

# **SANDIA REPORT**

SAND2017-XXXX

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Printed June 2017

## **PDCI Wide-Area Damping Control: PSLF Simulations of the 2017 Test Plan – Heavy Summer Case**

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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 spring/summer 2017. 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 and the 2014 dual export base case. Because of the large volume of plots, the results were divided into three reports corresponding to the three base cases. This report contains results from the 2016 heavy summer base case.

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

## ACKNOWLEDGMENTS

We gratefully acknowledge the support of the BPA Technology Innovation Office (Project No. 289, Project Manager: Dr. Jisun Kim, Technical Point of Contact: Dr. Dmitry Kosterev), the DOE Transmission Reliability Program (Program Manager: Mr. Phil Overholt), and the DOE Energy Storage Program (Program Manager: Dr. Imre Gyuk).

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TABLES

Table 1. Operating conditions of WECC base cases studied . . . . . 16



## NOMENCLATURE

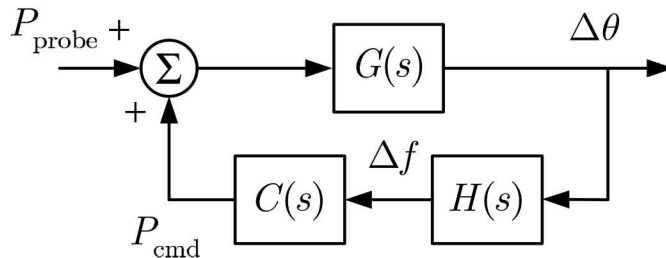
|      |                                                                                           |
|------|-------------------------------------------------------------------------------------------|
| AGC  | Automatic Generation Control                                                              |
| 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  $\Delta f$  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 ( $P_{\text{cmd}}$ ) noted as *PDCI Command Signal* and using a probing signal ( $P_{\text{probe}}$ ) 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  $P_{\text{probe}}$  can come from the controller during open loop testing. The scenarios simulated in this report, 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 team plans to conduct closed-loop tests on the PDCI in Spring and Summer 2017. A test plan has been approved by BPA with the first phase of tests scheduled to begin in May 2017. The 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) PSLF base cases. Table 1 summarizes the primary operating characteristics of the three base cases used in the study. The primary operating characteristics include the real power flow on the PDCI as well as the real and reactive power flows on the California-Oregon Intertie (COI). The three WECC base cases used for this study are the Heavy Summer 2016 base case, the Light Summer 2016 base case, and the Dual Export 2014 base case. A custom model of the controller was developed using PSLF to run the simulations. The results of the 2016 heavy summer base case simulations are presented here. Simulation results of the 2016 test plans were described in [1]. Conference papers written by the project team based on 2016 test plans and results include [2, 3, 4, 5, 6].

The objectives of the 2017 tests plans are: (a) Assess the controller’s ability to add damping to the North-South B mode, (b) Evaluate the controller’s effects on all other WECC modes, (c) Exercise the controller’s supervisory functions, and (d) Investigate the controller’s impact on the PDCI system itself.

**Table 1. Operating conditions of WECC base cases studied**

| Quantity                  | Heavy Summer 2016 | Light Summer 2016 | Dual Export 2014 |
|---------------------------|-------------------|-------------------|------------------|
| PDCI Active Power (MW)    | 3100              | 1950              | XXXX             |
| COI Active Power (MW)     | 3810              | 2650              | XXXX             |
| COI Reactive Power (MVar) | -440              | -437              | XXXX             |

Two types of tests are proposed in the 2017 test plans. The first type of test is an active short-term test. These tests are individual sequences typically lasting less than one hour and closely monitored by the project team. Examples include Chief Joseph brake pulses, probing signals, and forced oscillations applied to the system with the controller configured in both open and closed-loop operation. The second type of test is an active long-term test. In this type of test, the controller is configured for closed-loop operation only. The purpose of this test is to evaluate control performance under continuous operation of approximately 30 days. Controller limits are set to a safe level to avoid any adverse results. This is necessary because for much of the 30 day test, the project team will not be physically present in front of the controller hardware.

For each of the three base cases used in this study, four test sequences are simulated. The first test sequence is negative gain testing. The purpose of this test is to assess controller performance in a worst case gain assignment that is extremely unlikely to ever happen in practice, but nonetheless needs to be tested as a measure of safety margin. The second test sequence is to evaluate controller limits by applying large gain values. The third test sequence is to conduct a comparison test of Chief Joseph brake insertions with two different pulse durations: 0.5 sec and 1.0 sec. The fourth test sequence is to add forced oscillations of 30 MW at four different frequencies: 0.4 Hz, 1 Hz, 3 Hz, and 5 Hz.

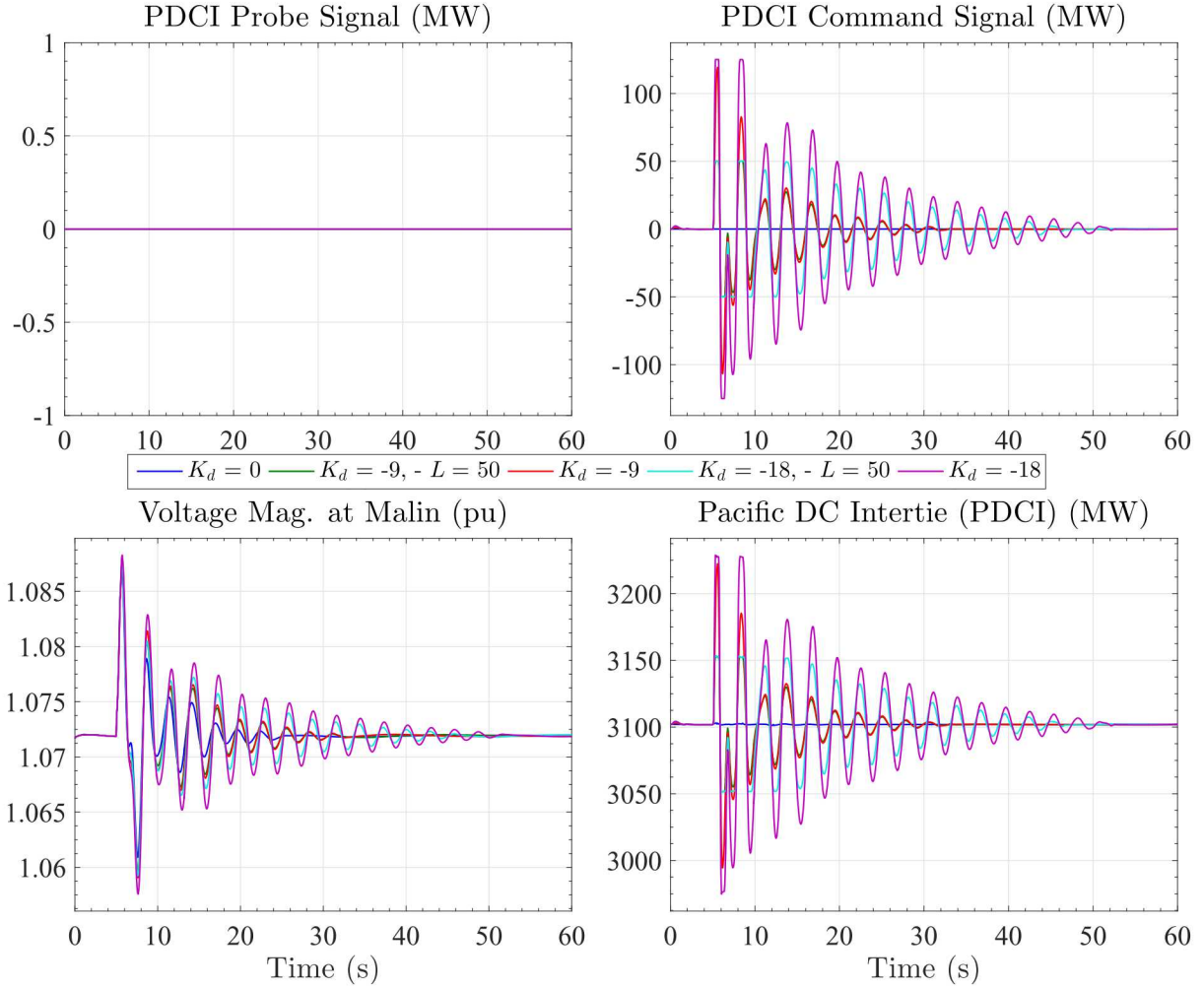
To determine controller performance during very high stress grid conditions, rare events are added to the negative gain and controller limits test sequences. These rare events include a double Palo Verde trip, a BC-US separation, a BC-Alberta separation, and Chief Joseph brake pulses added to each of these events.

Due to the large volume of plots produced by this study, the full compilation of simulation results is divided into three different reports, one corresponding to each of the three different base cases used: 2016 Heavy Summer base case, 2016 Light Summer base case, and 2014 Dual Export base case. This report contains results from the 2016 heavy summer base case.

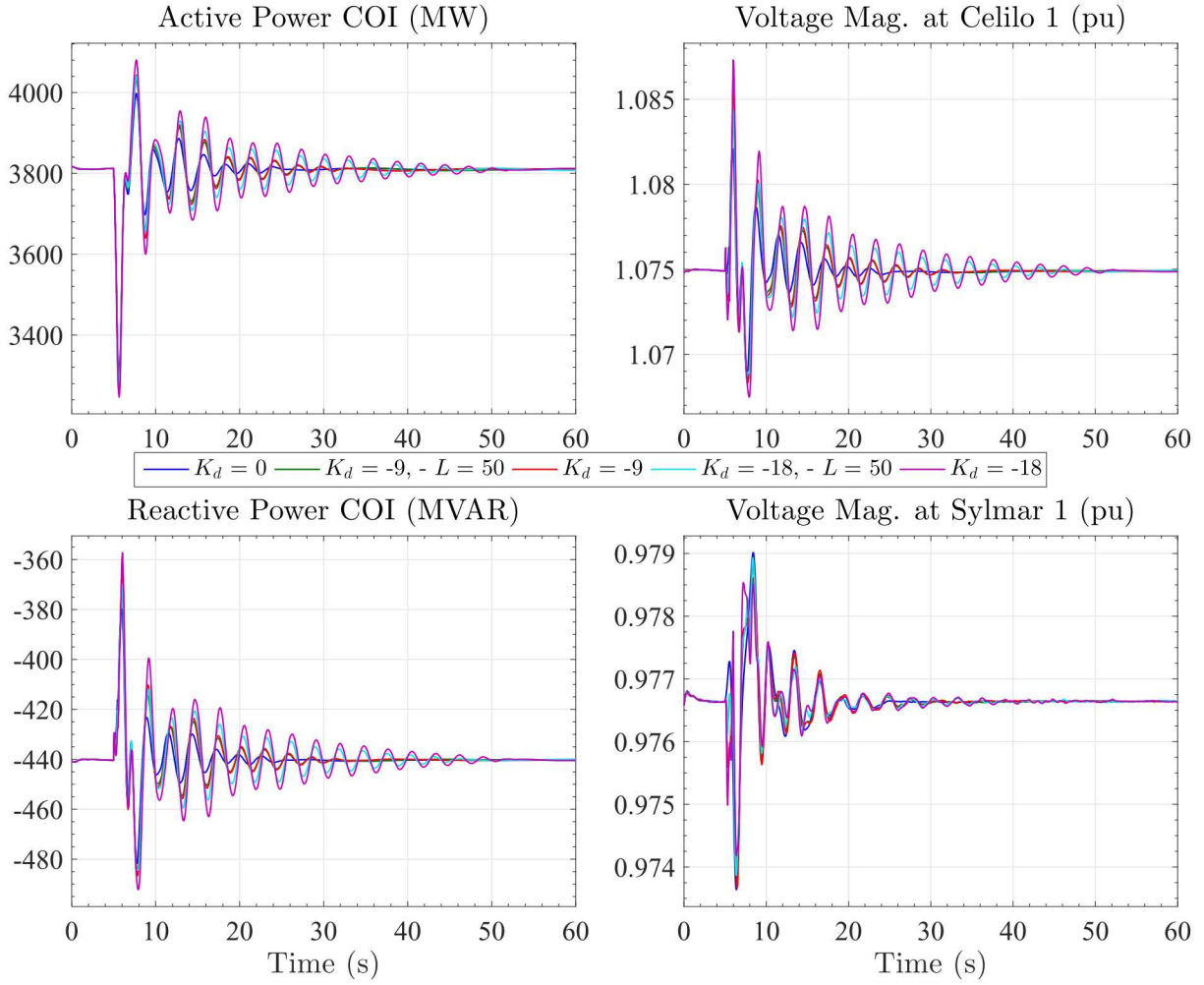


## 2. NEGATIVE GAIN TESTING

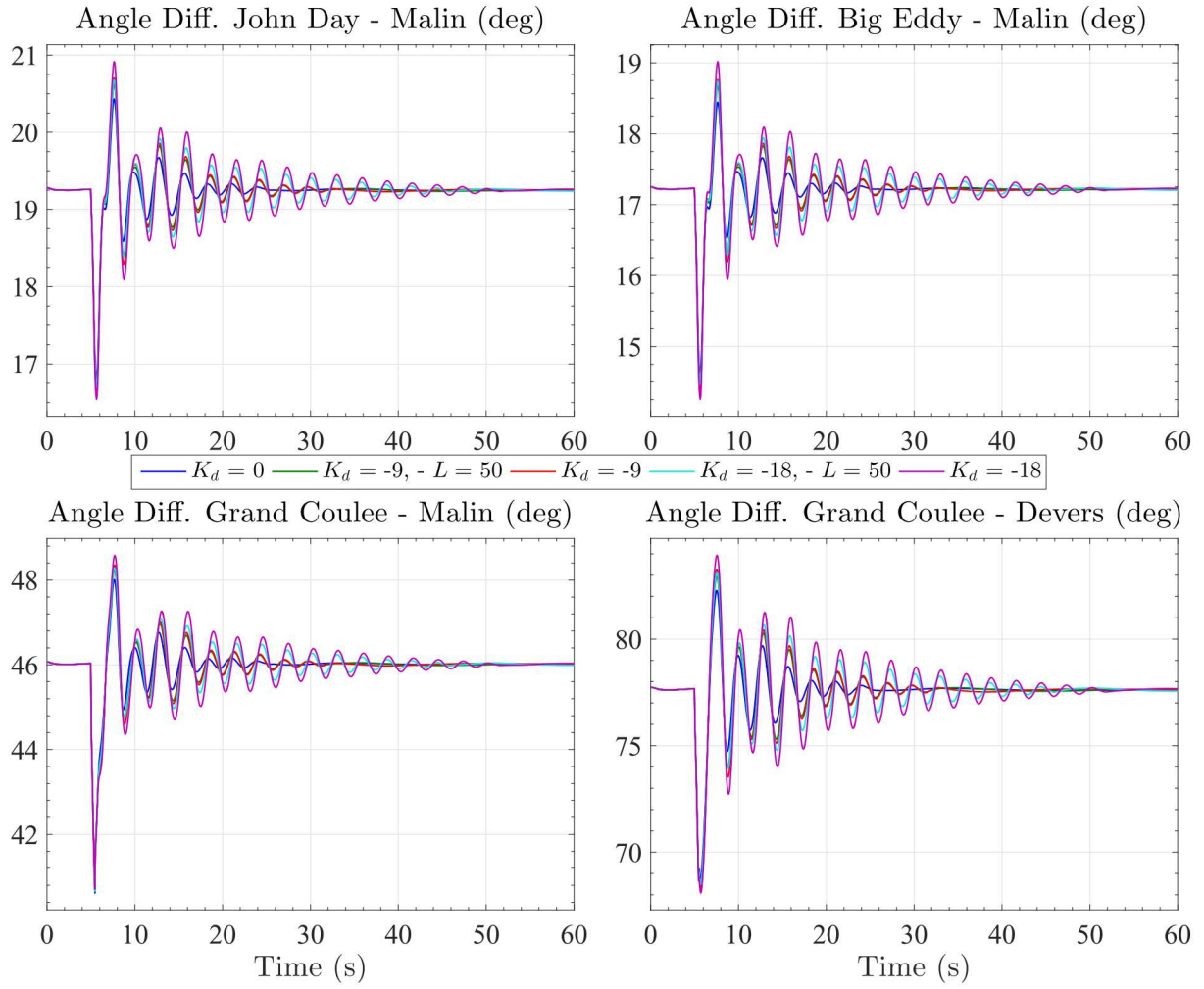
### 2.1. Test System: Heavy Summer 2016. Event: Chief Joe Brake



