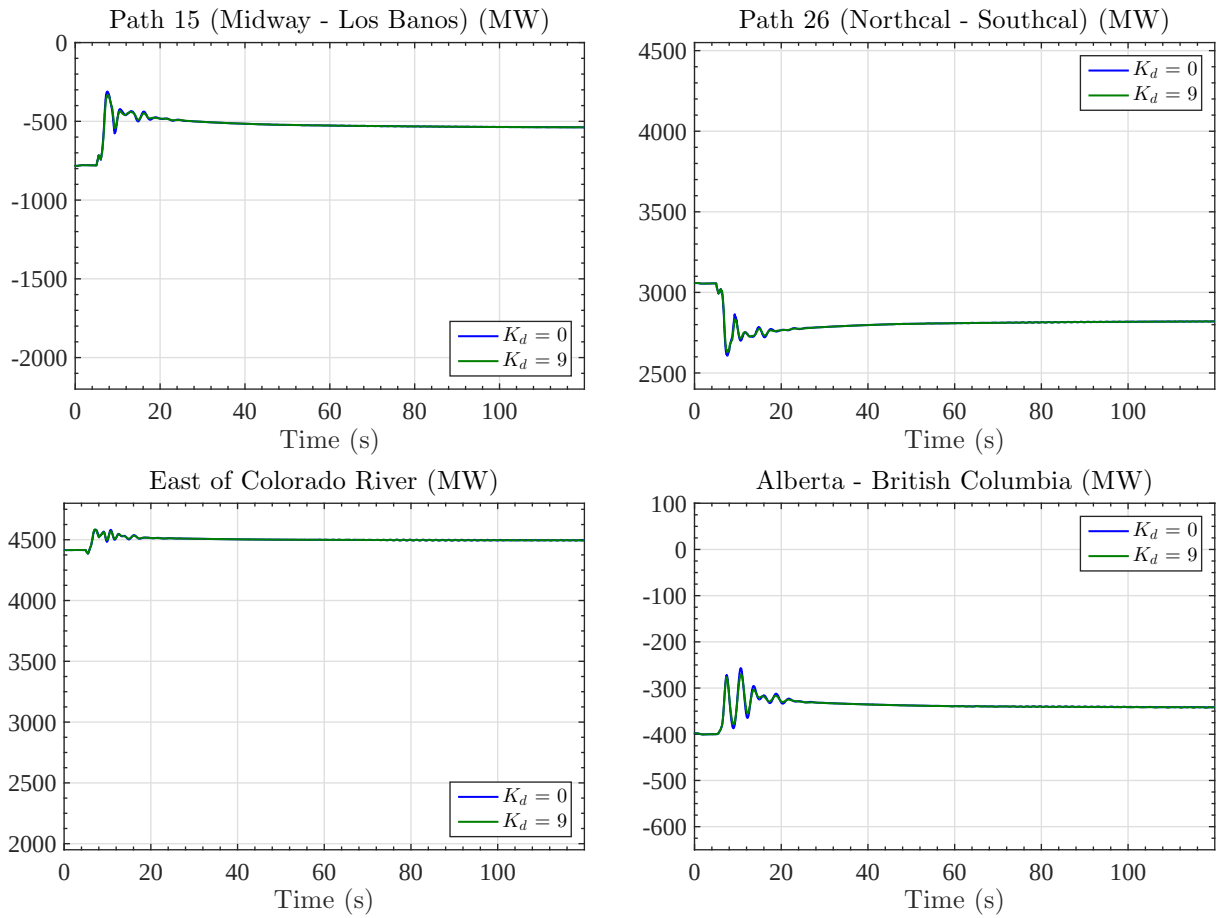


Figure 342. Active power flows. Event: 200 MW pulses followed by CGS outage.

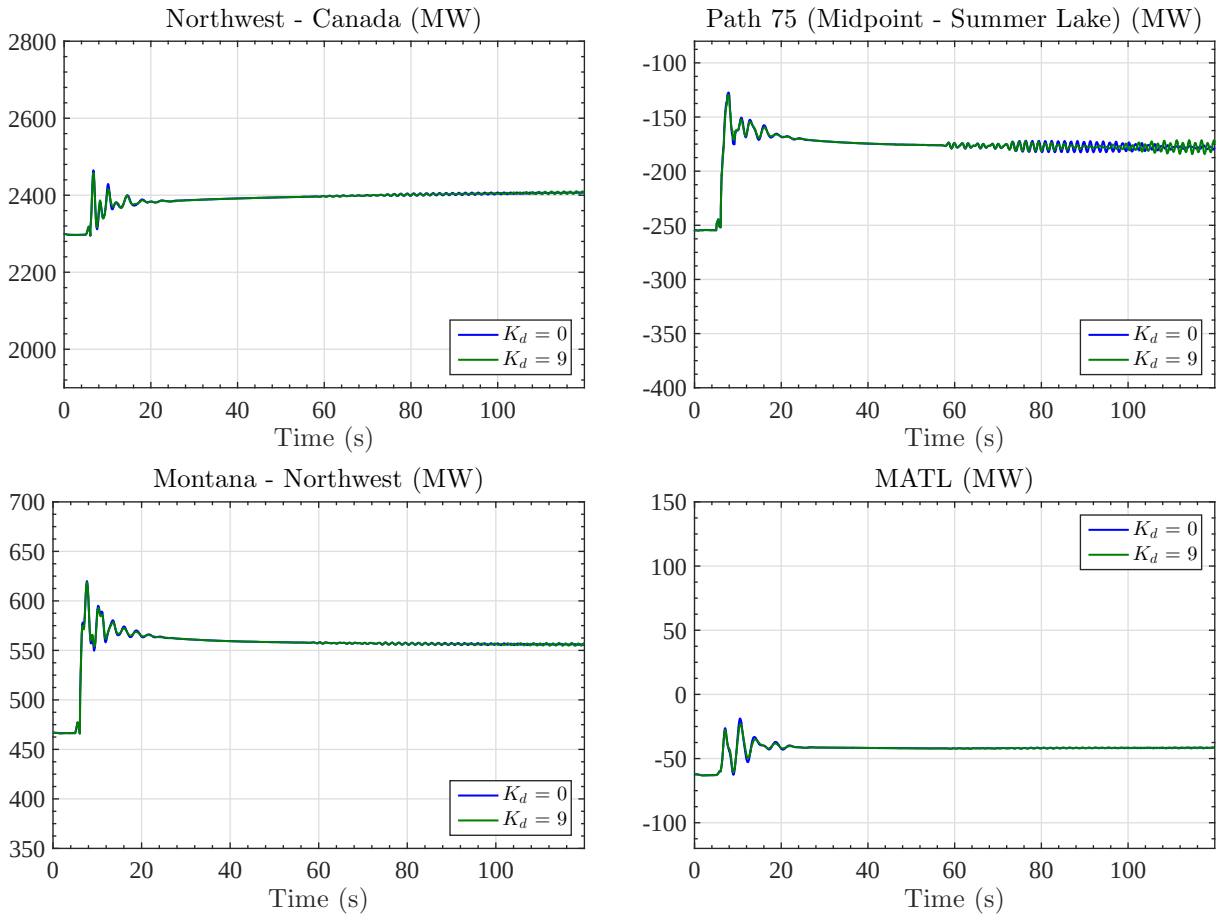


Figure 343. Active power flows. Event: 200 MW pulses followed by CGS outage.

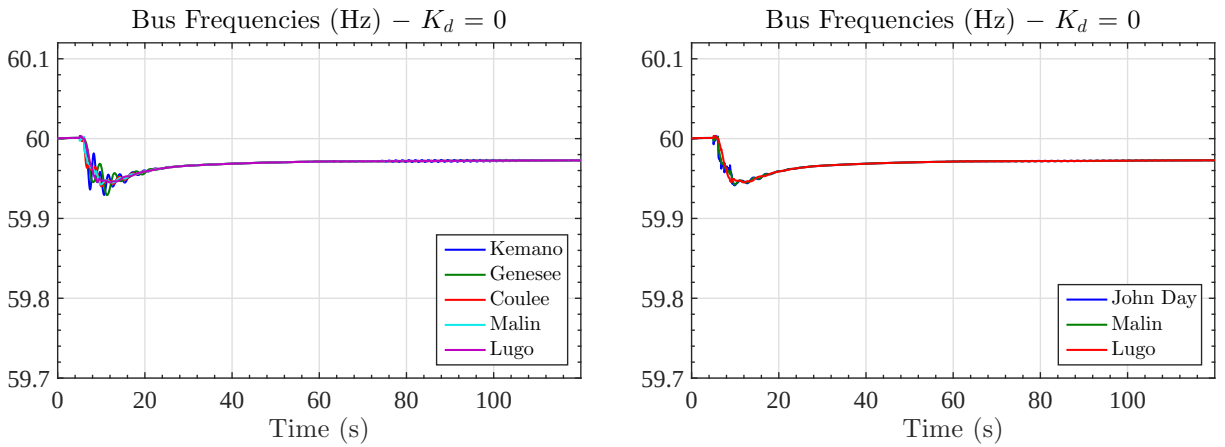


Figure 344. Bus frequencies. Event: 200 MW pulses followed by CGS outage.

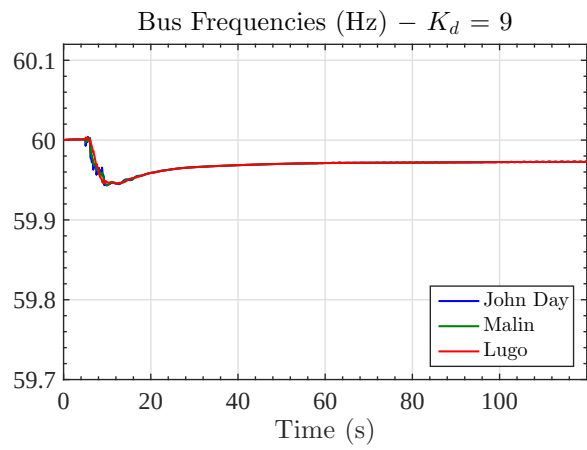
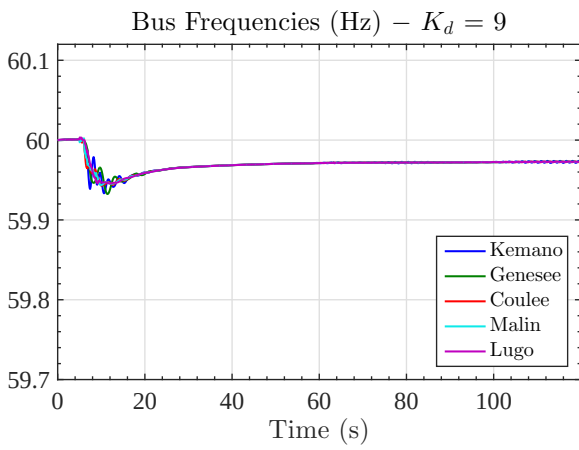


Figure 345. Bus frequencies. Event: 200 MW pulses followed by CGS outage.