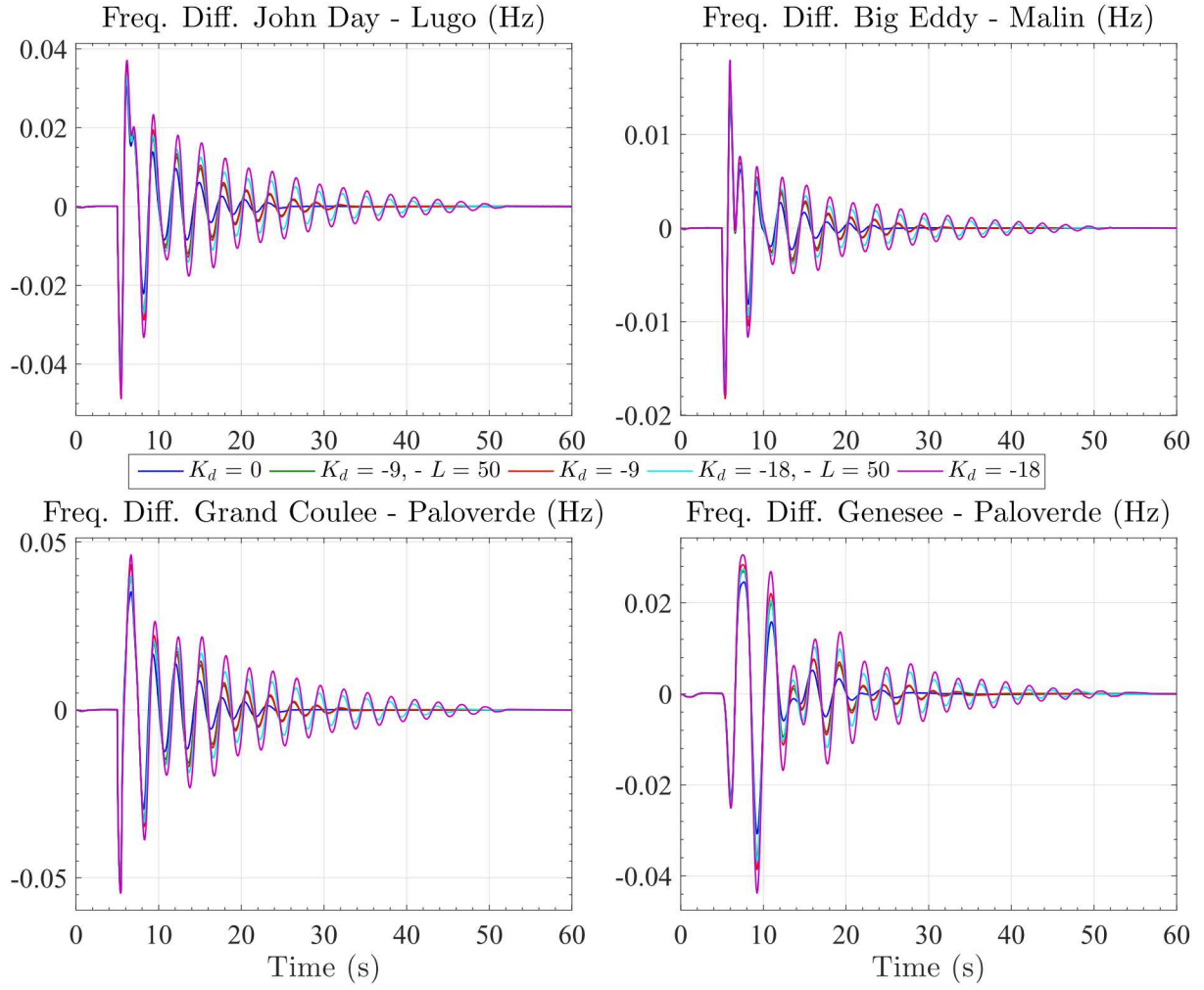
**Figure 2. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake**



**Figure 3. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake**

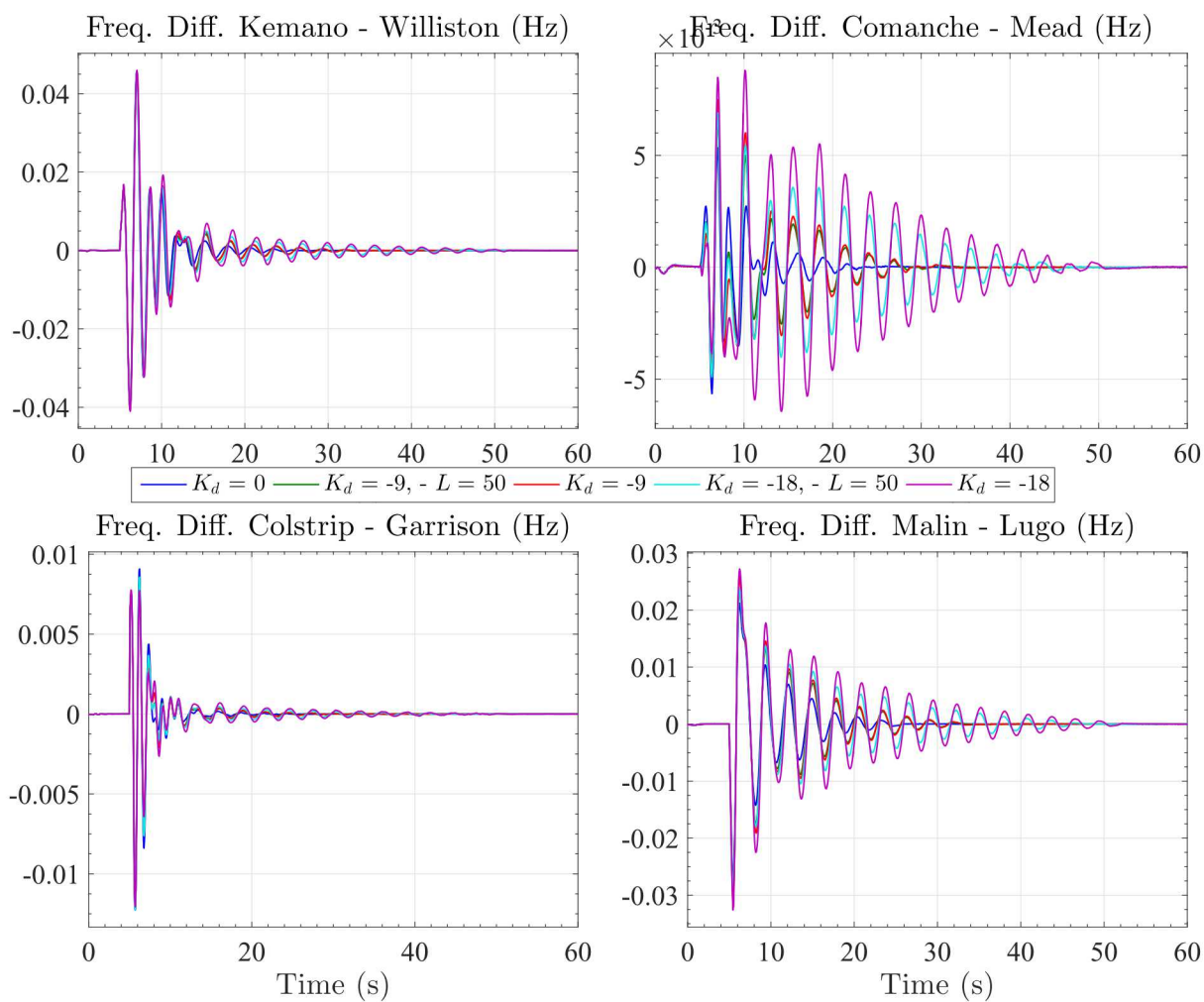


**Figure 4. Angle differences. Event: Chief Joe Brake**

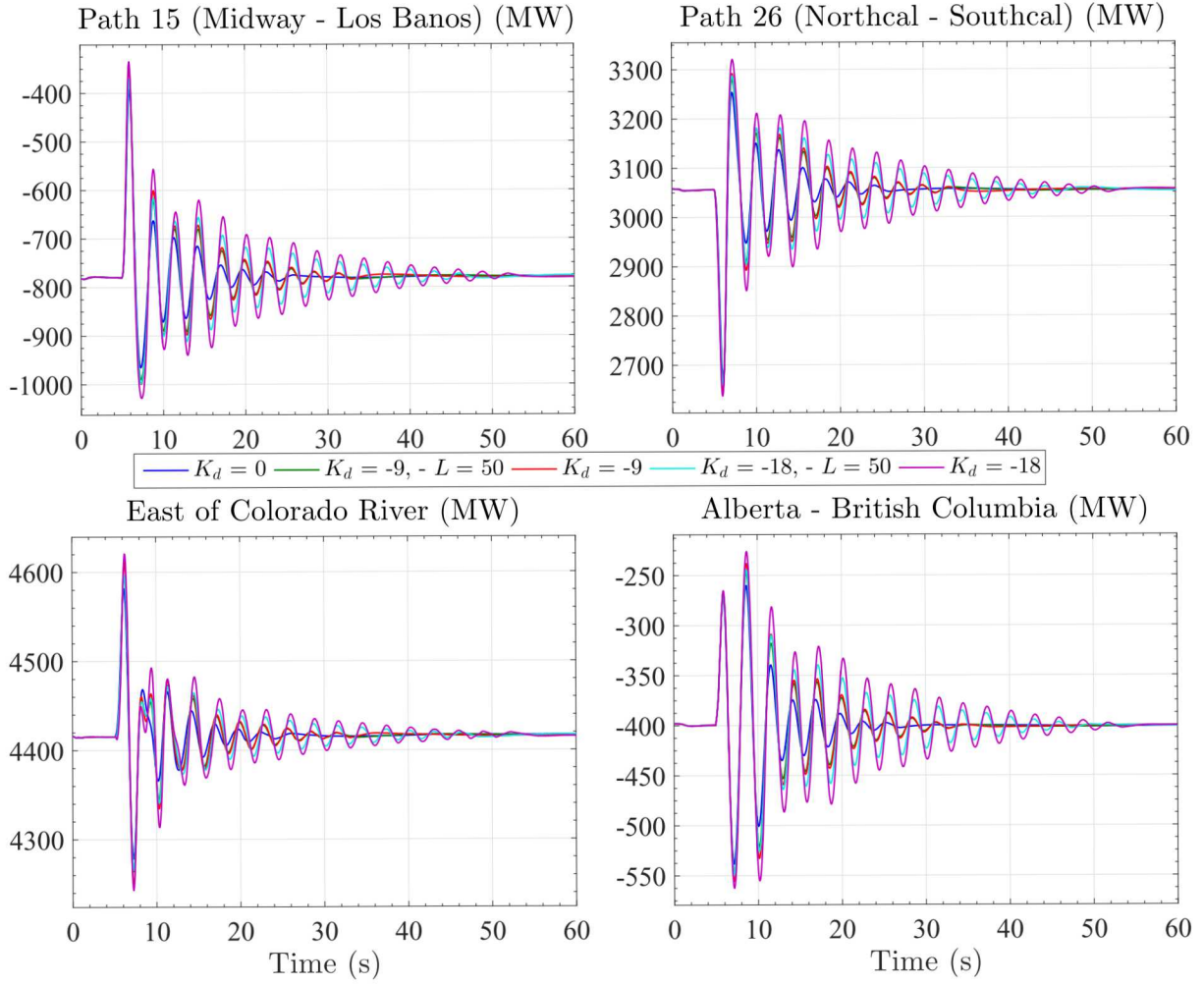


**Figure 5. Frequency differences. Event: Chief Joe Brake**

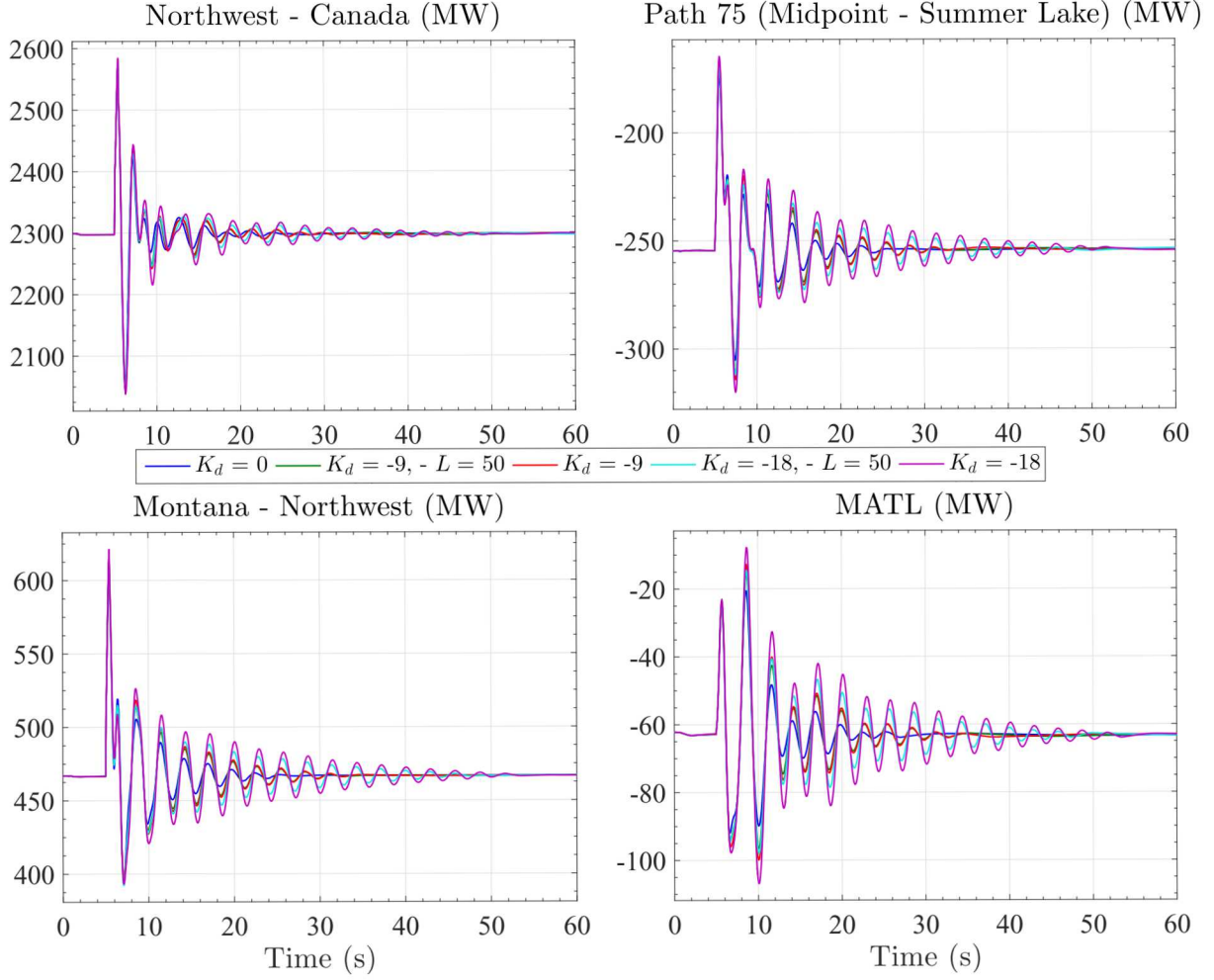




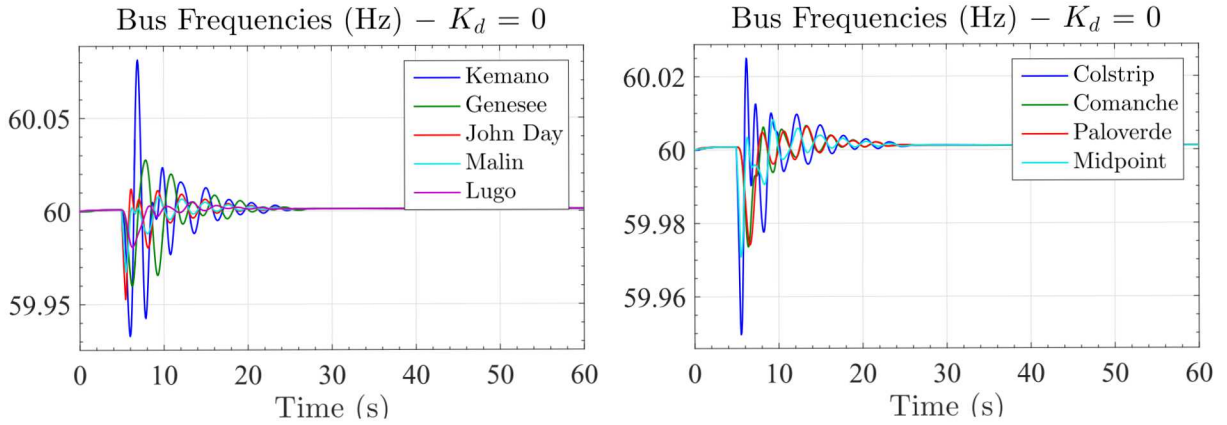
**Figure 6. Frequency differences. Event: Chief Joe Brake**



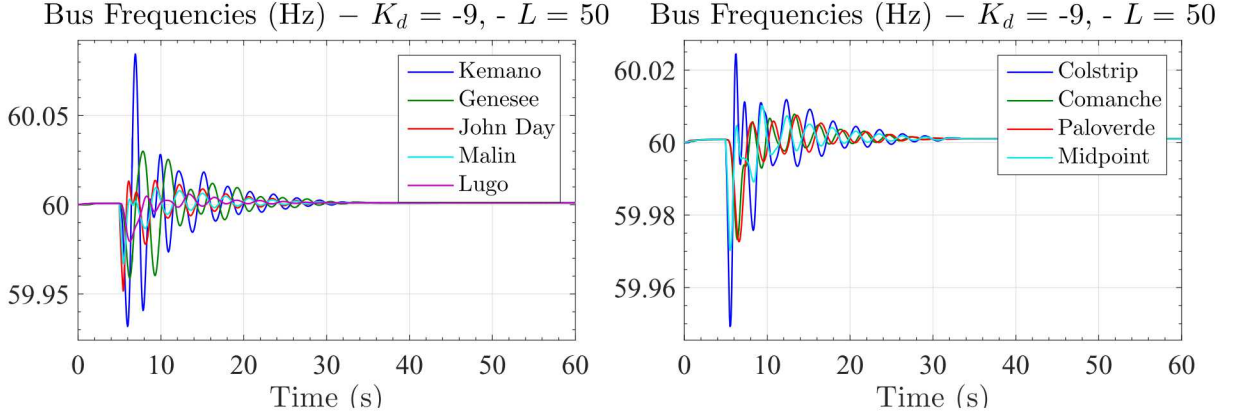
**Figure 7. Active power flows. Event: Chief Joe Brake**



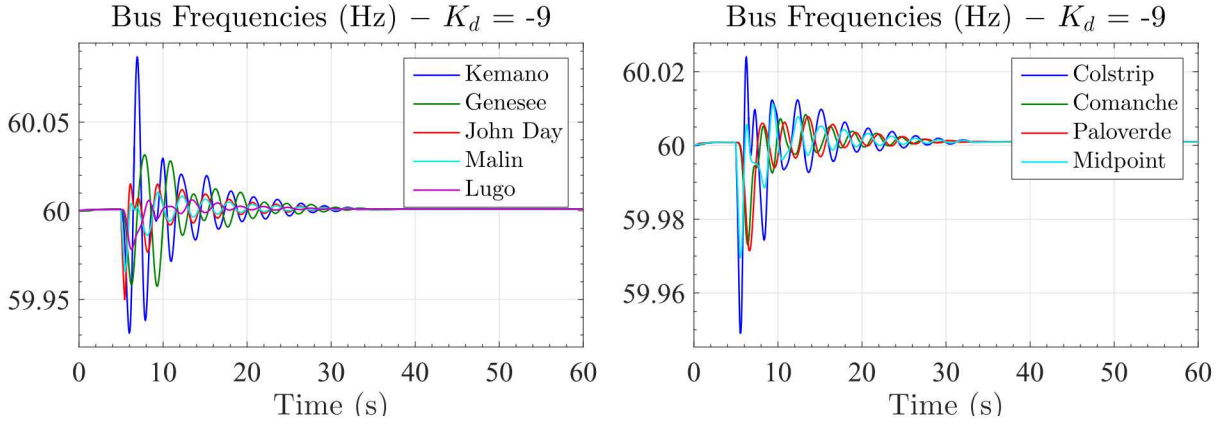
**Figure 8. Active power flows. Event: Chief Joe Brake**