5.1.7. Test System: Heavy Summer 2016. Event: MSF 20 MW followed by forced oscillation

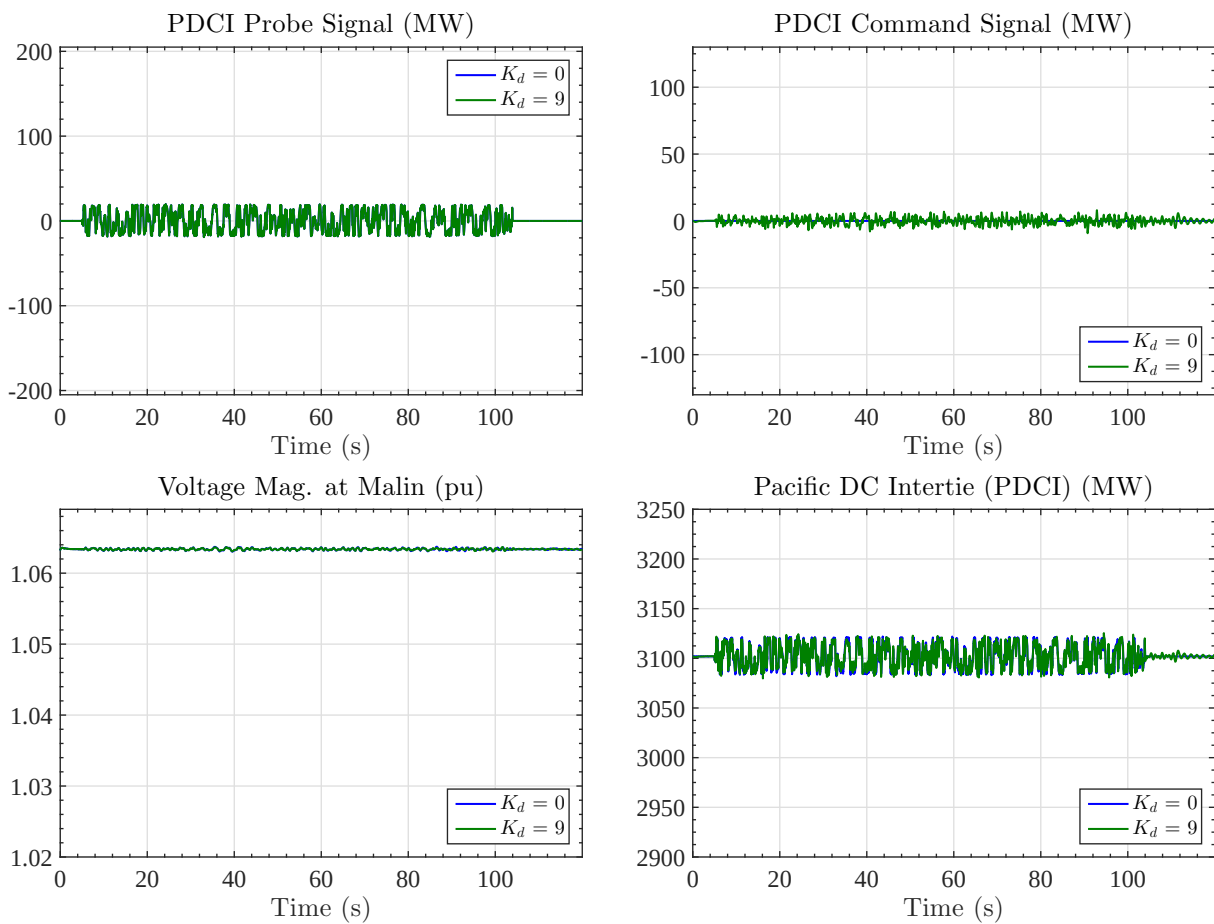


Figure 346. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 20 MW followed by forced oscillation.

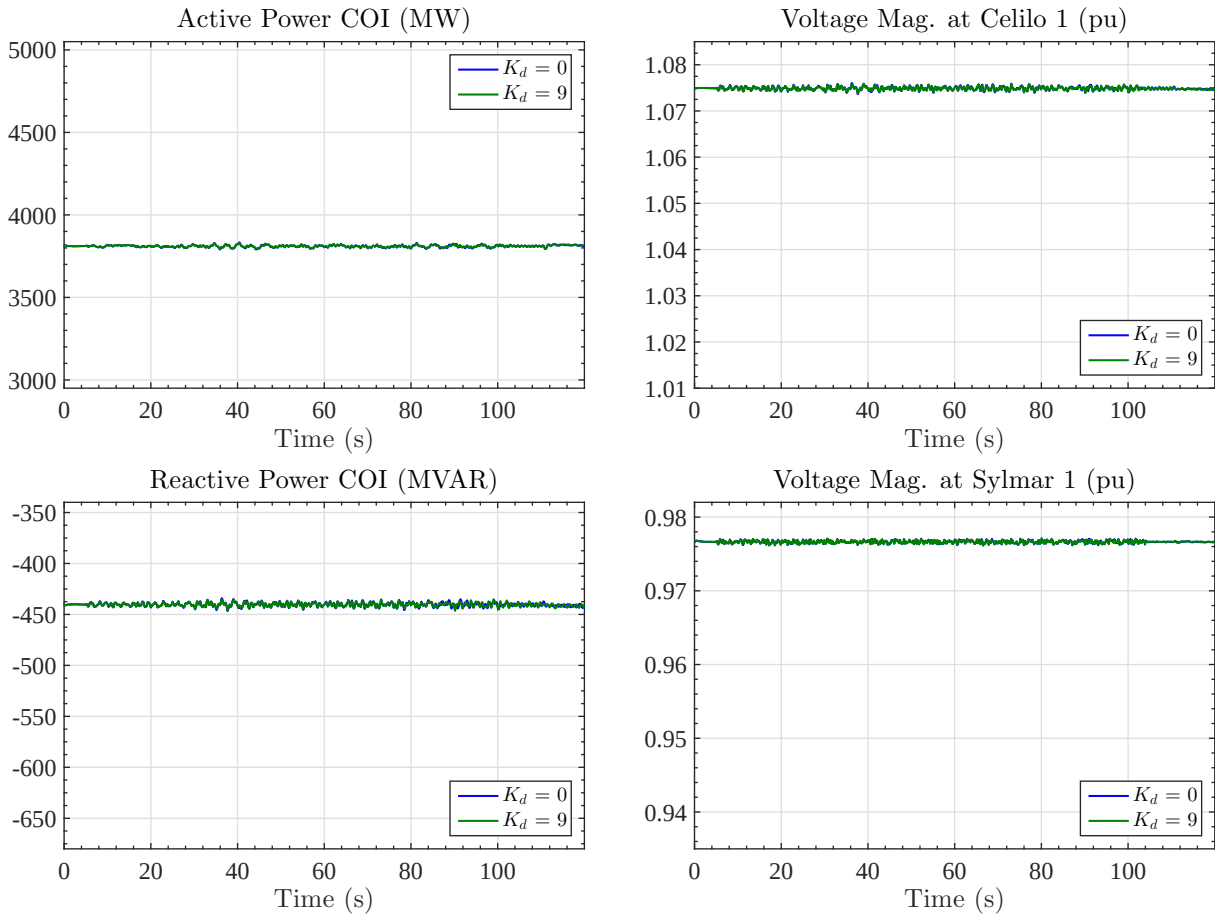


Figure 347. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 20 MW followed by forced oscillation.

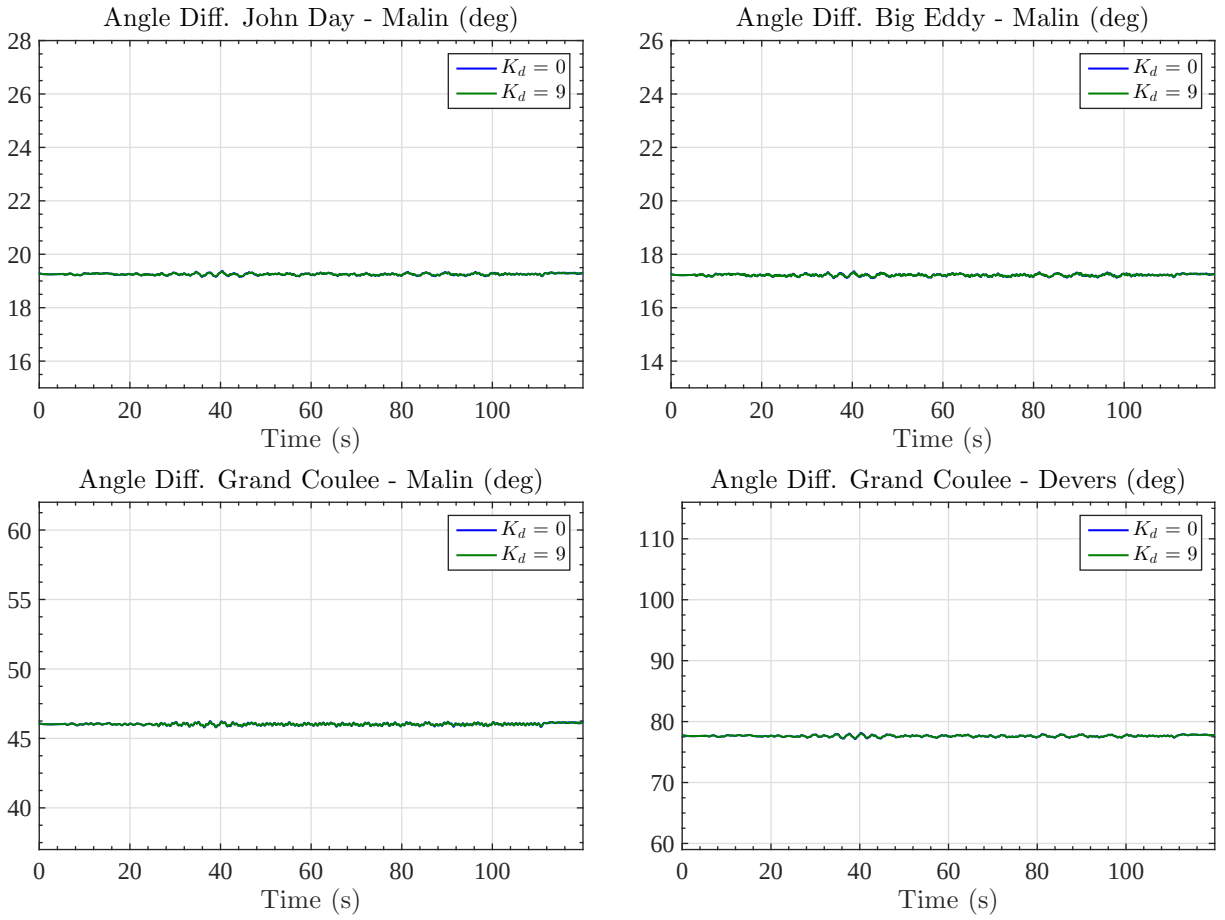


Figure 348. Angle differences. Event: MSF 20 MW followed by forced oscillation.