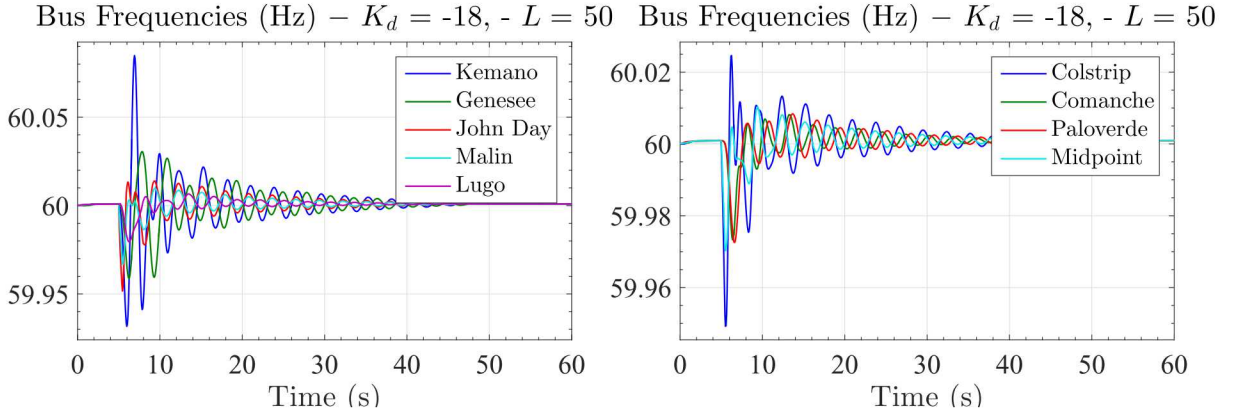
**Figure 9. Bus frequencies. Event: Chief Joe Brake**



**Figure 10. Bus frequencies. Event: Chief Joe Brake**

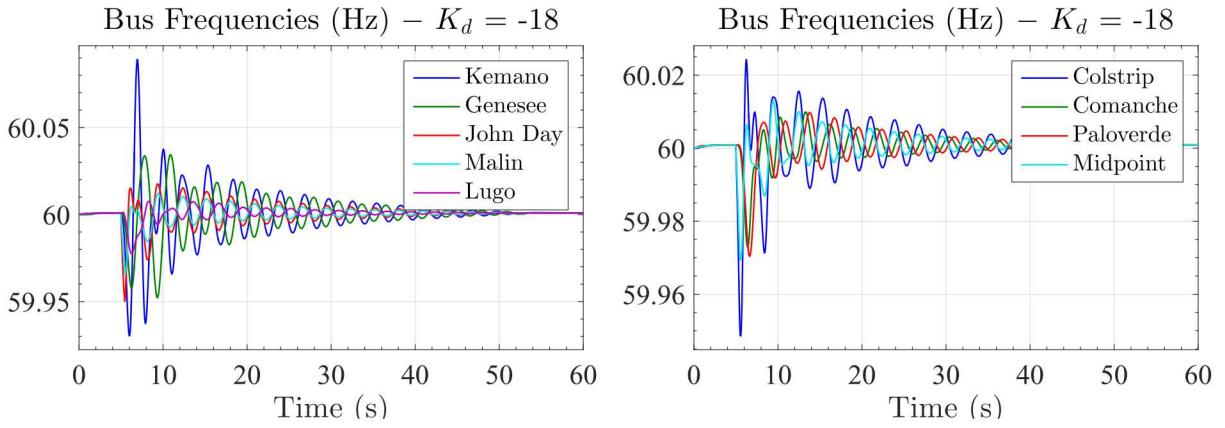


**Figure 11. Bus frequencies. Event: Chief Joe Brake**



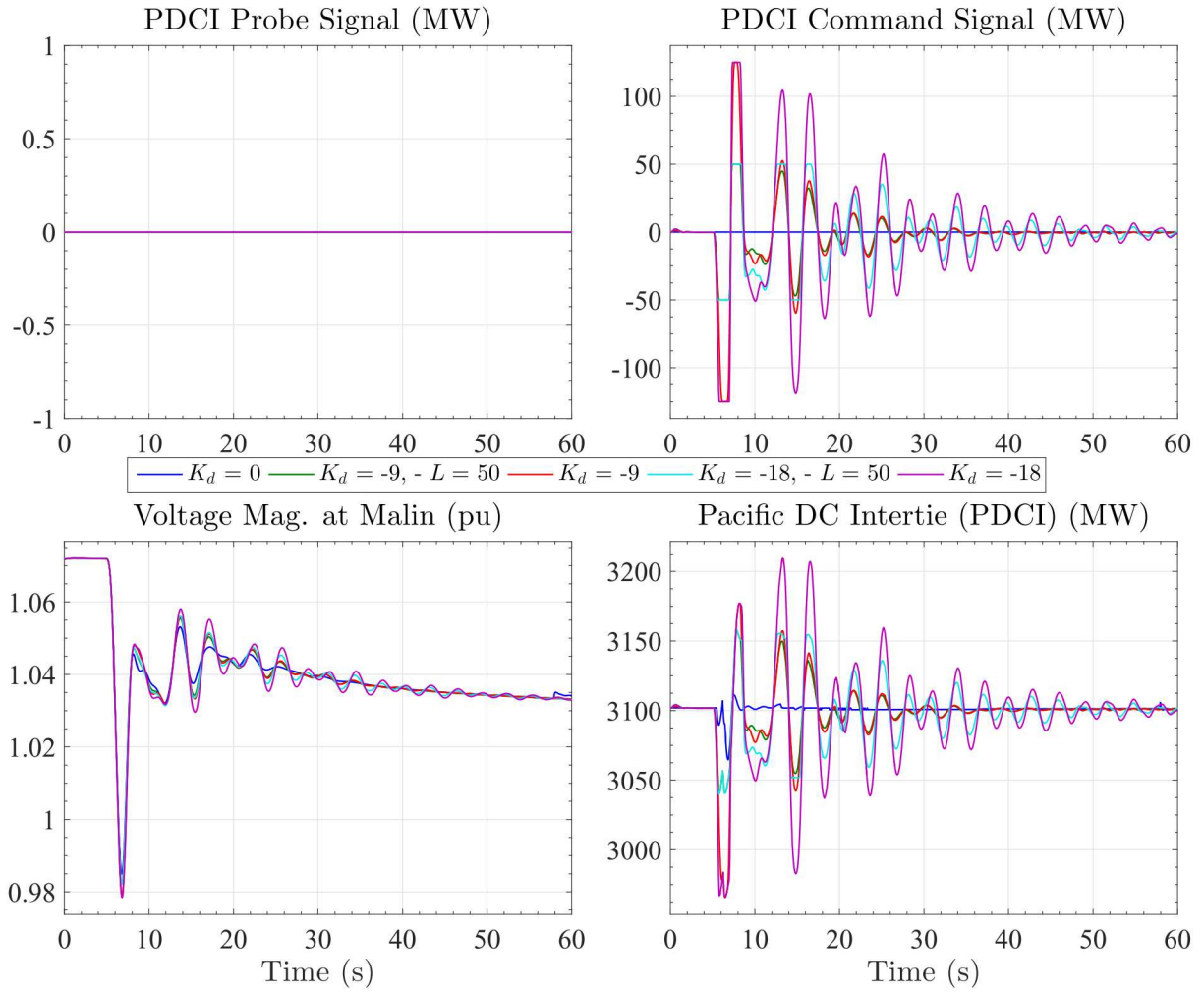
**Figure 12. Bus frequencies. Event: Chief Joe Brake**



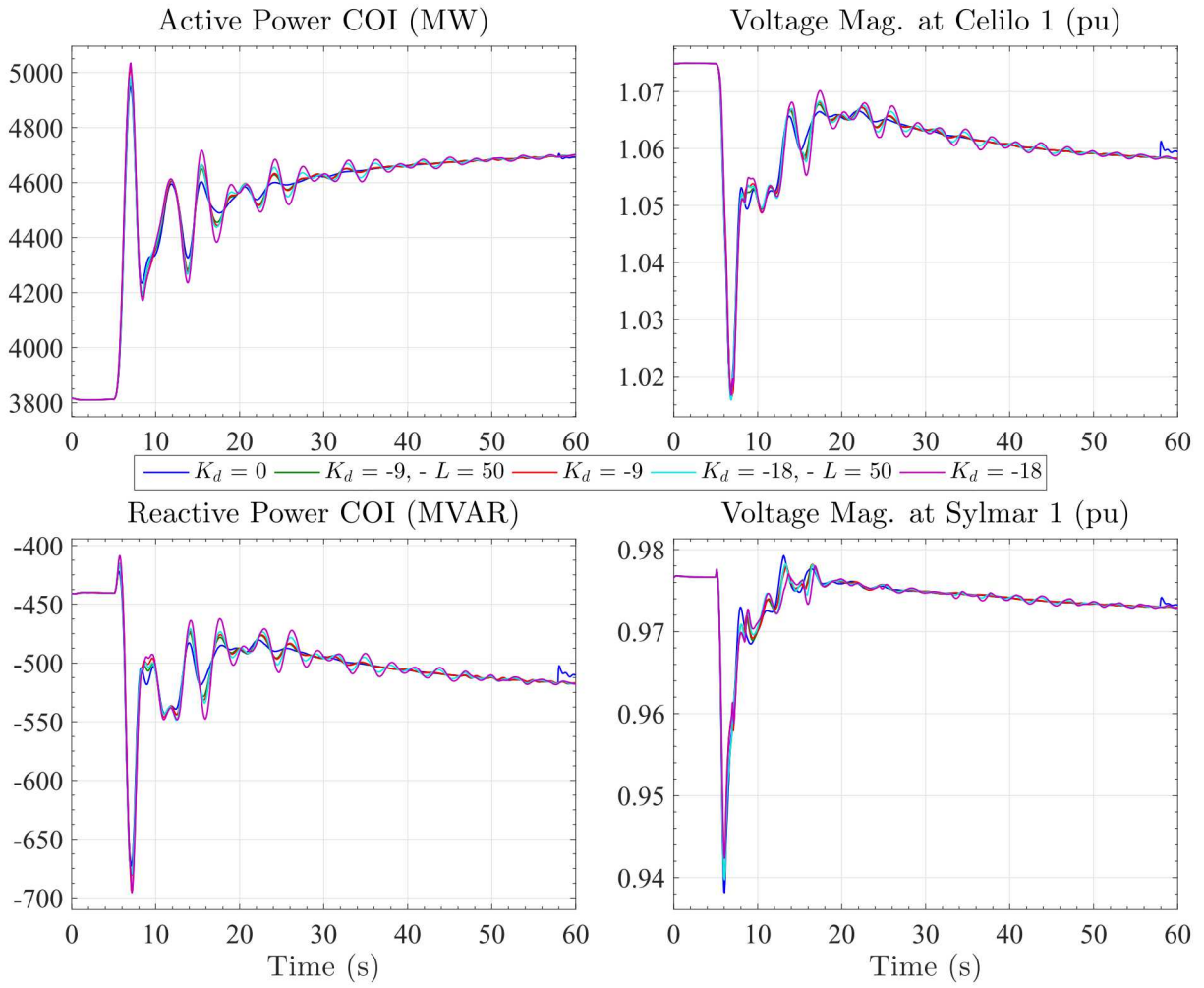


**Figure 13. Bus frequencies. Event: Chief Joe Brake**

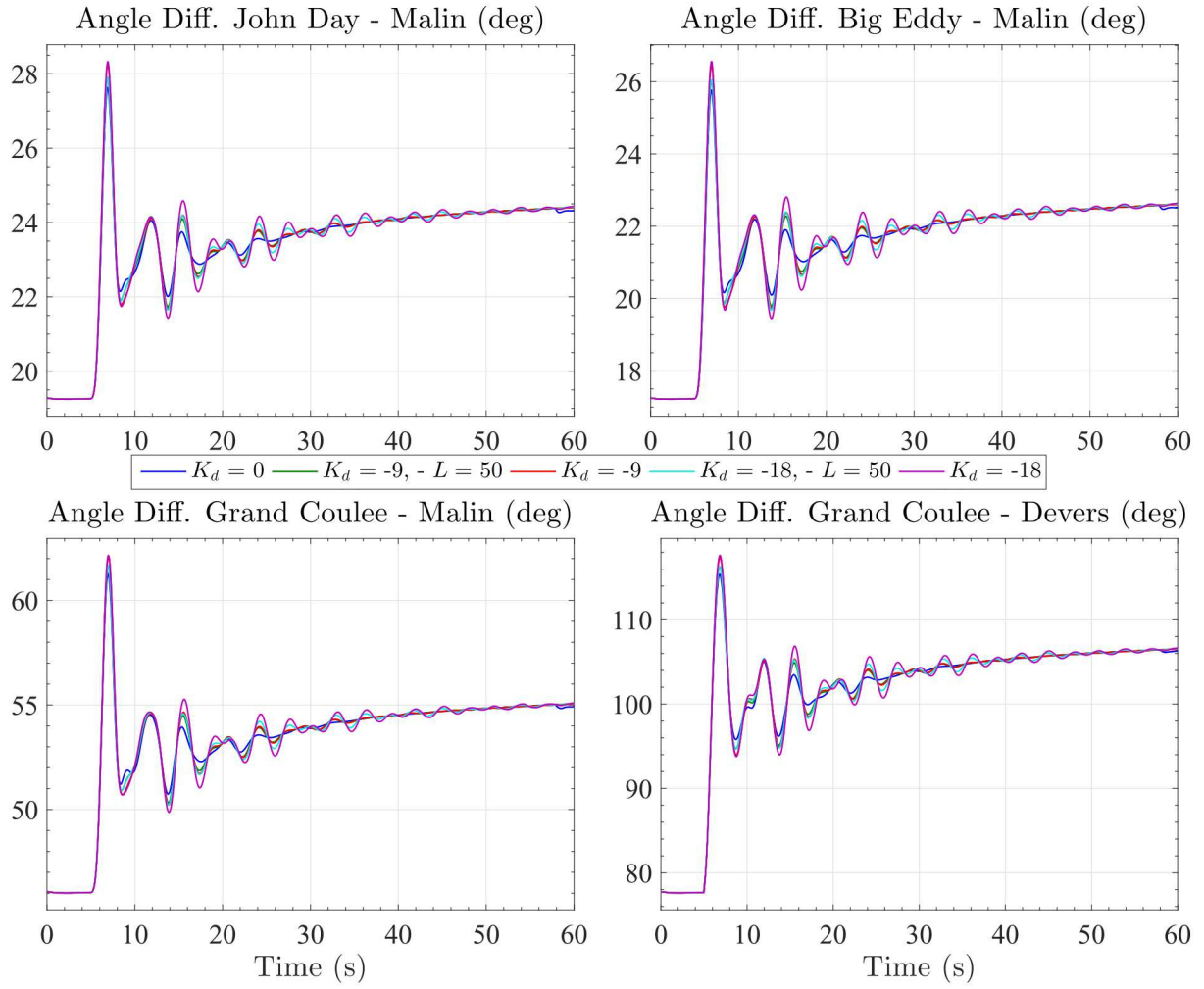
## 2.2. Test System: Heavy Summer 2016. Event: Double Palo Verde Trip



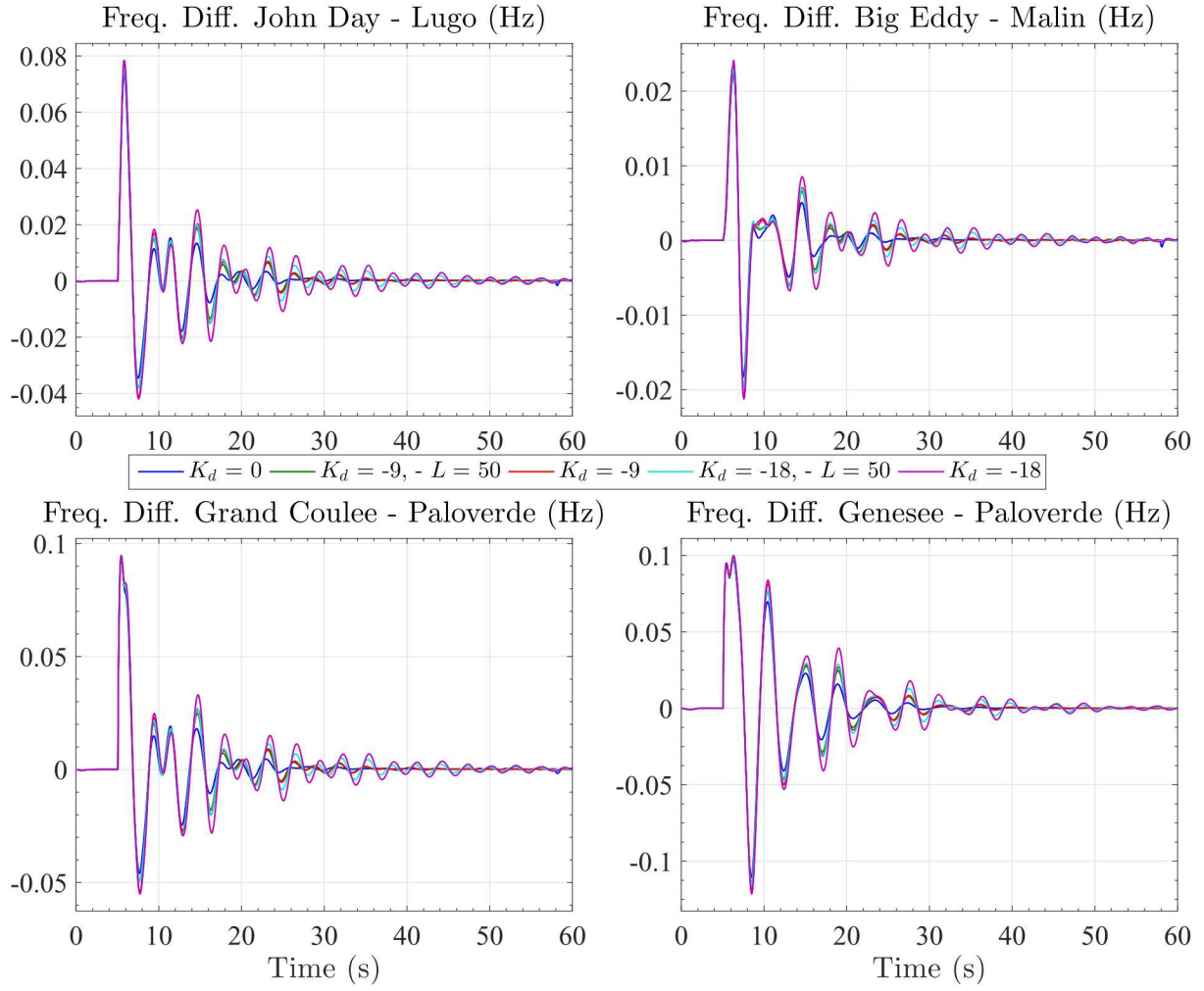
**Figure 14. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Double Palo Verde Trip**



**Figure 15. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Double Palo Verde Trip**

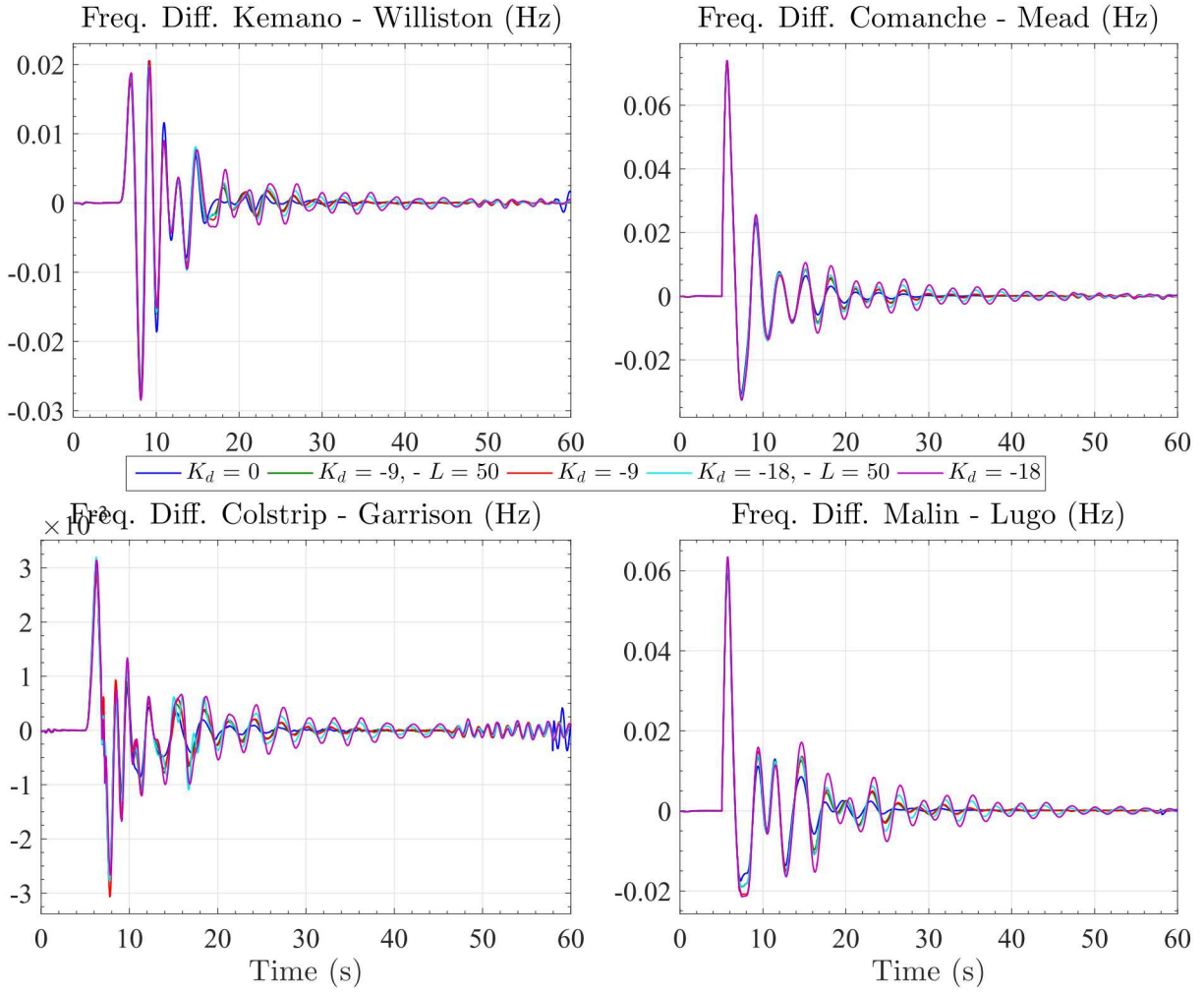


**Figure 16. Angle differences. Event: Double Palo Verde Trip**

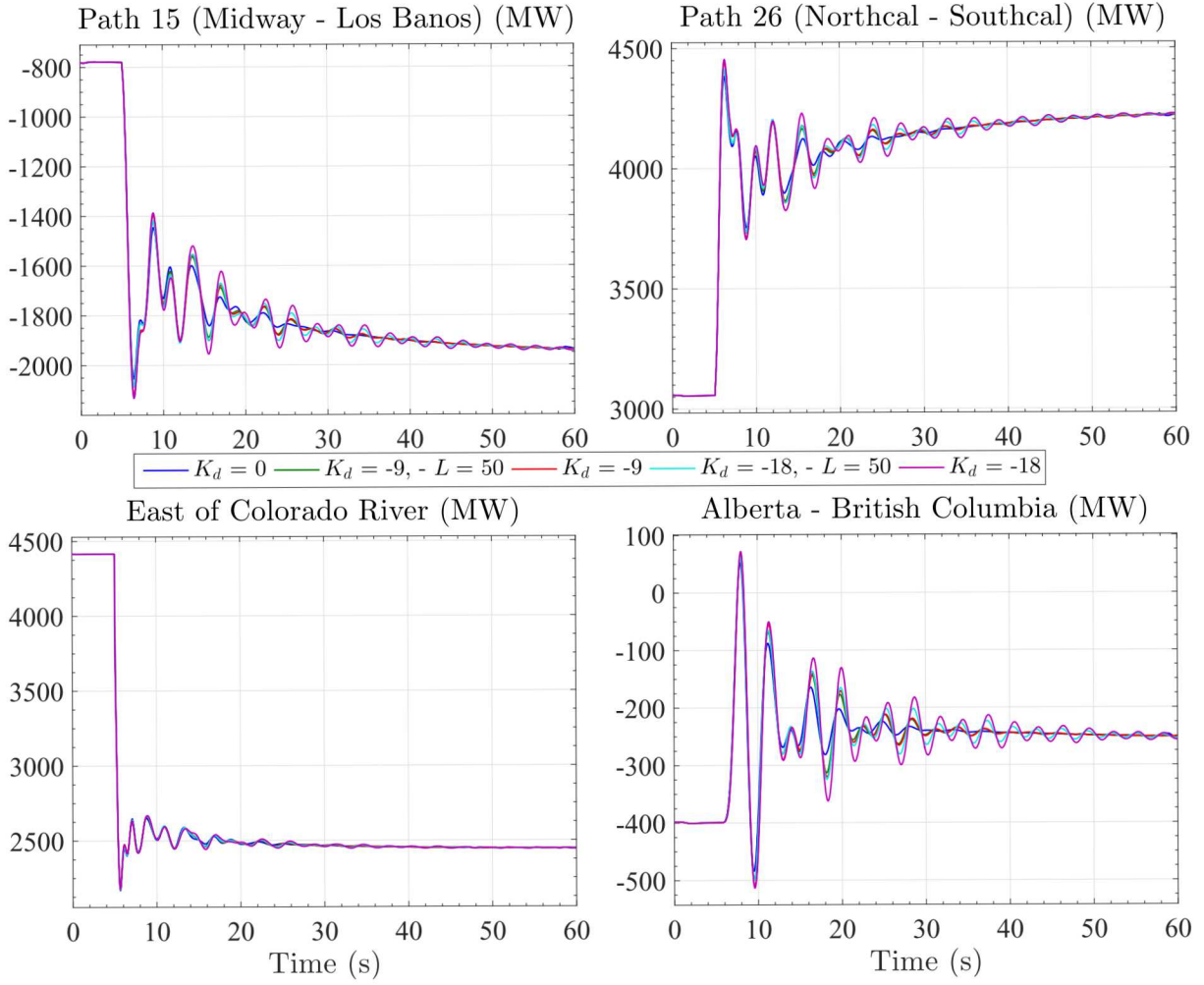


**Figure 17. Frequency differences. Event: Double Palo Verde Trip**

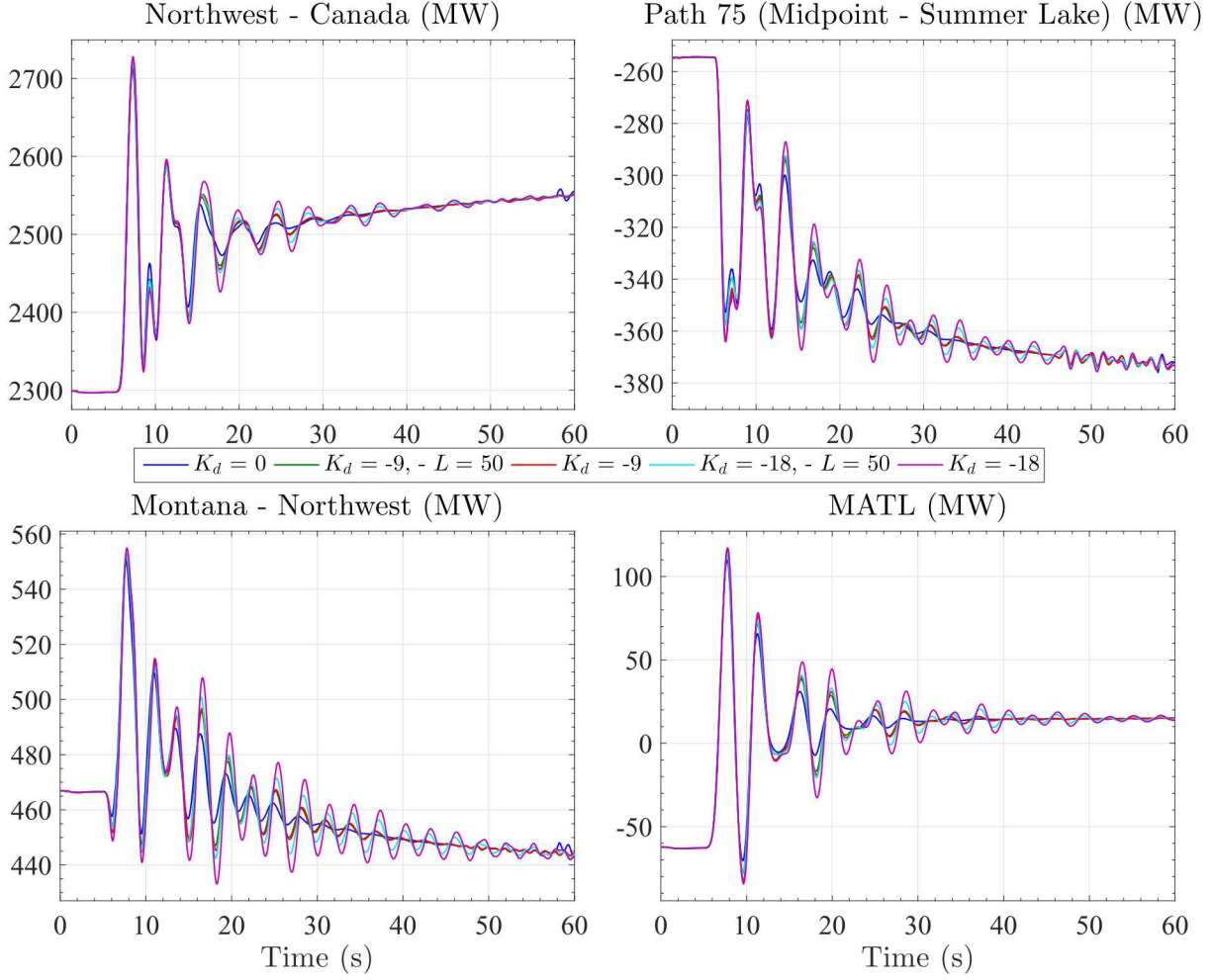




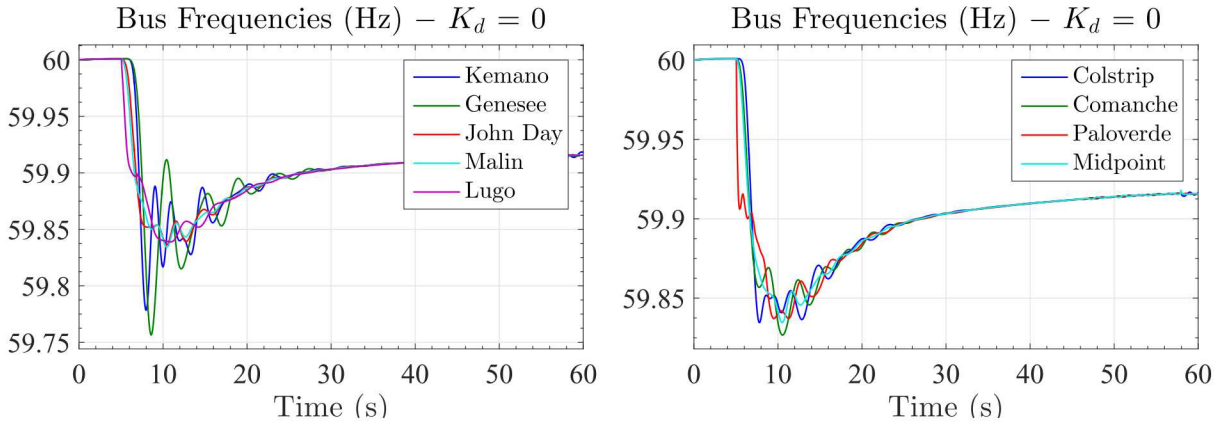
**Figure 18. Frequency differences. Event: Double Palo Verde Trip**



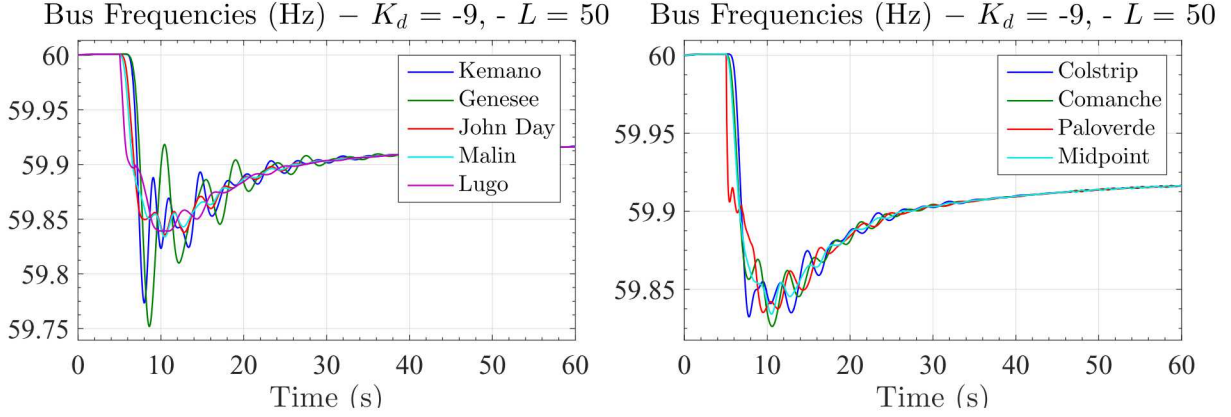
**Figure 19. Active power flows. Event: Double Palo Verde Trip**



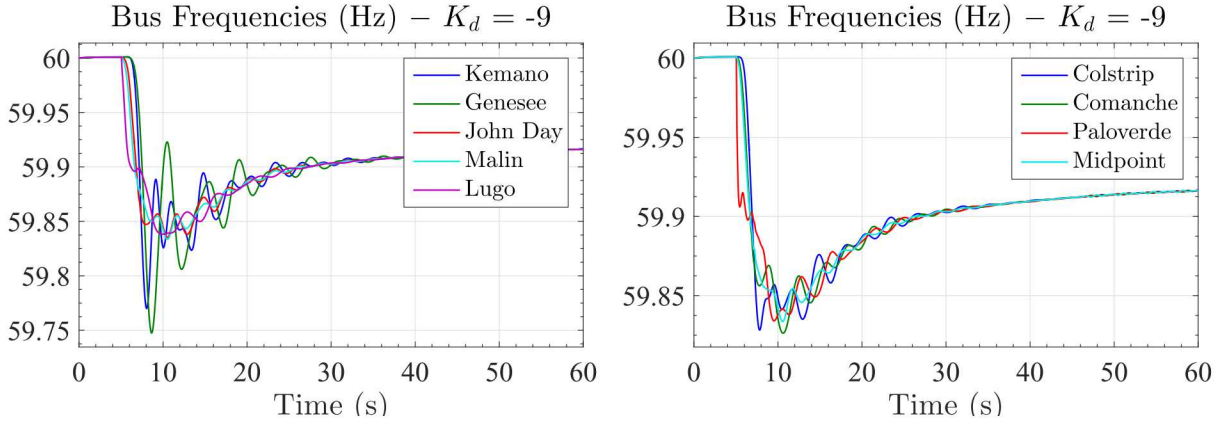
**Figure 20. Active power flows. Event: Double Palo Verde Trip**