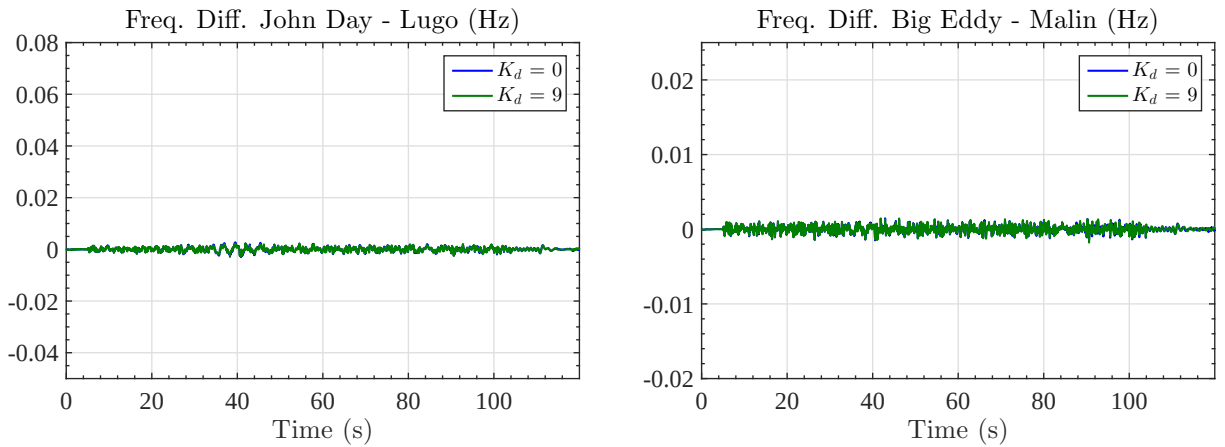


Figure 349. Frequency differences. Event: MSF 20 MW followed by forced oscillation.

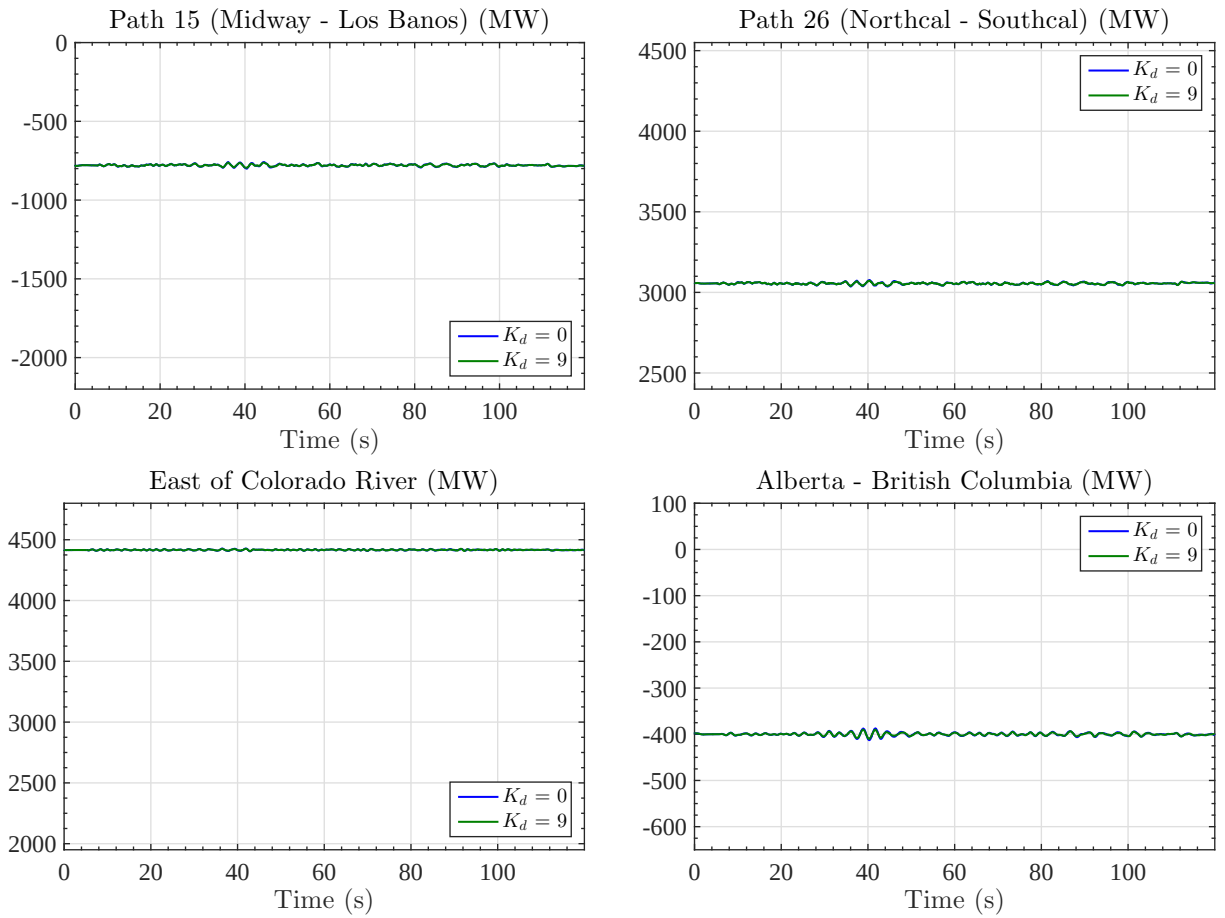


Figure 350. Active power flows. Event: MSF 20 MW followed by forced oscillation.

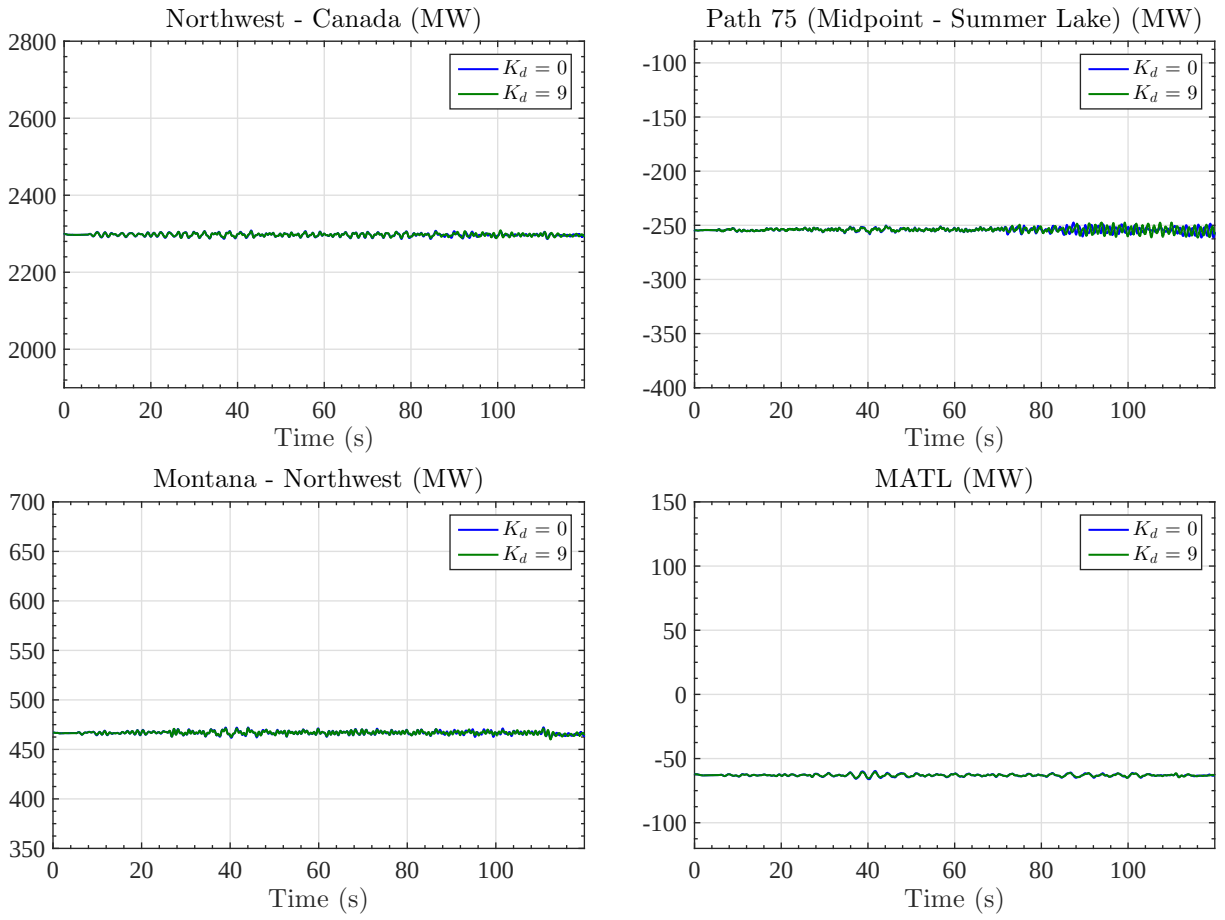


Figure 351. Active power flows. Event: MSF 20 MW followed by forced oscillation.

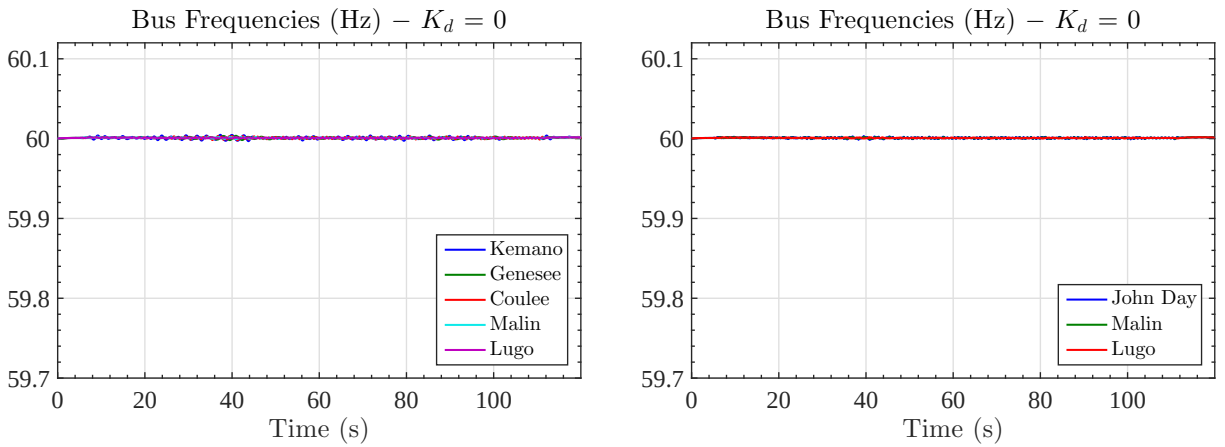


Figure 352. Bus frequencies. Event: MSF 20 MW followed by forced oscillation.

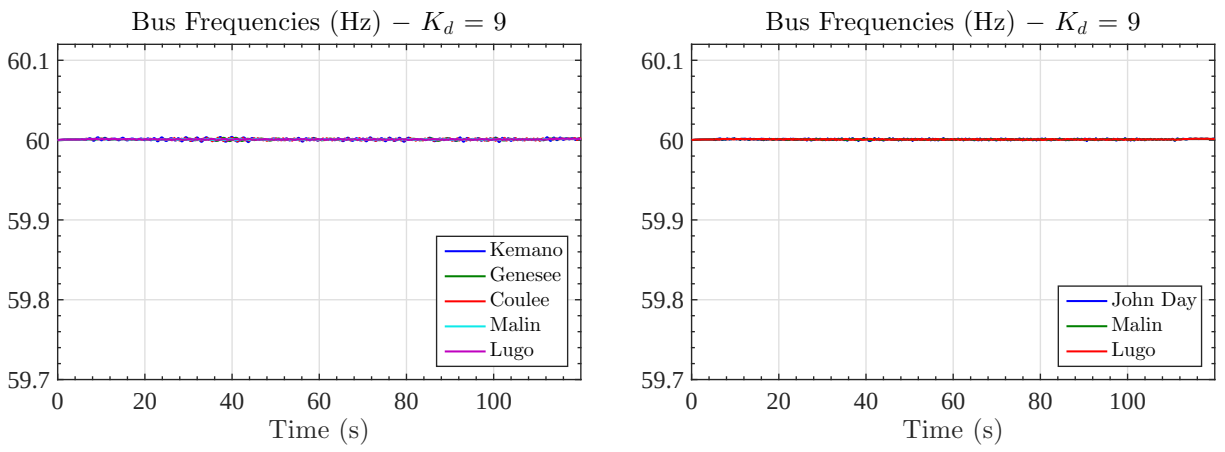


Figure 353. Bus frequencies. Event: MSF 20 MW followed by forced oscillation.

5.1.8. Test System: Heavy Summer 2016. Event: MSF 20 MW followed by double Palo Verde outage

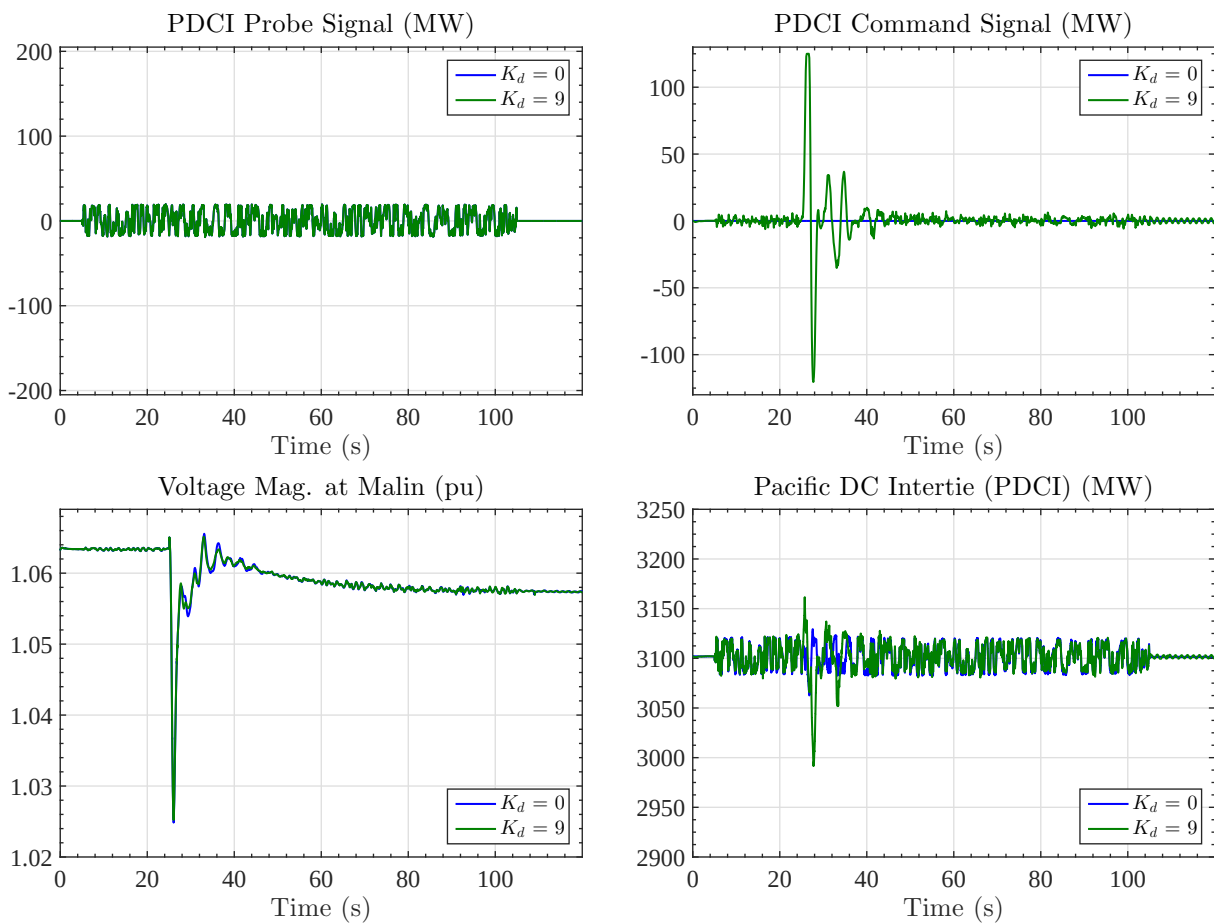


Figure 354. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 20 MW followed by double Palo Verde outage.

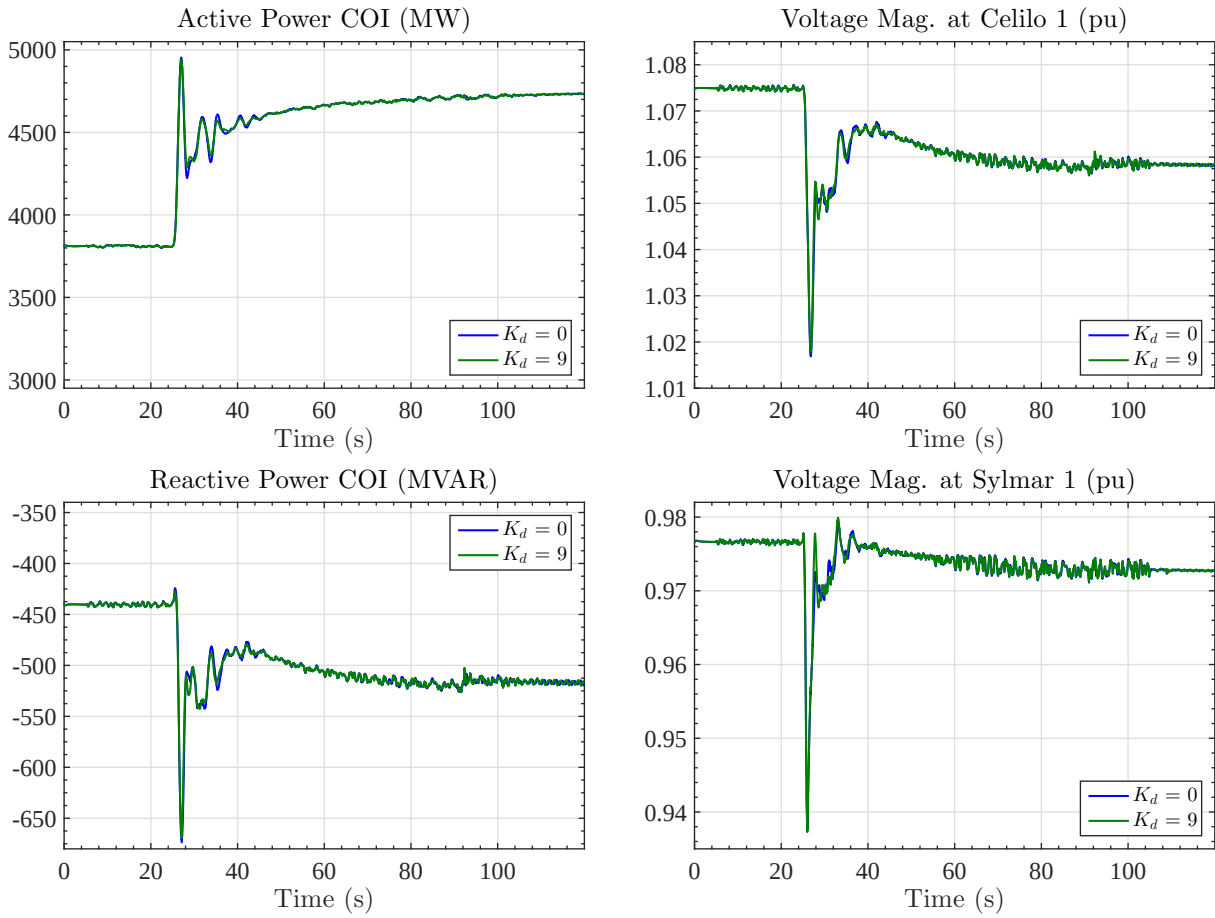


Figure 355. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 20 MW followed by double Palo Verde outage.