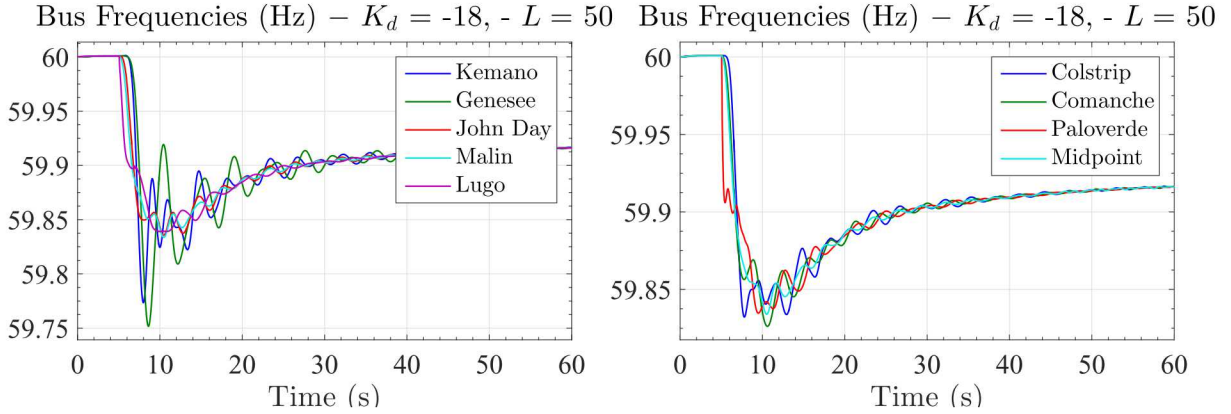
**Figure 21. Bus frequencies. Event: Double Palo Verde Trip**



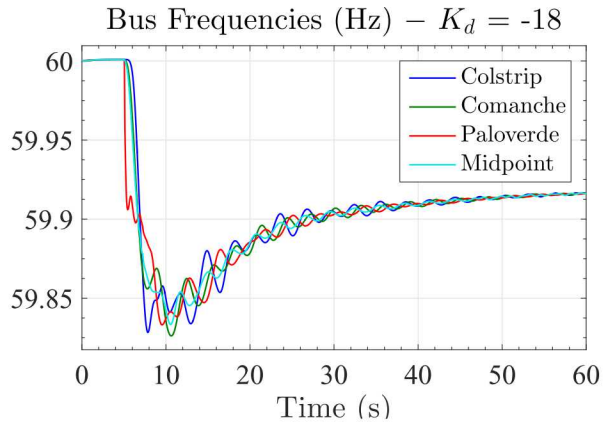
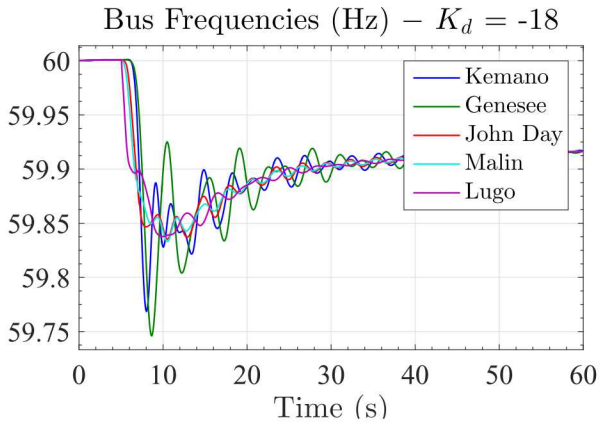
**Figure 22. Bus frequencies. Event: Double Palo Verde Trip**



**Figure 23. Bus frequencies. Event: Double Palo Verde Trip**



**Figure 24. Bus frequencies. Event: Double Palo Verde Trip**



**Figure 25. Bus frequencies. Event: Double Palo Verde Trip**



### 2.3. Test System: Heavy Summer 2016. Event: BC-US Separation

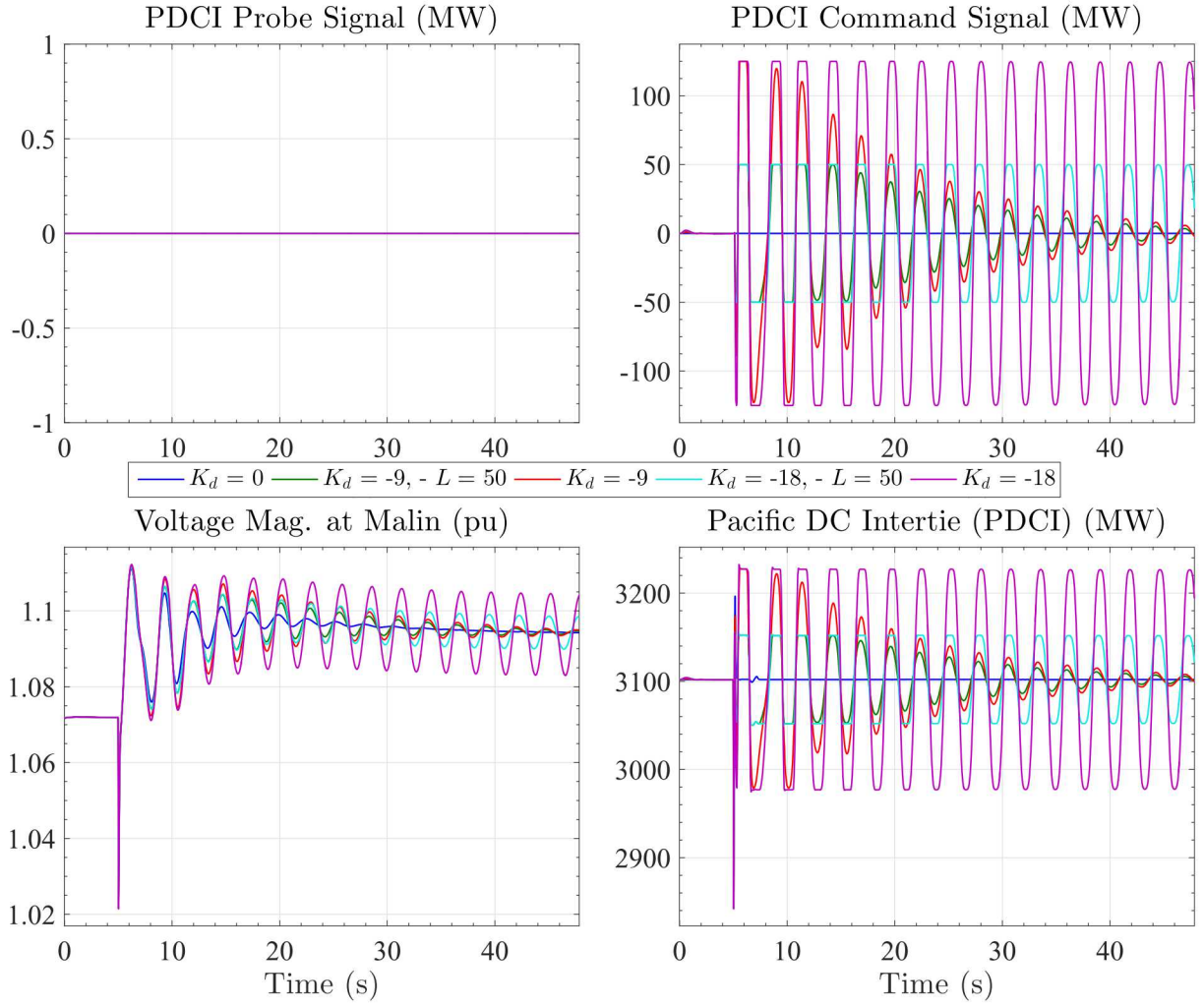
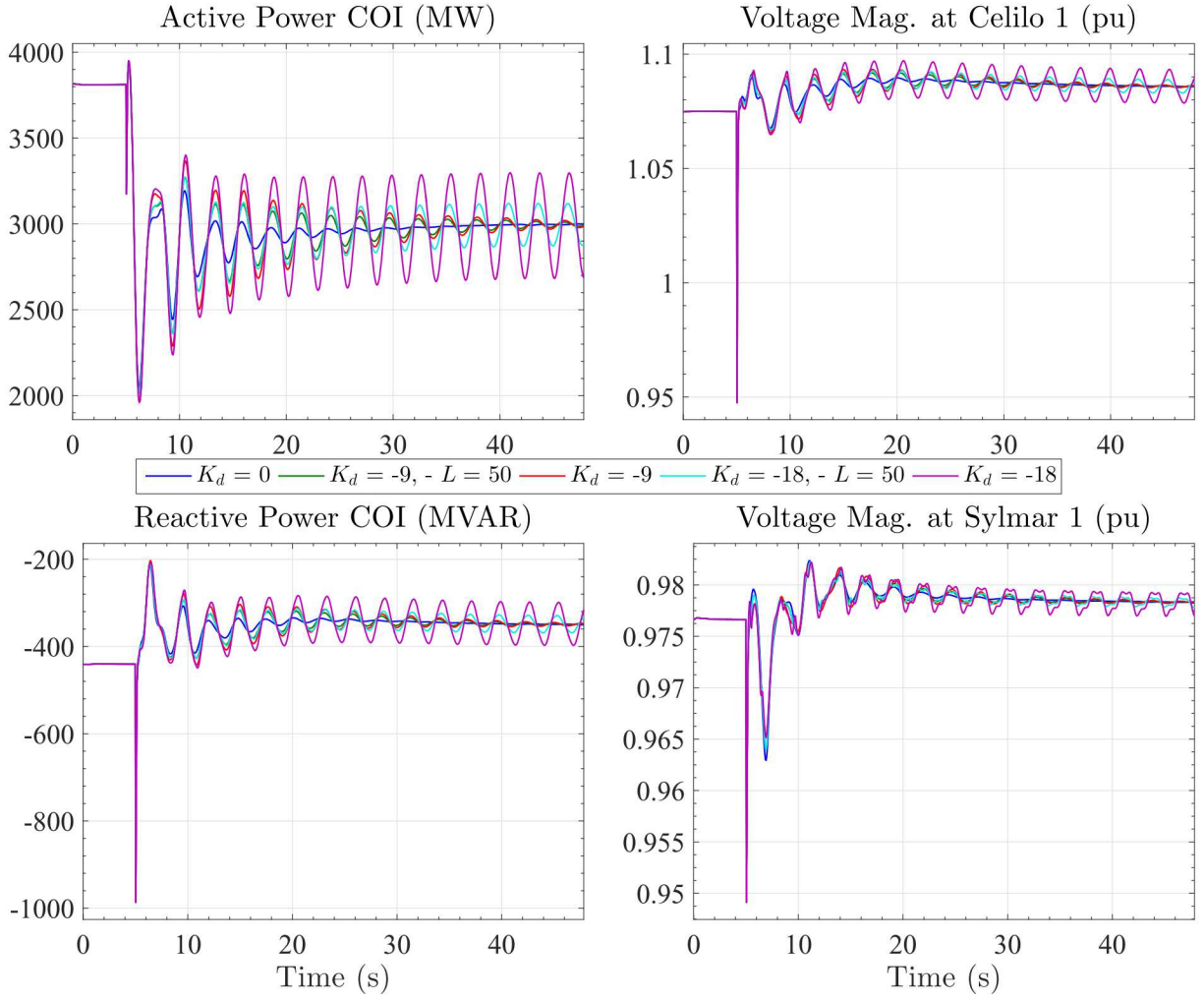
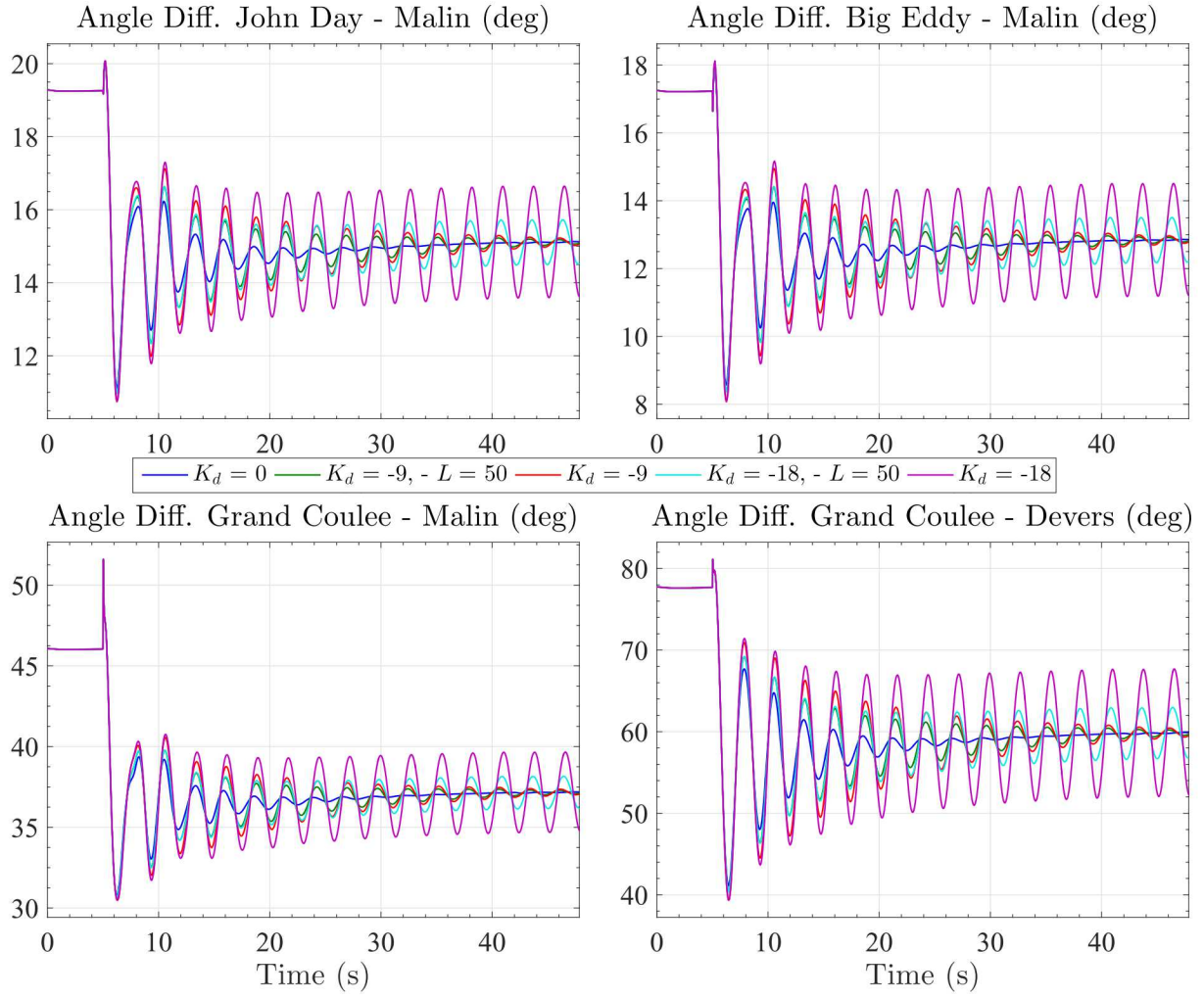


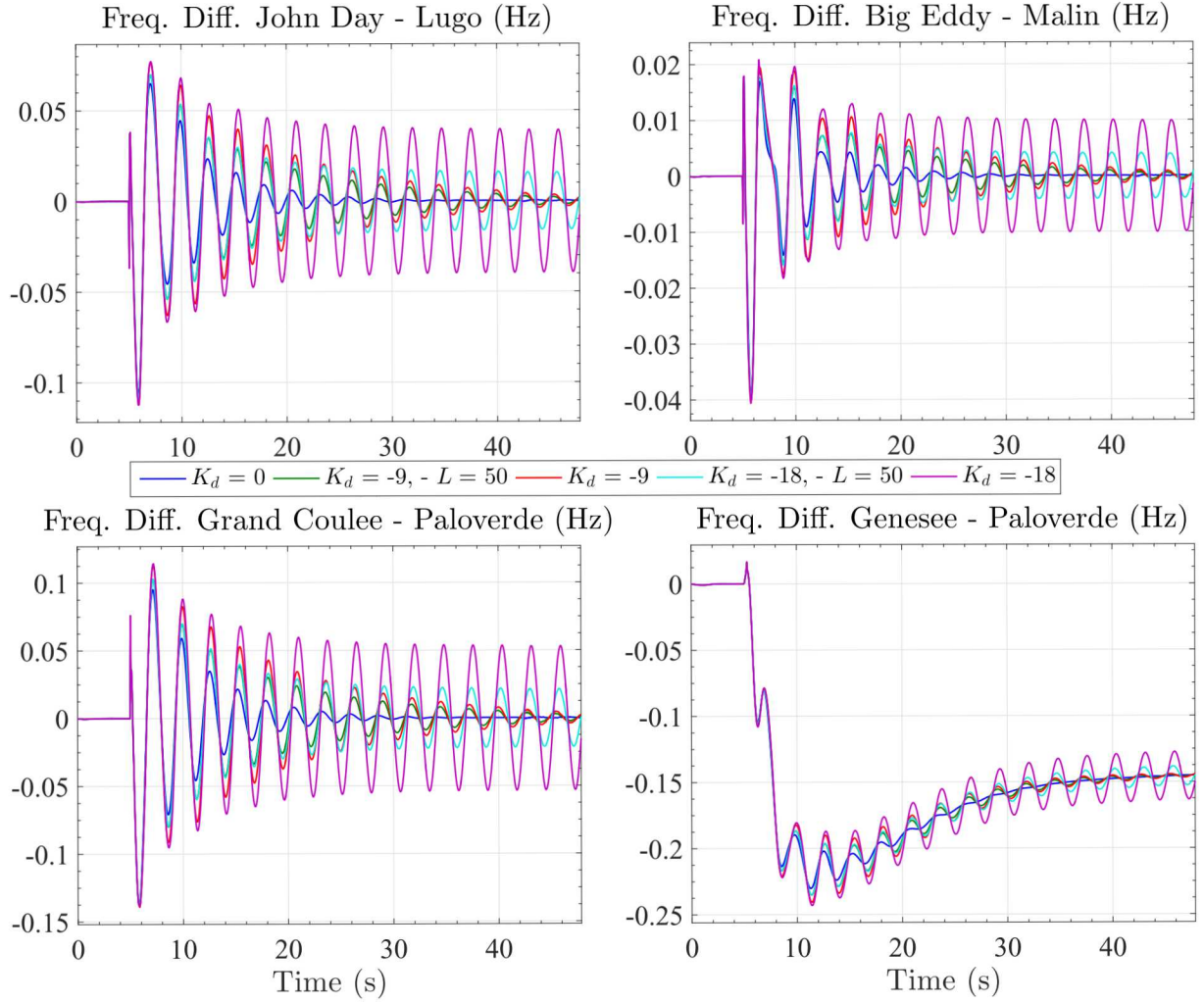
Figure 26. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-US Separation