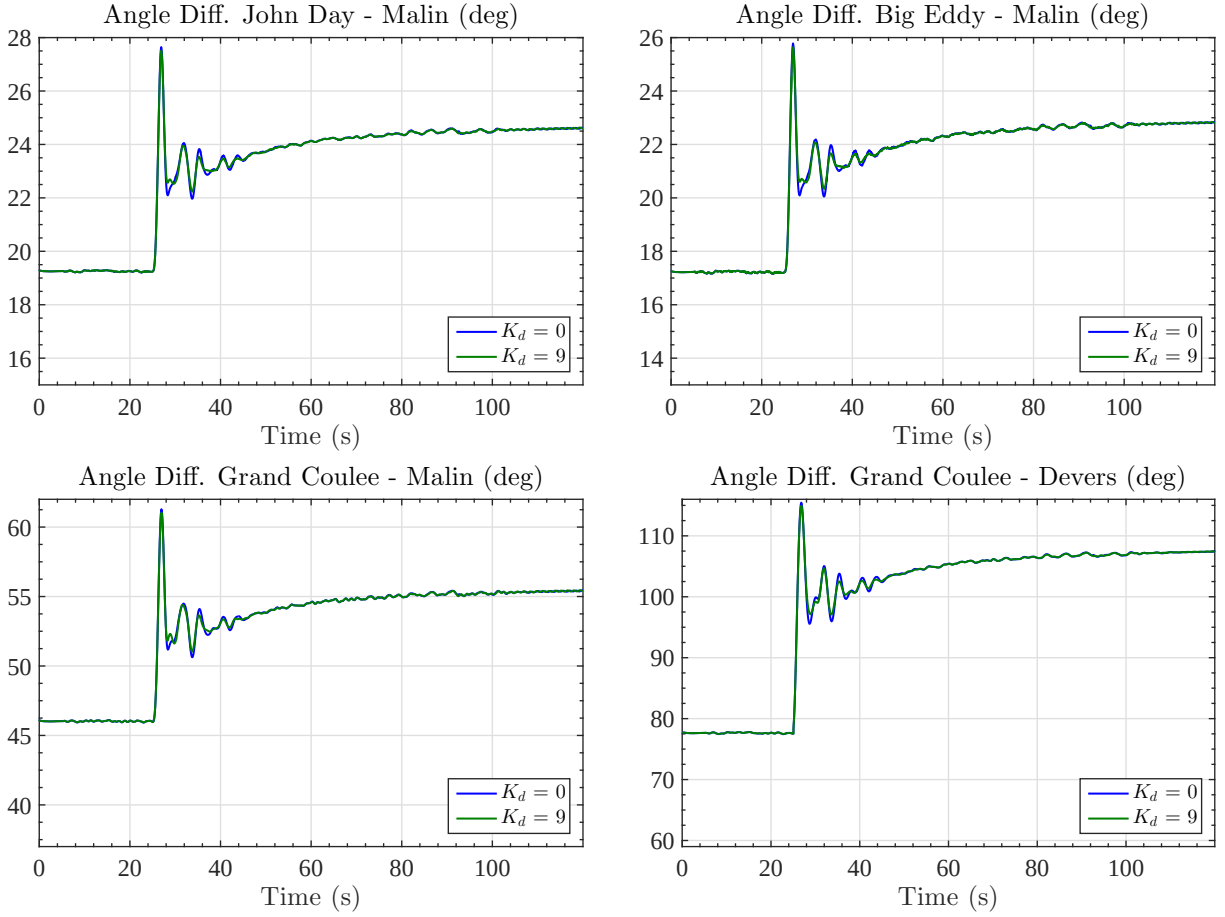


Figure 356. Angle differences. Event: MSF 20 MW followed by double Palo Verde outage.

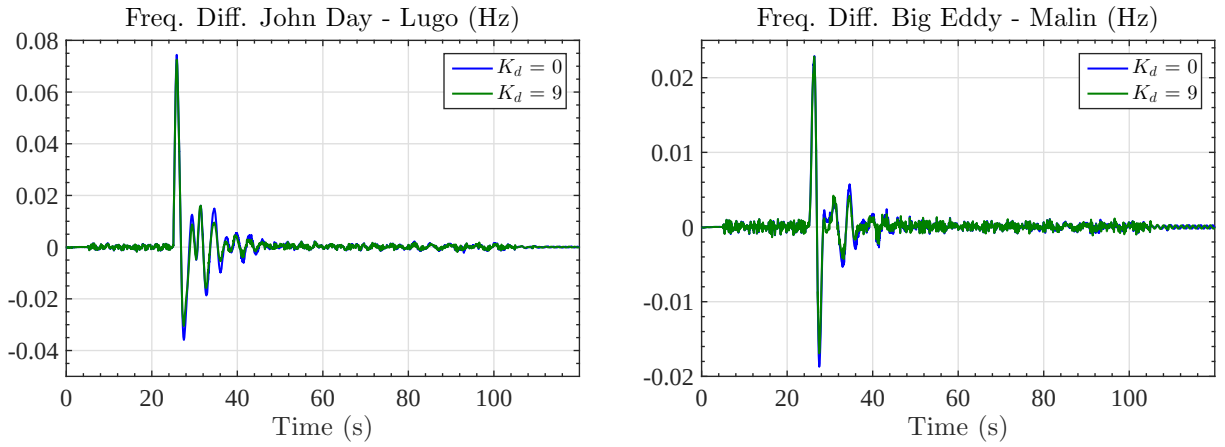


Figure 357. Frequency differences. Event: MSF 20 MW followed by double Palo Verde outage.

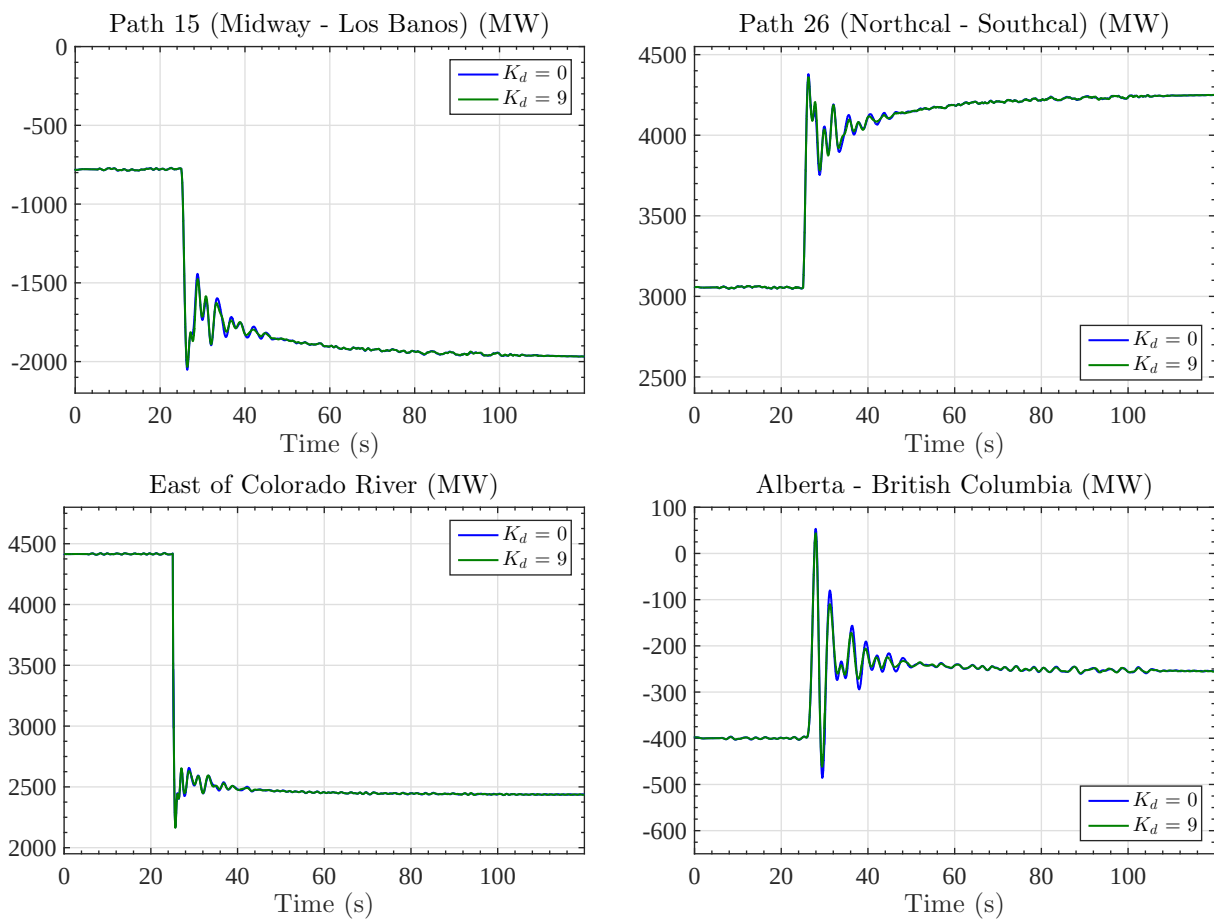


Figure 358. Active power flows. Event: MSF 20 MW followed by double Palo Verde outage.

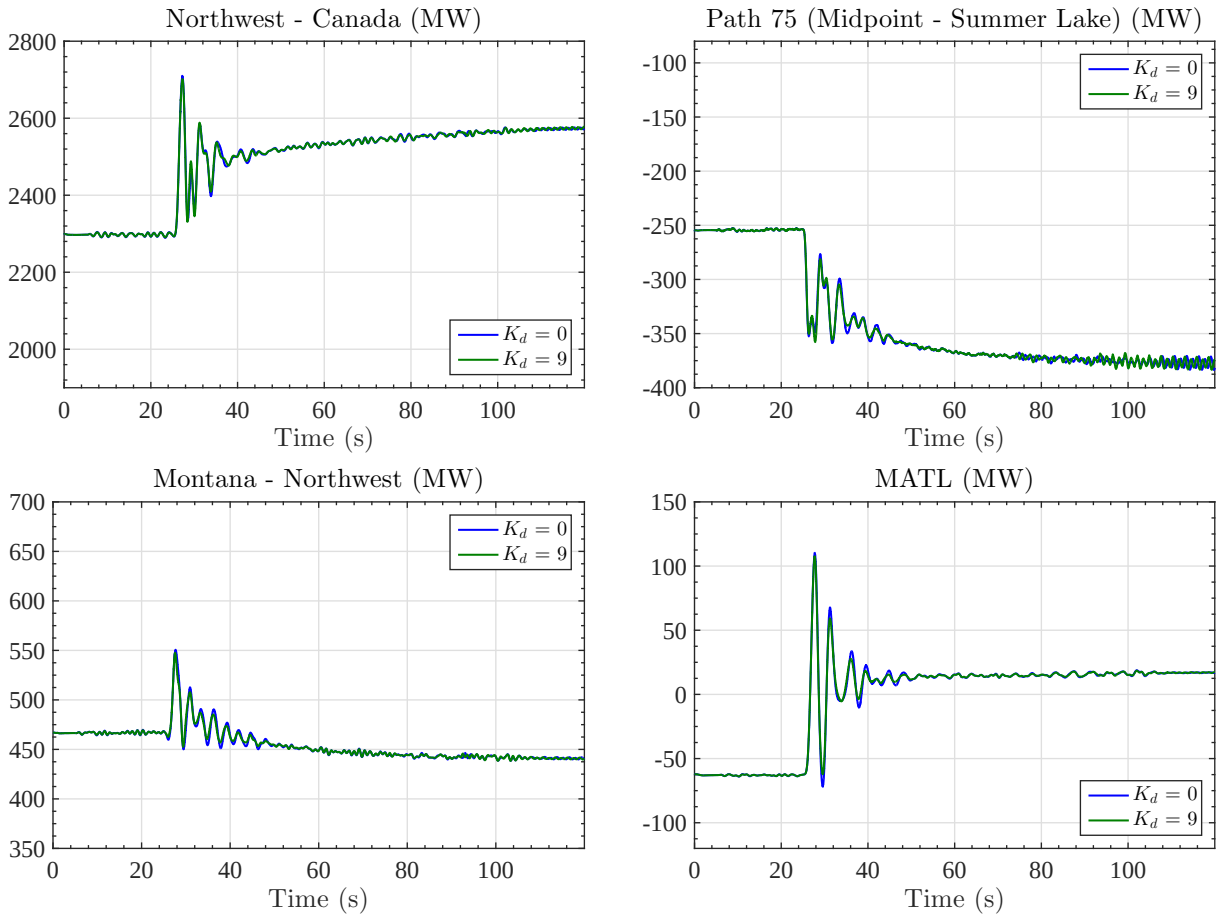


Figure 359. Active power flows. Event: MSF 20 MW followed by double Palo Verde outage.

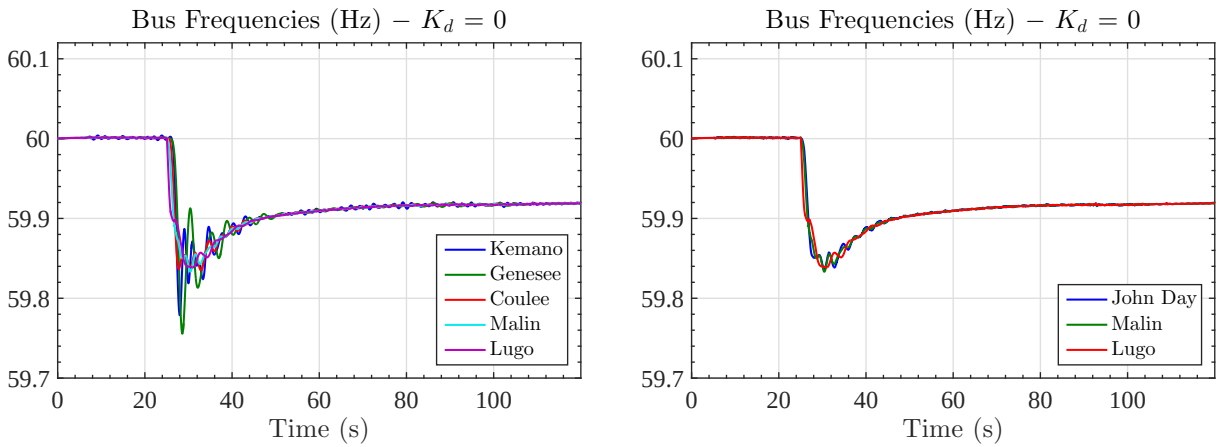


Figure 360. Bus frequencies. Event: MSF 20 MW followed by double Palo Verde outage.

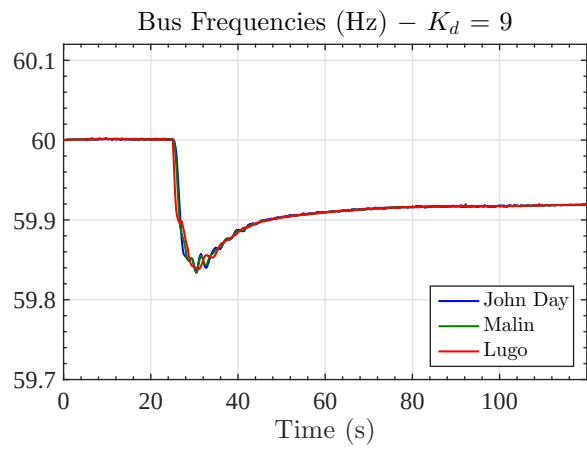
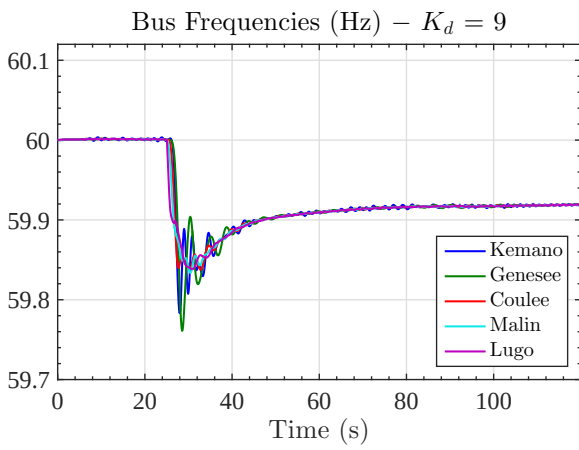


Figure 361. Bus frequencies. Event: MSF 20 MW followed by double Palo Verde outage.

5.1.9. Test System: Heavy Summer 2016. Event: MSF 20 MW followed by CGS outage

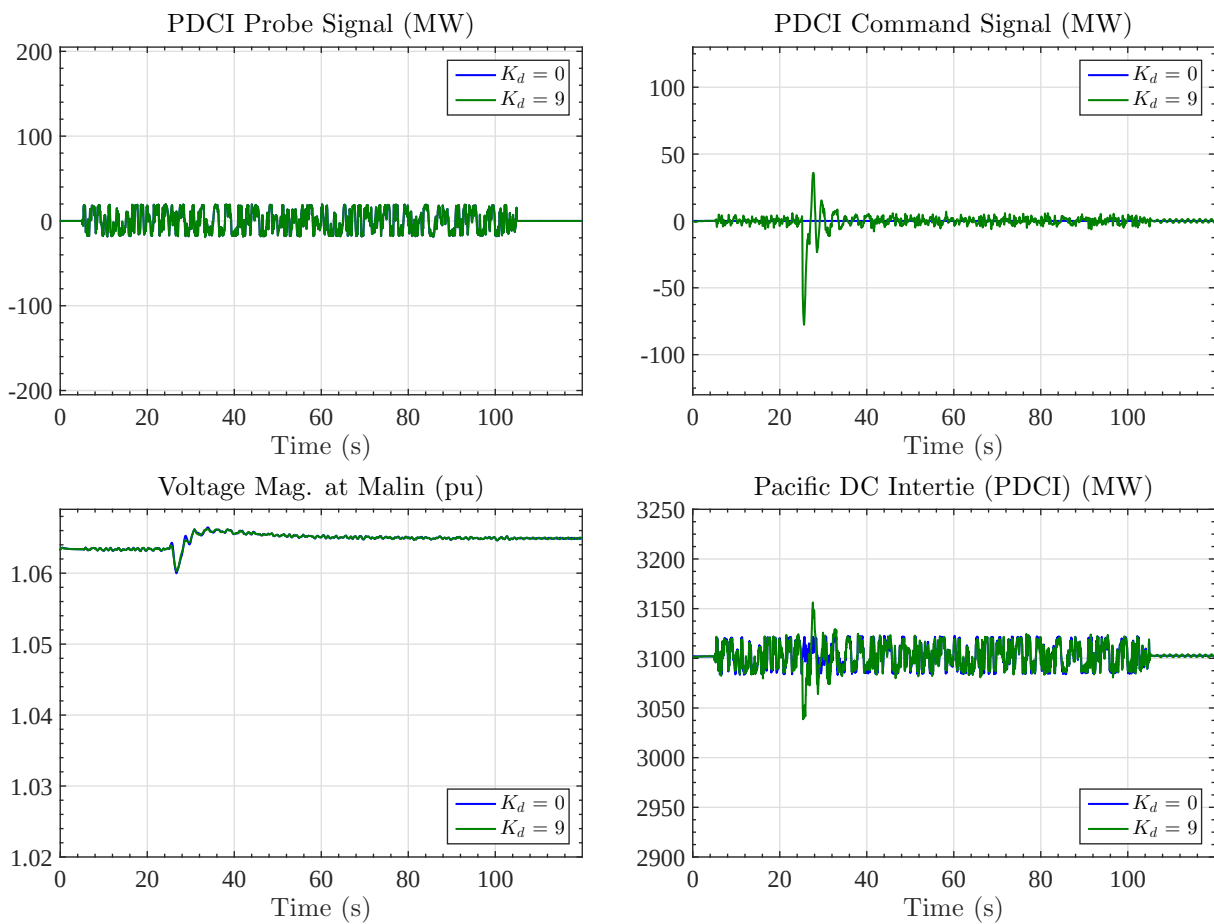


Figure 362. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: MSF 20 MW followed by CGS outage.