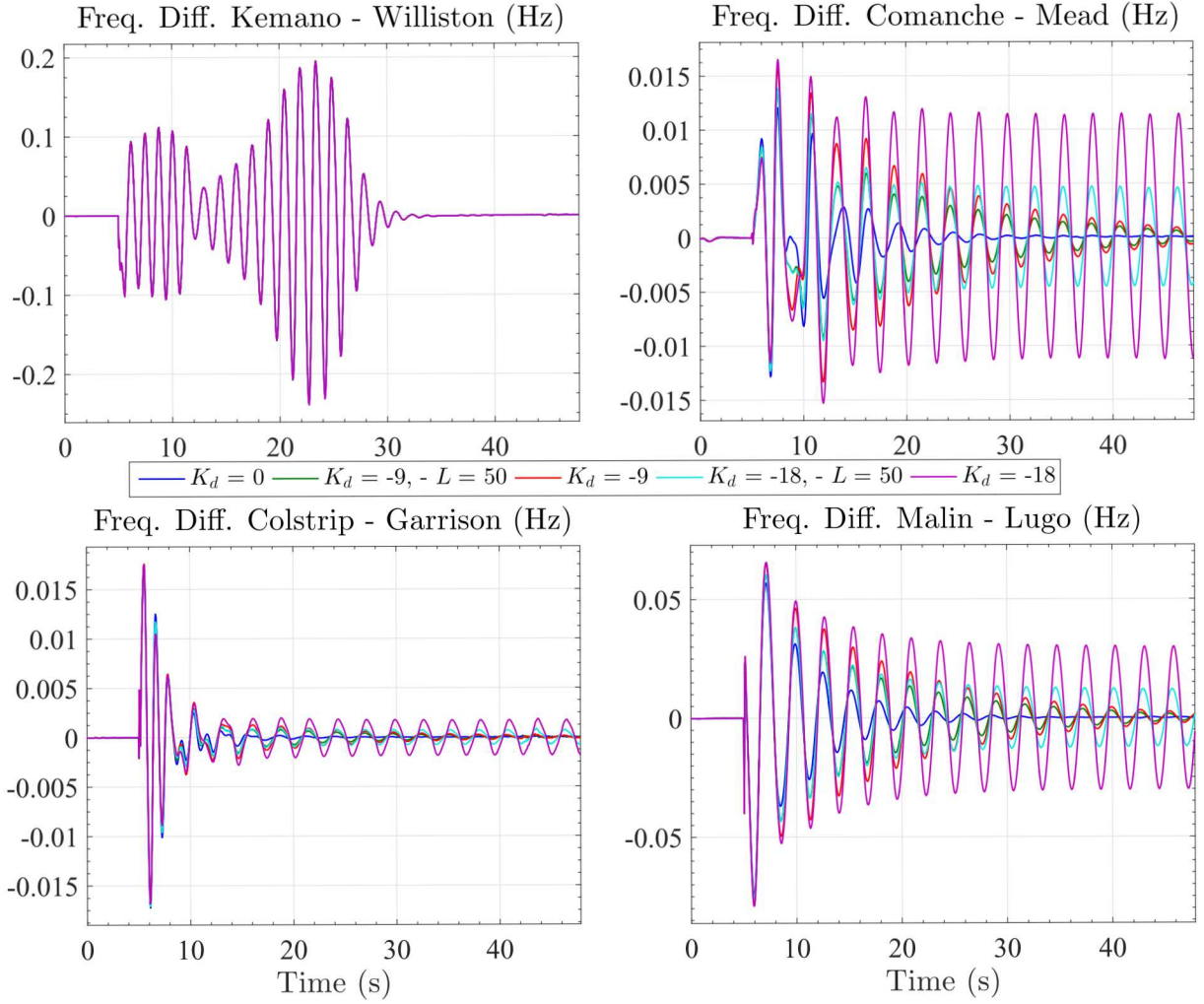
**Figure 27. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-US Separation**



**Figure 28. Angle differences. Event: BC-US Separation**

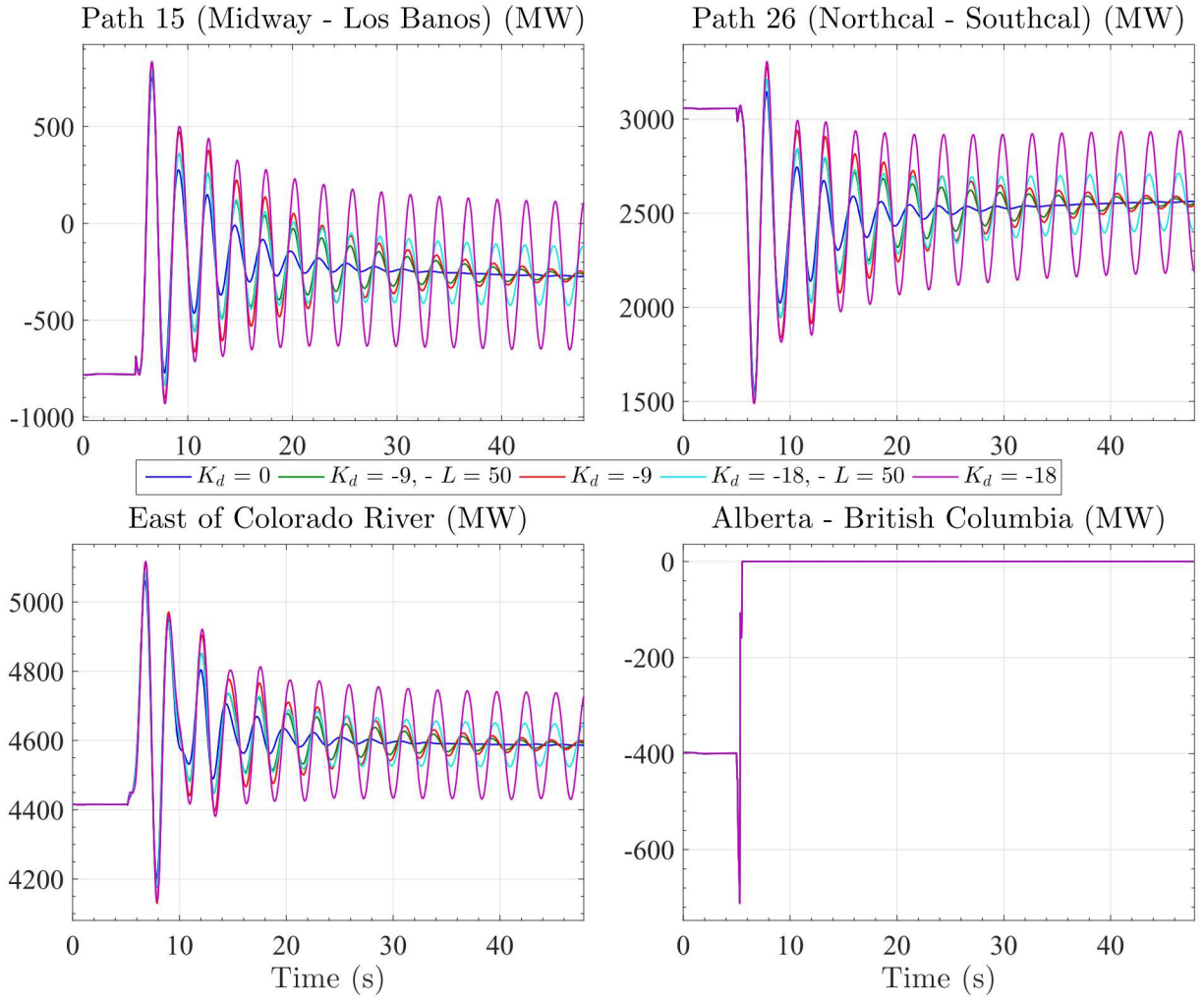


**Figure 29. Frequency differences. Event: BC-US Separation**

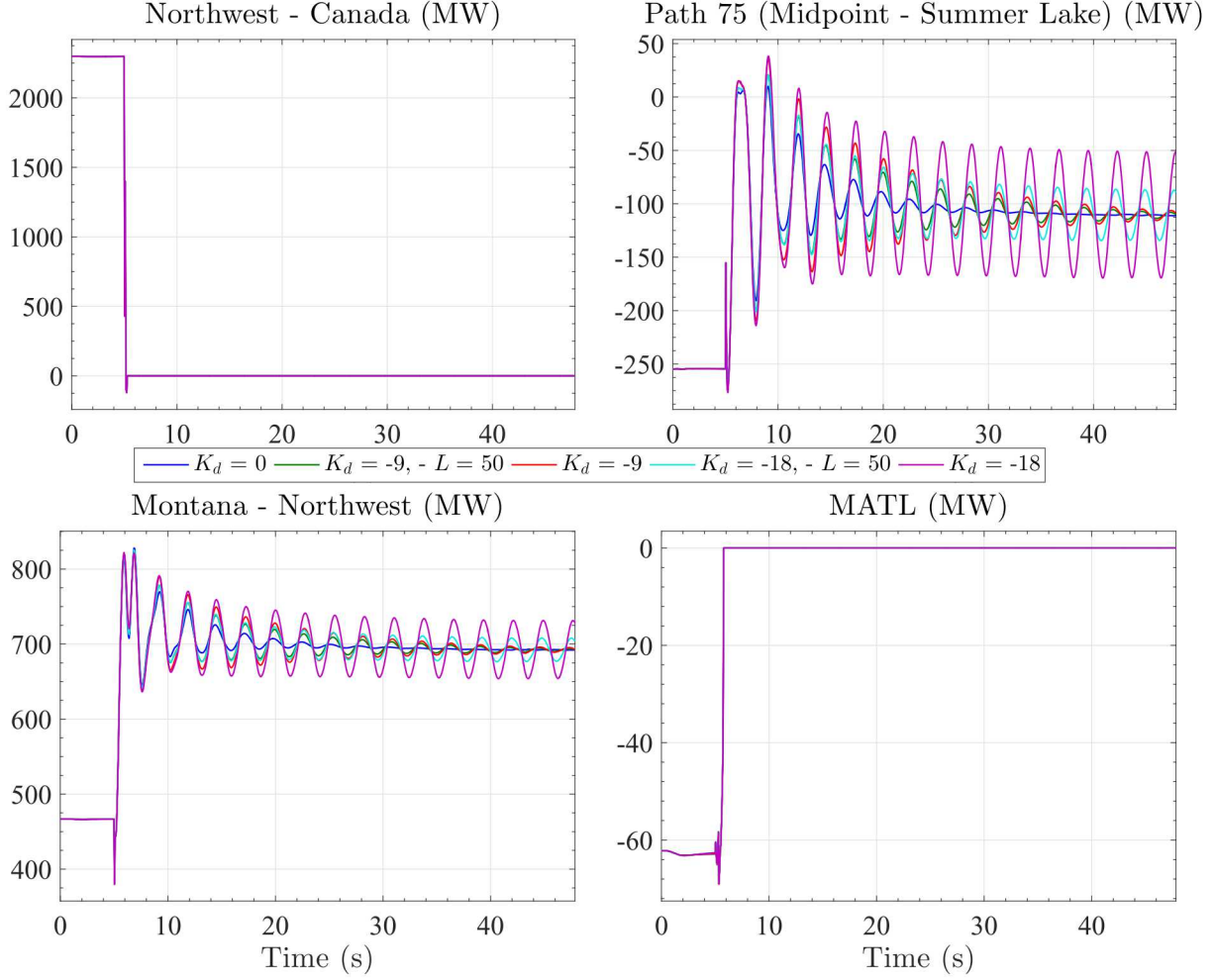


**Figure 30. Frequency differences. Event: BC-US Separation**

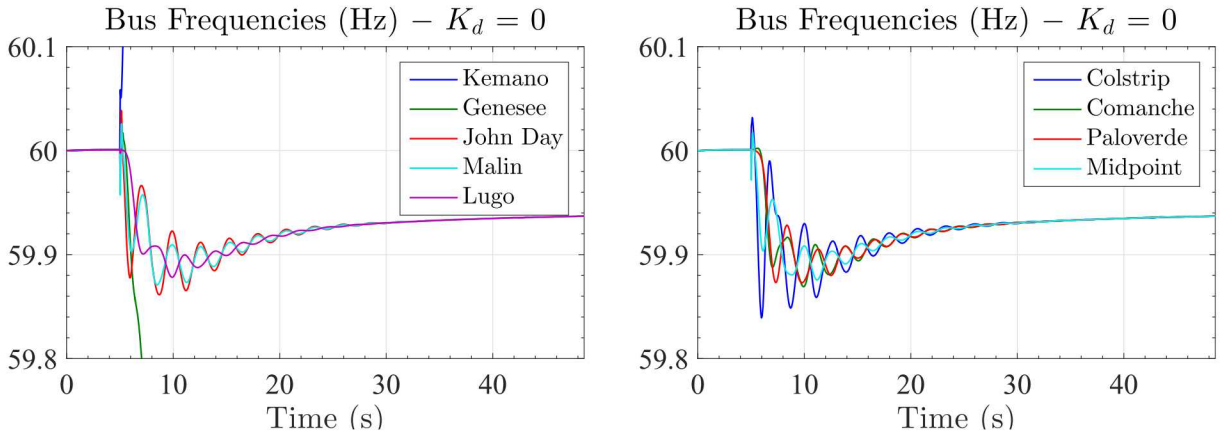




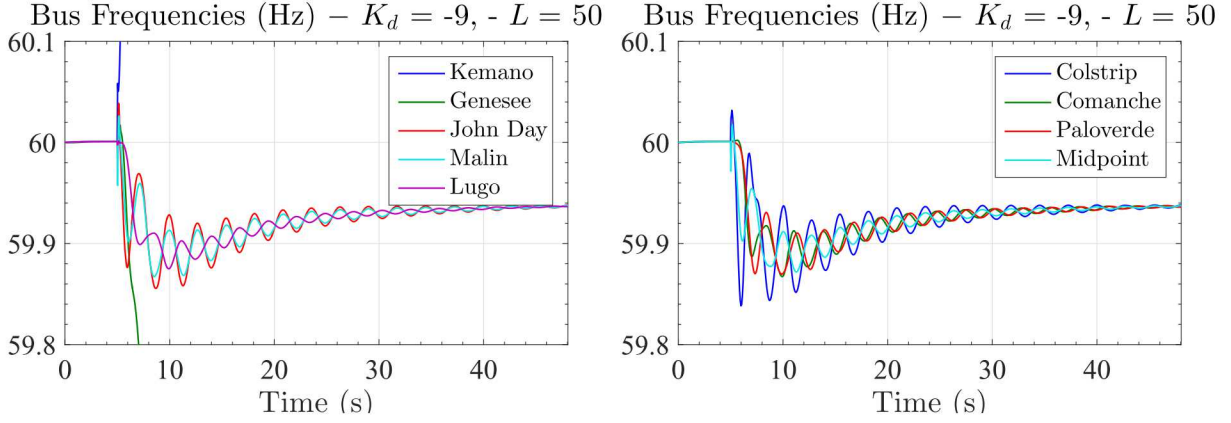
**Figure 31. Active power flows. Event: BC-US Separation**



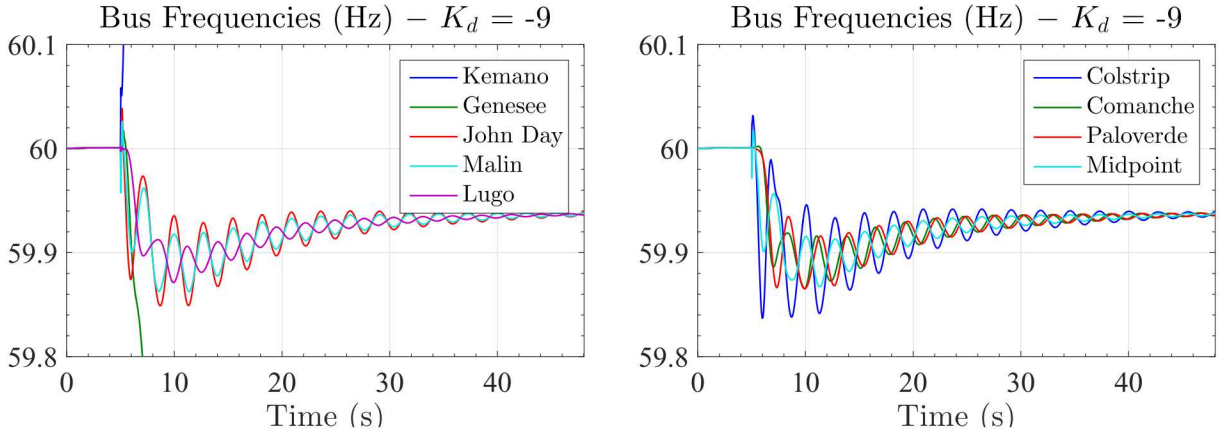
**Figure 32. Active power flows. Event: BC-US Separation**



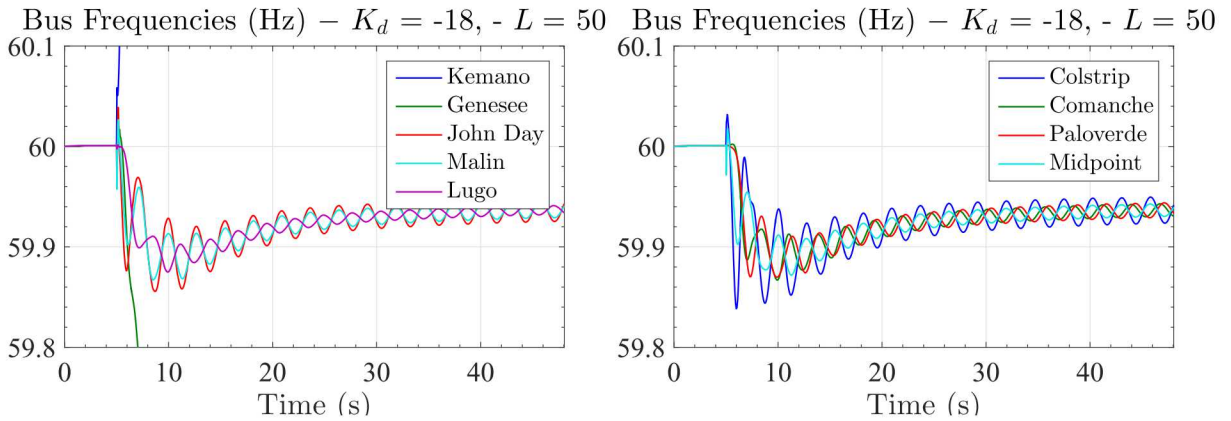
**Figure 33. Bus frequencies. Event: BC-US Separation**



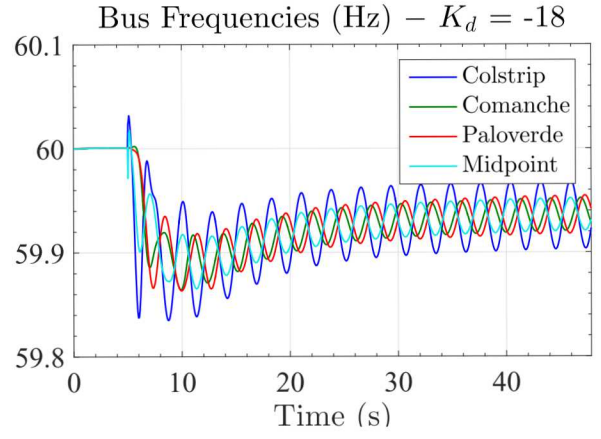
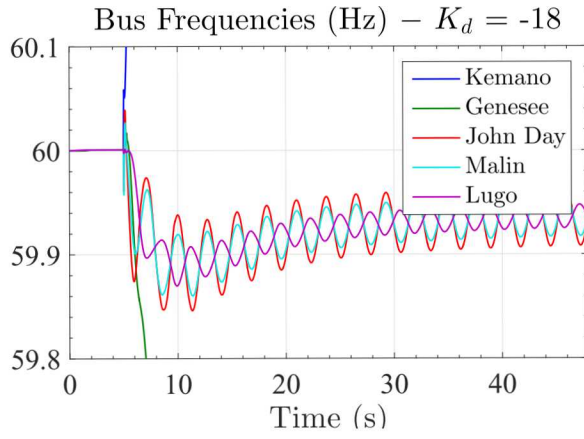
**Figure 34. Bus frequencies. Event: BC-US Separation**



**Figure 35. Bus frequencies. Event: BC-US Separation**

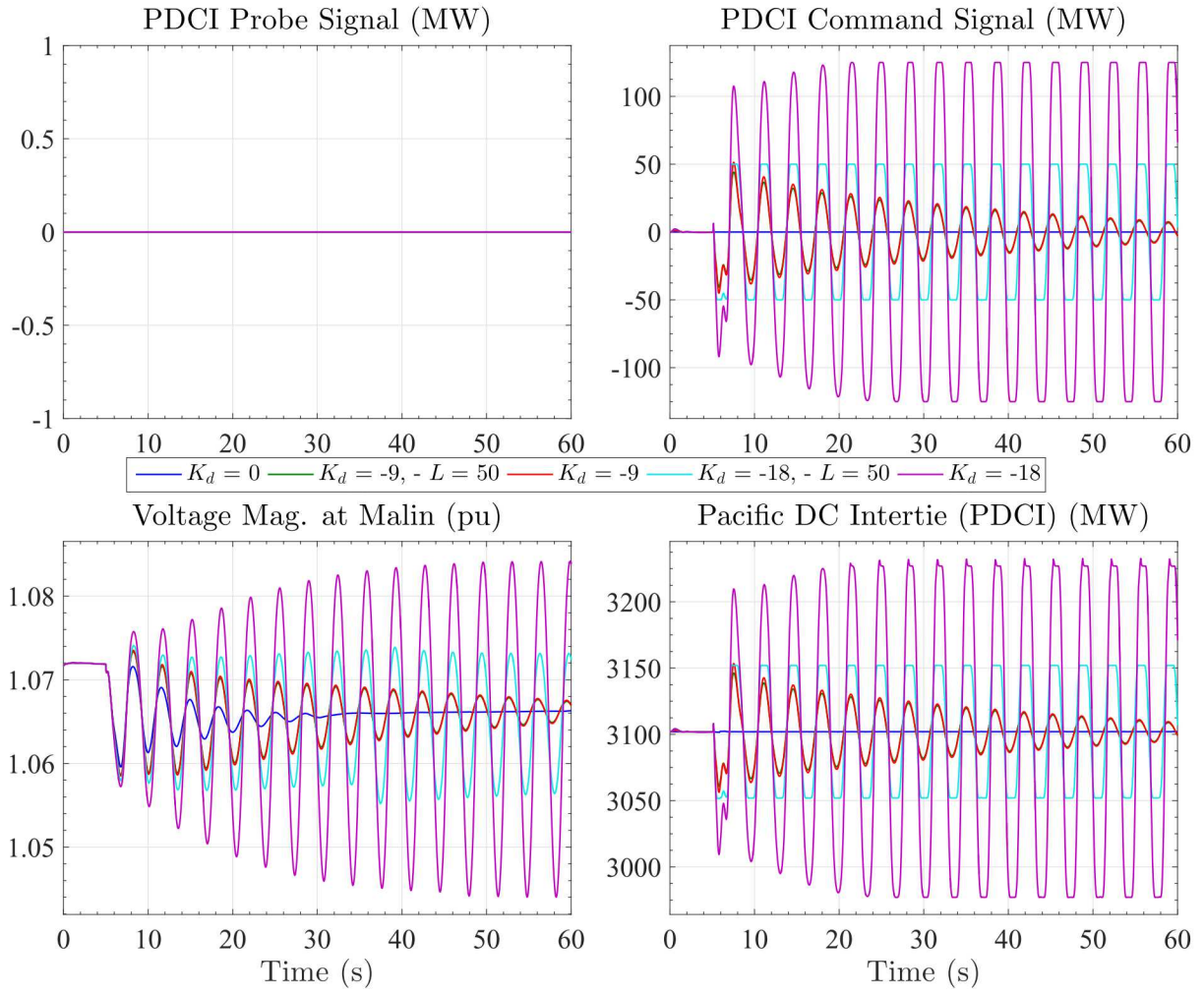


**Figure 36. Bus frequencies. Event: BC-US Separation**



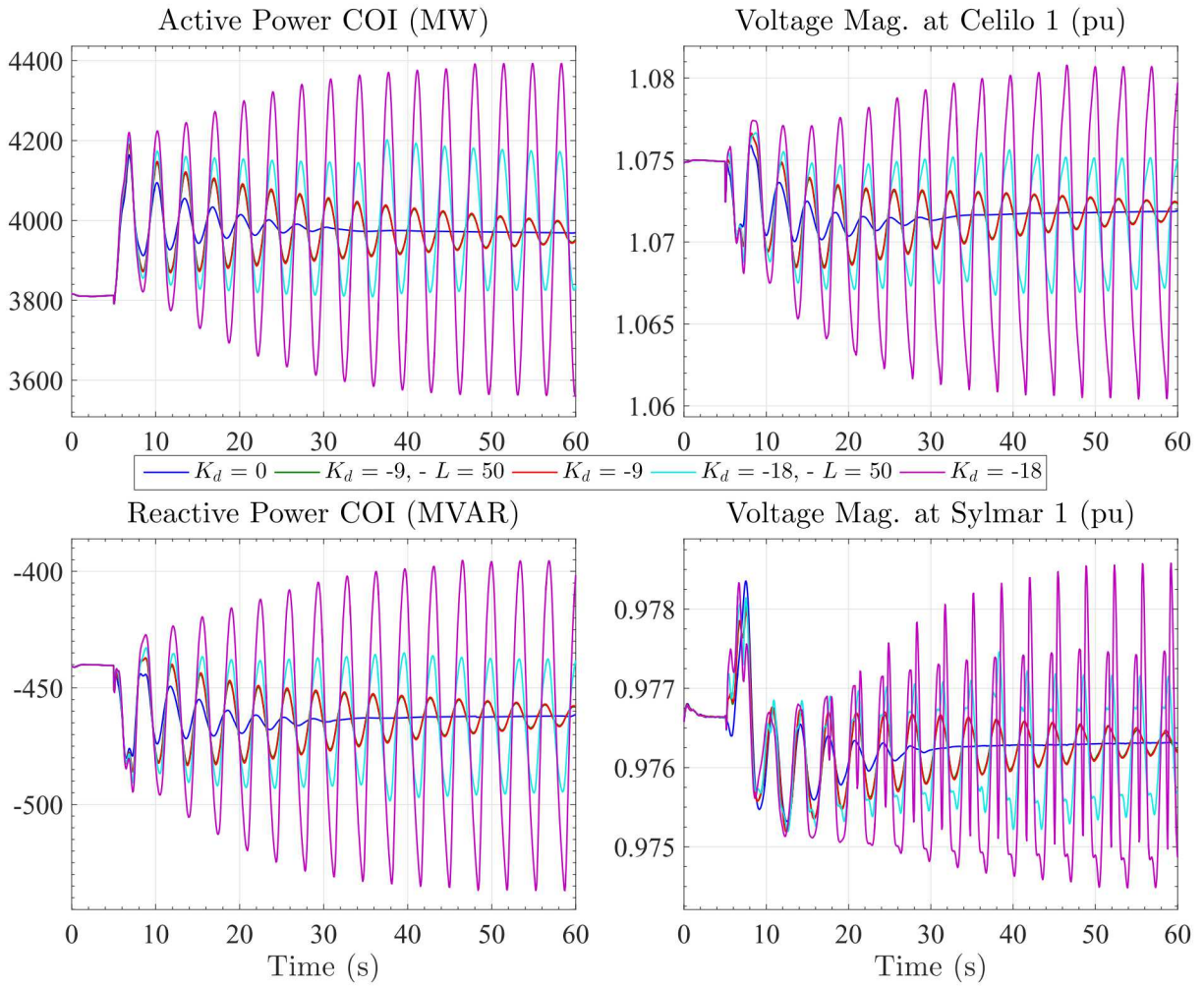
**Figure 37. Bus frequencies. Event: BC-US Separation**