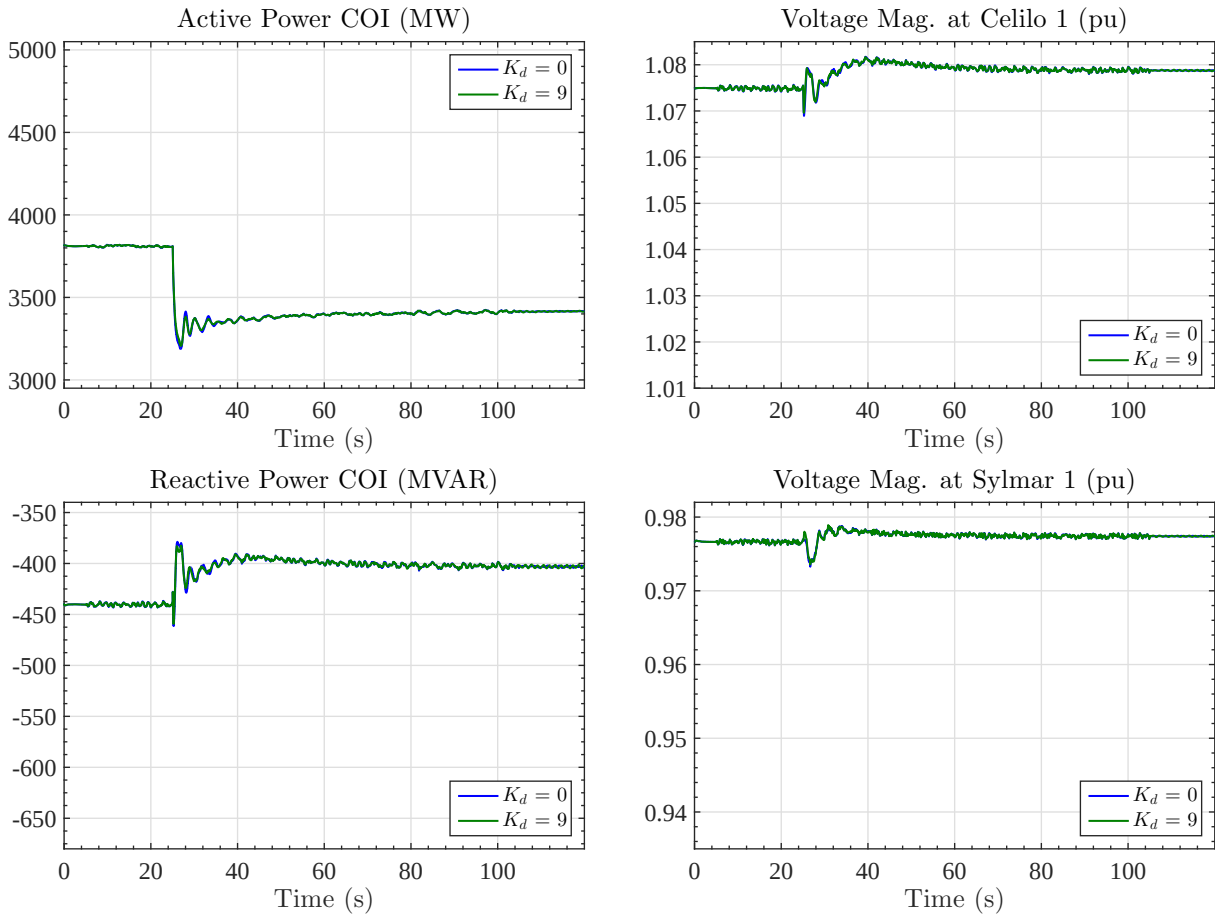


Figure 363. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: MSF 20 MW followed by CGS outage.

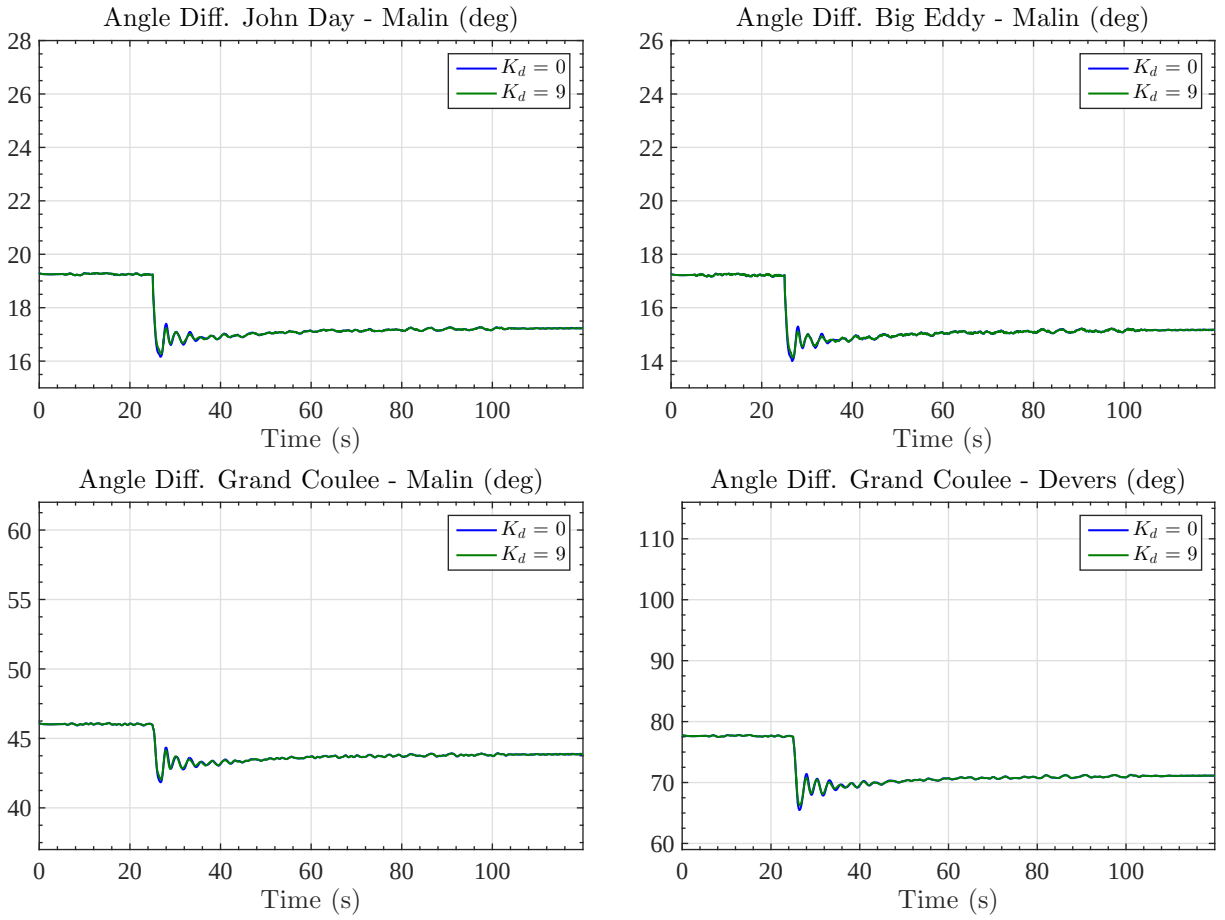


Figure 364. Angle differences. Event: MSF 20 MW followed by CGS outage.

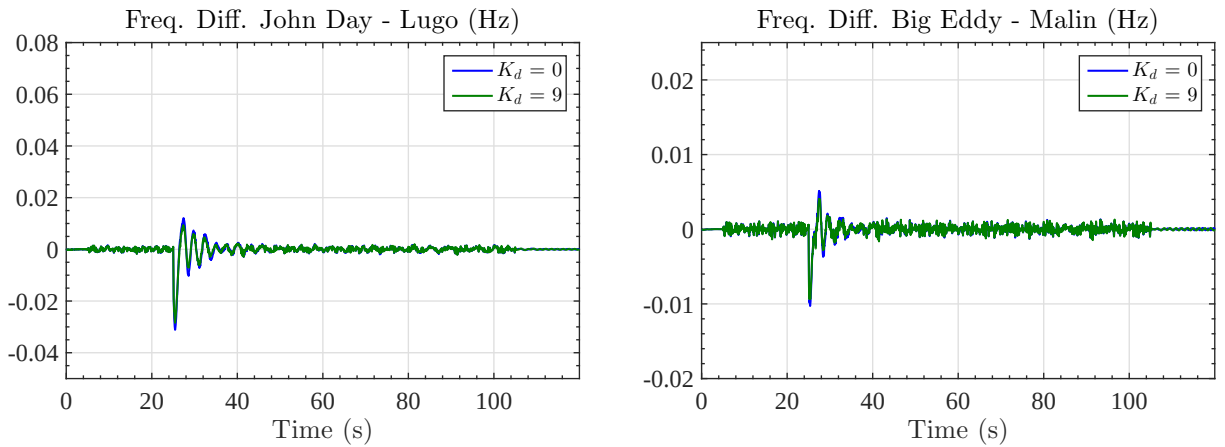


Figure 365. Frequency differences. Event: MSF 20 MW followed by CGS outage.

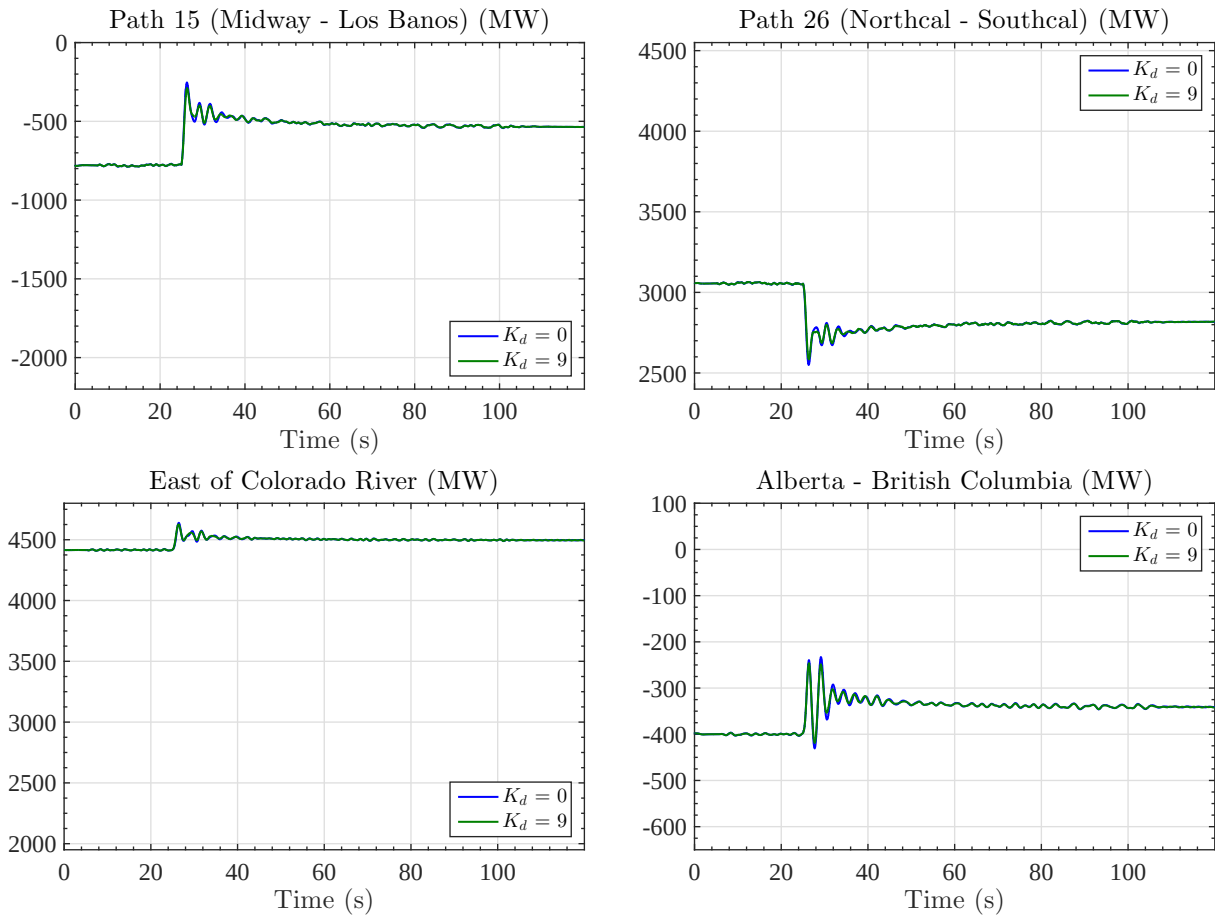


Figure 366. Active power flows. Event: MSF 20 MW followed by CGS outage.

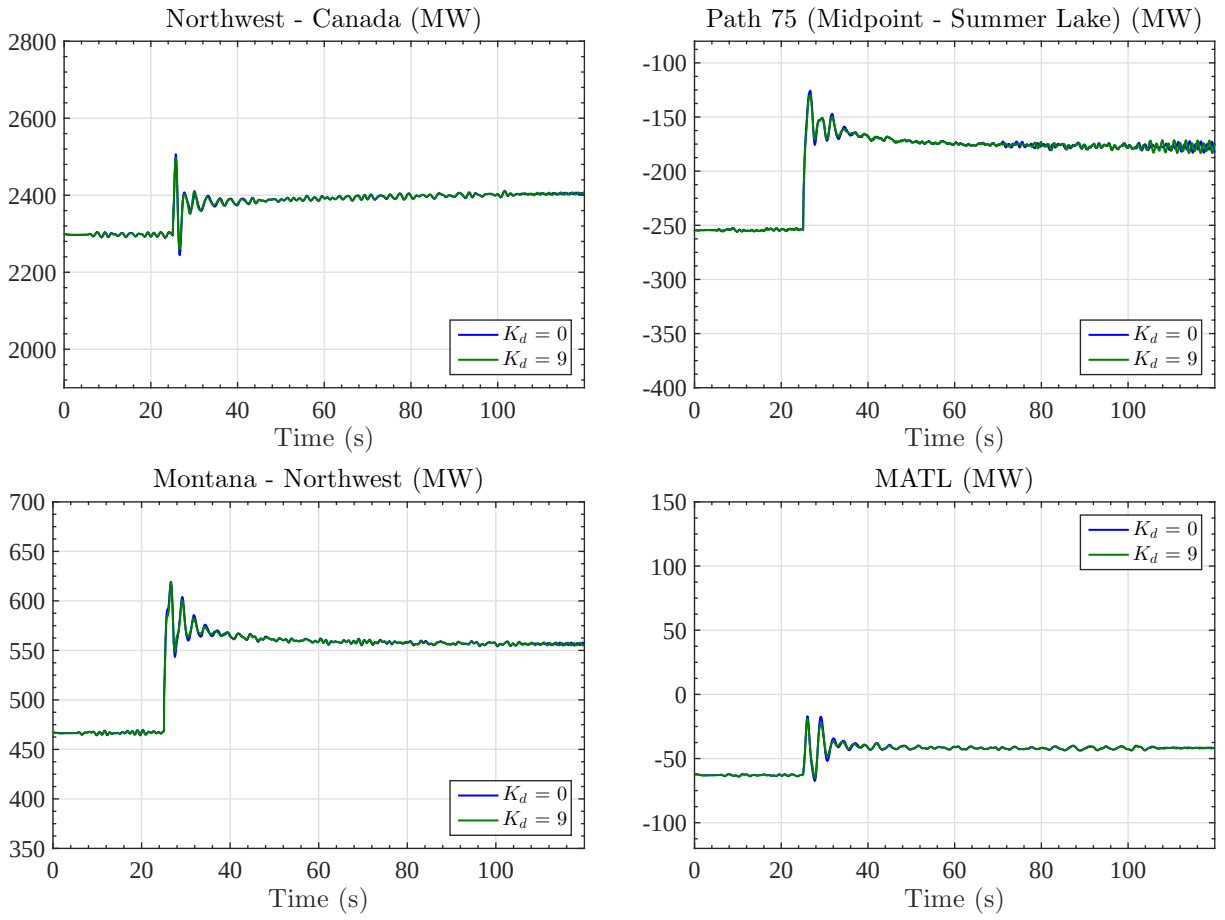


Figure 367. Active power flows. Event: MSF 20 MW followed by CGS outage.

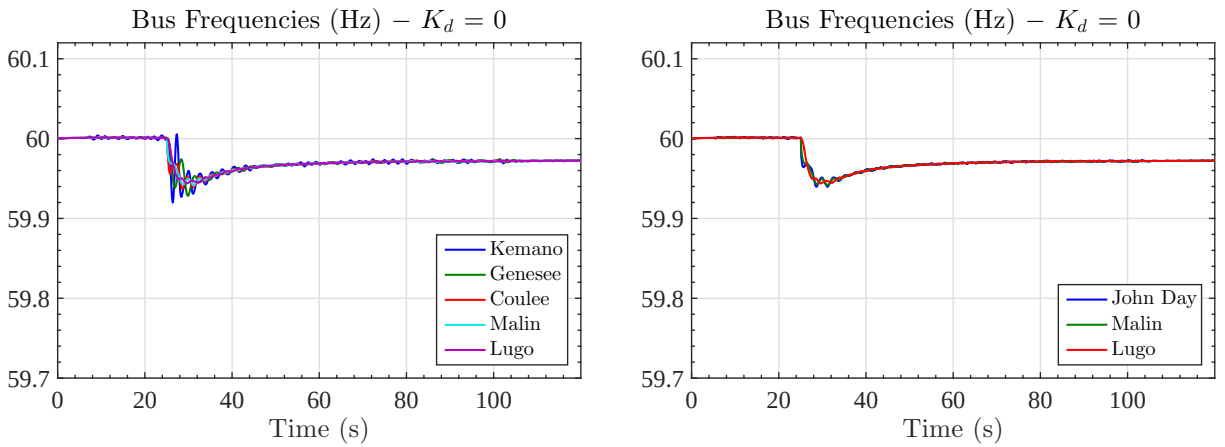


Figure 368. Bus frequencies. Event: MSF 20 MW followed by CGS outage.

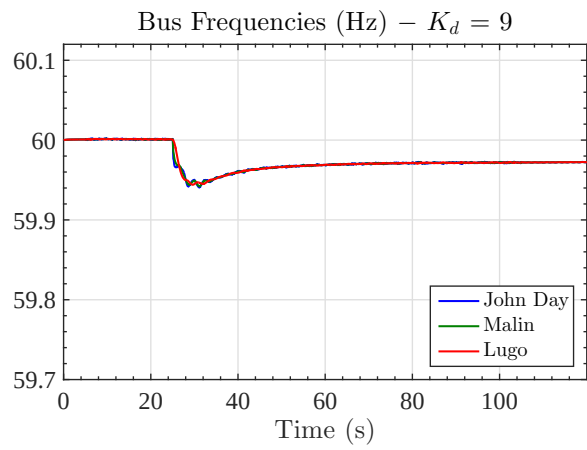
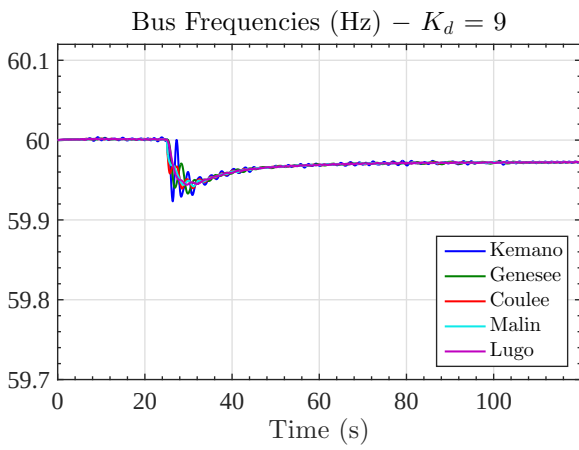


Figure 369. Bus frequencies. Event: MSF 20 MW followed by CGS outage.

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