## 2.4. Test System: Heavy Summer 2016. Event: BC-AB Separation

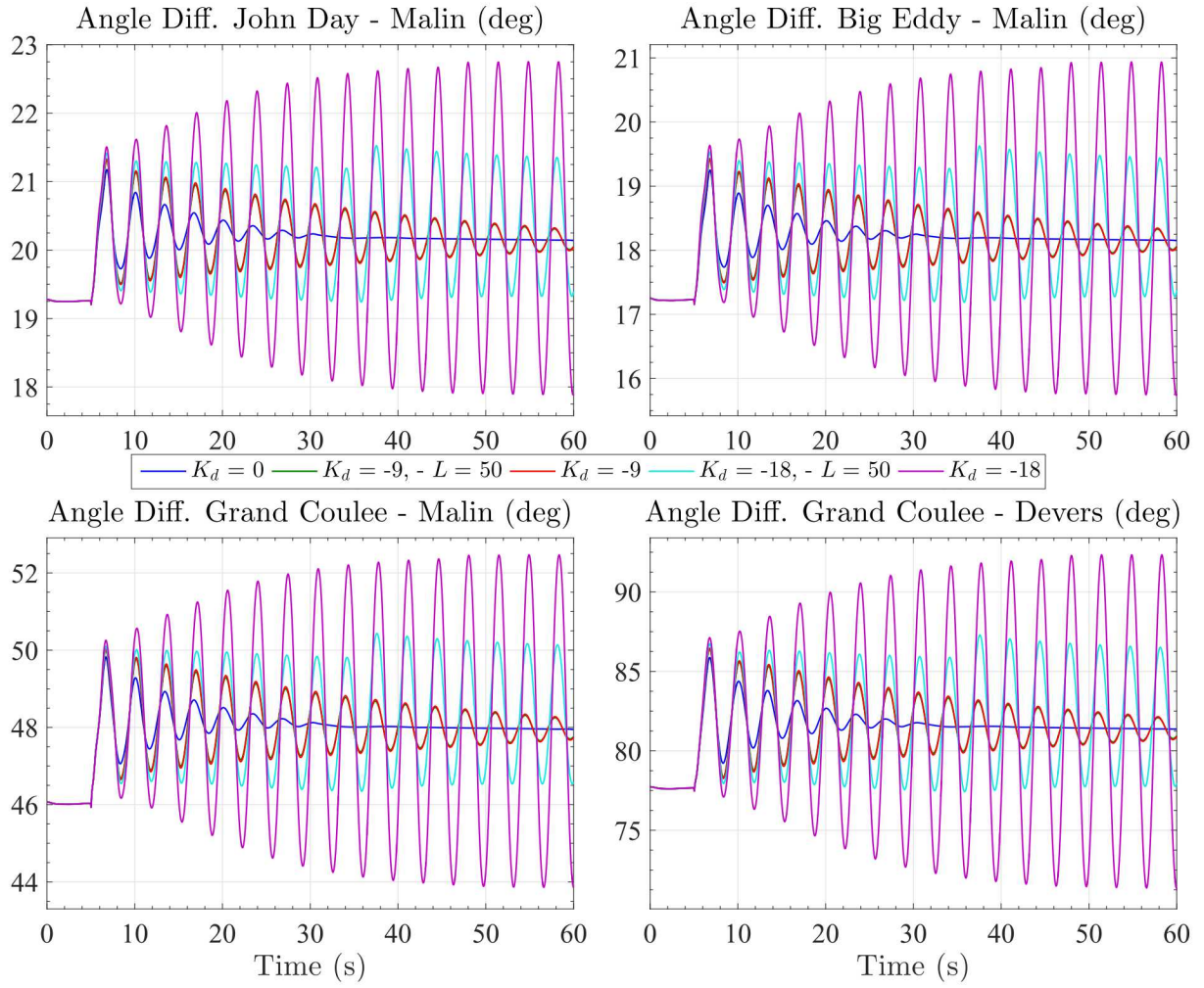


**Figure 38. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-AB Separation**

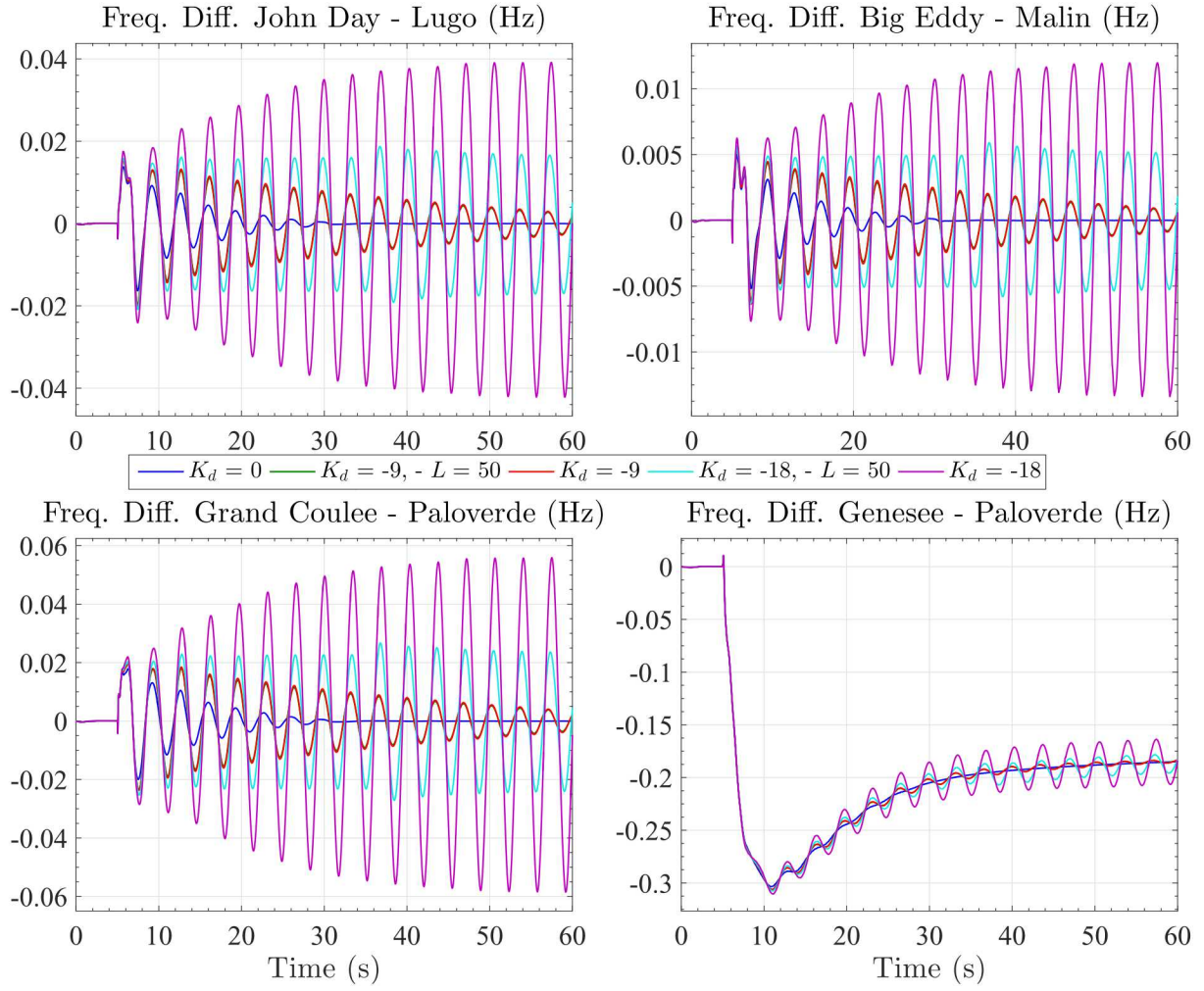




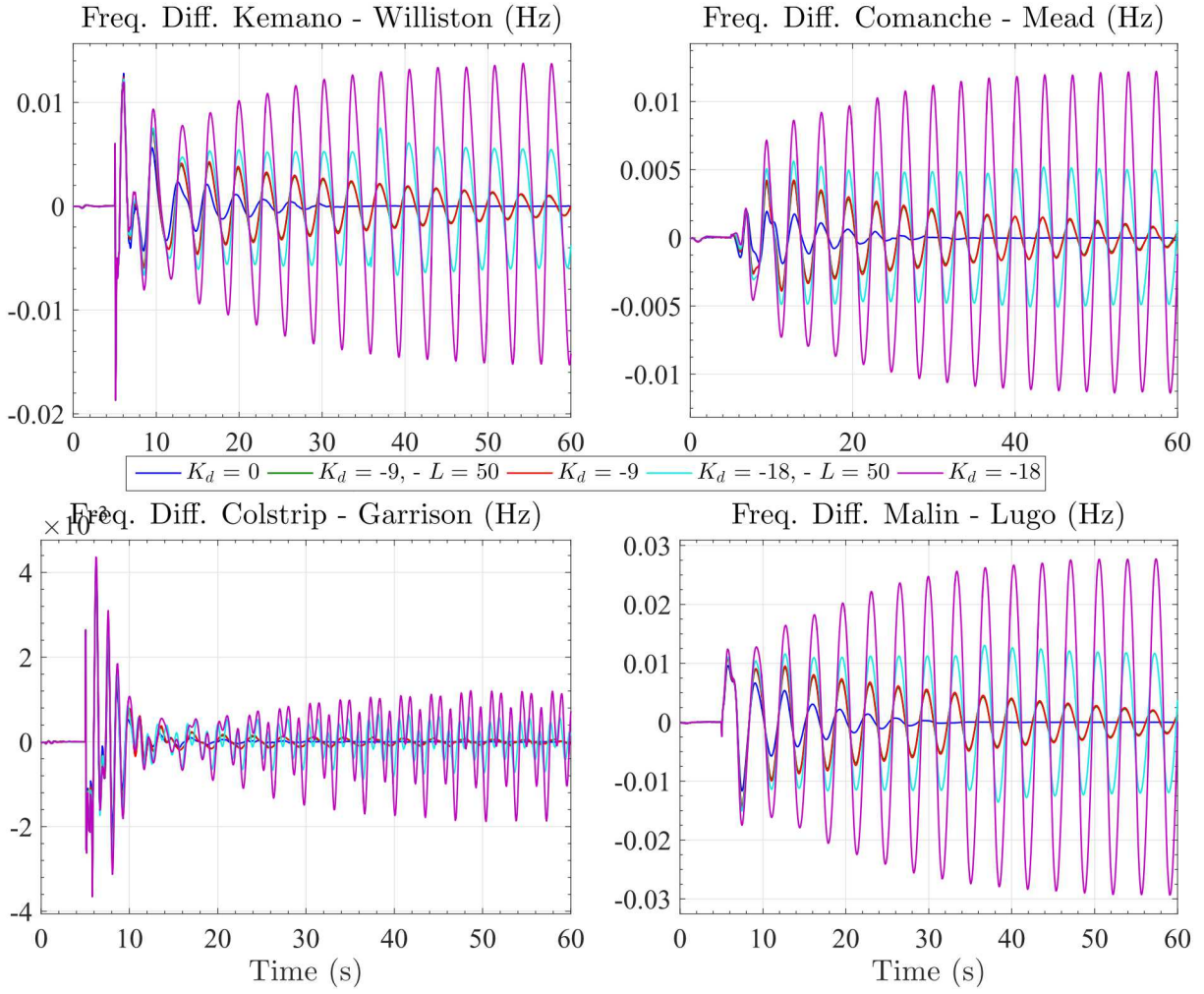
**Figure 39. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-AB Separation**



**Figure 40. Angle differences. Event: BC-AB Separation**

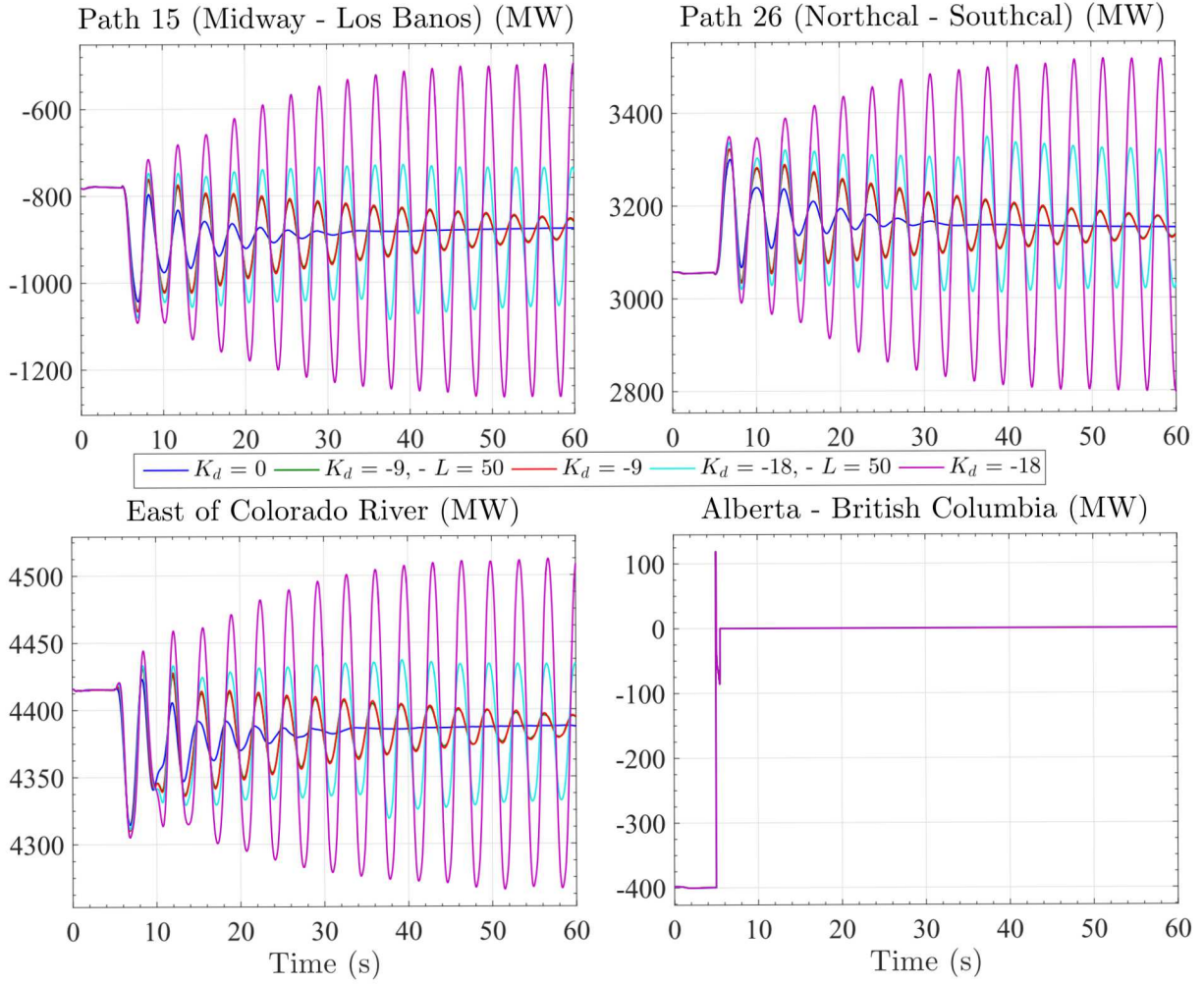


**Figure 41. Frequency differences. Event: BC-AB Separation**



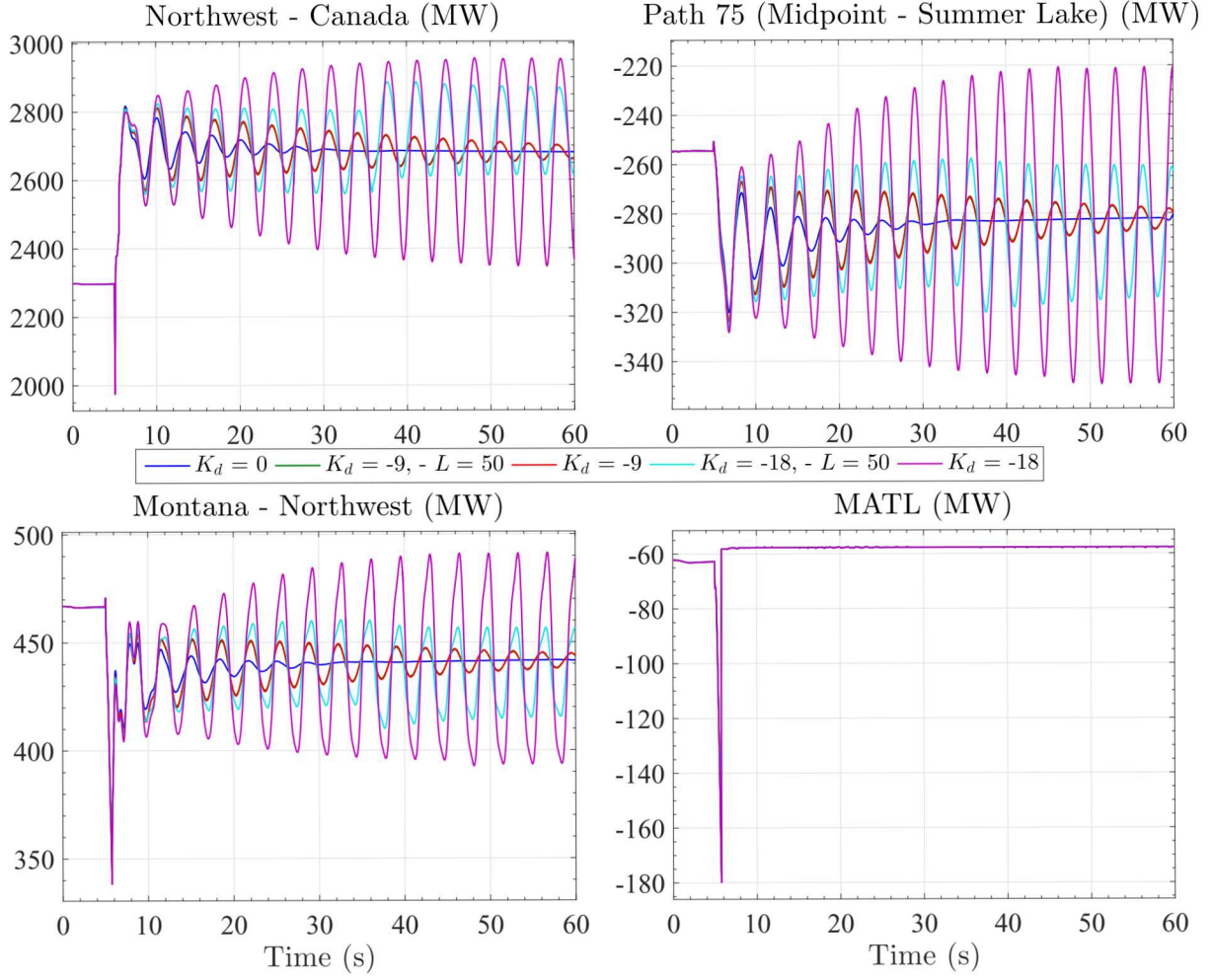
**Figure 42. Frequency differences. Event: BC-AB Separation**



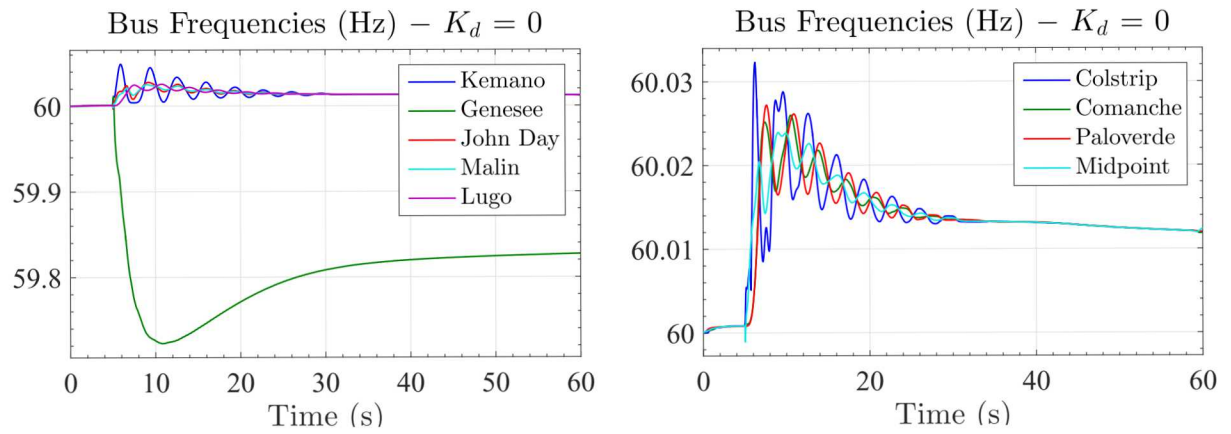


**Figure 43. Active power flows. Event: BC-AB Separation**

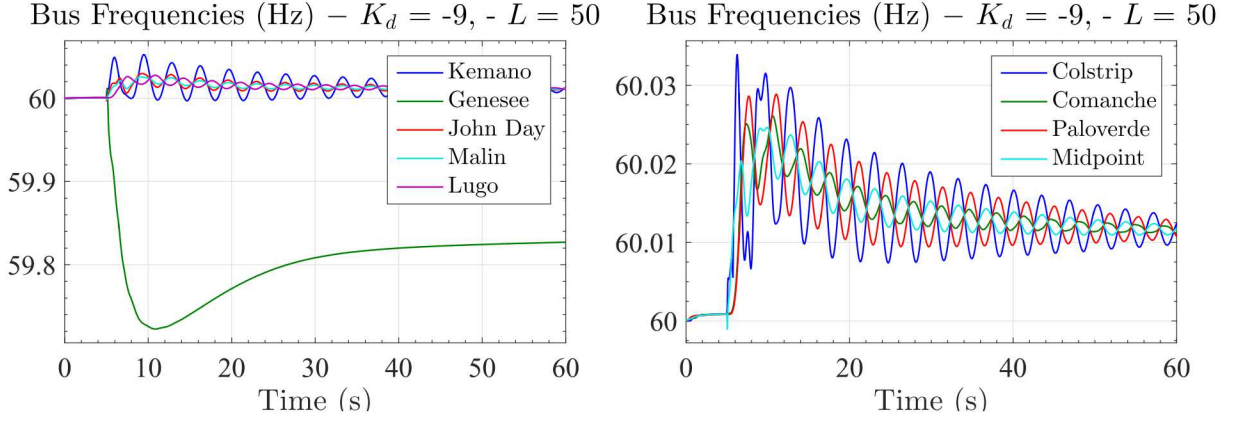




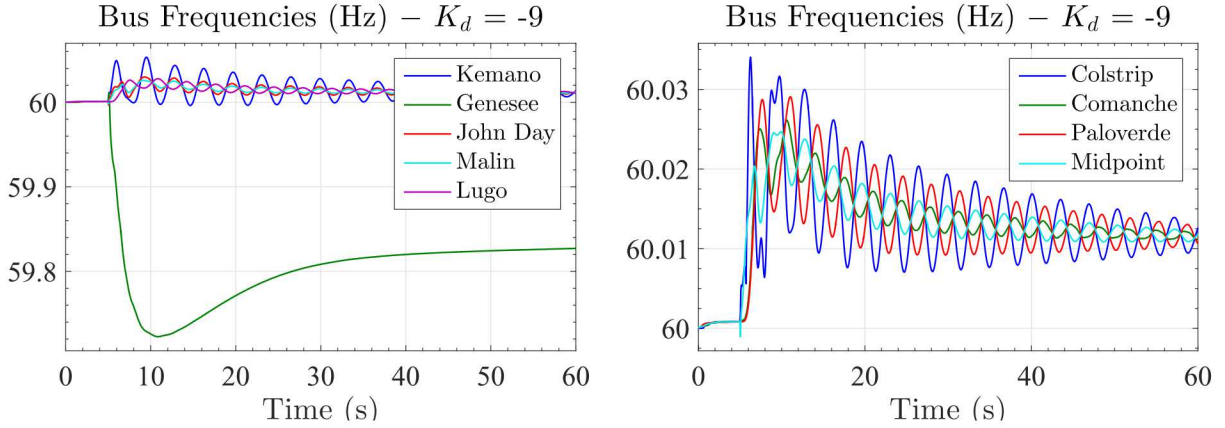
**Figure 44. Active power flows. Event: BC-AB Separation**



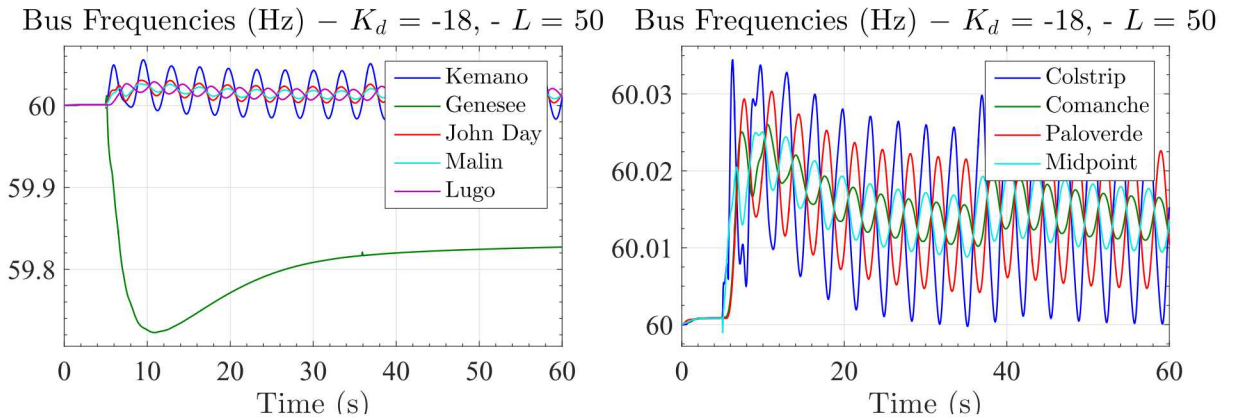
**Figure 45. Bus frequencies. Event: BC-AB Separation**



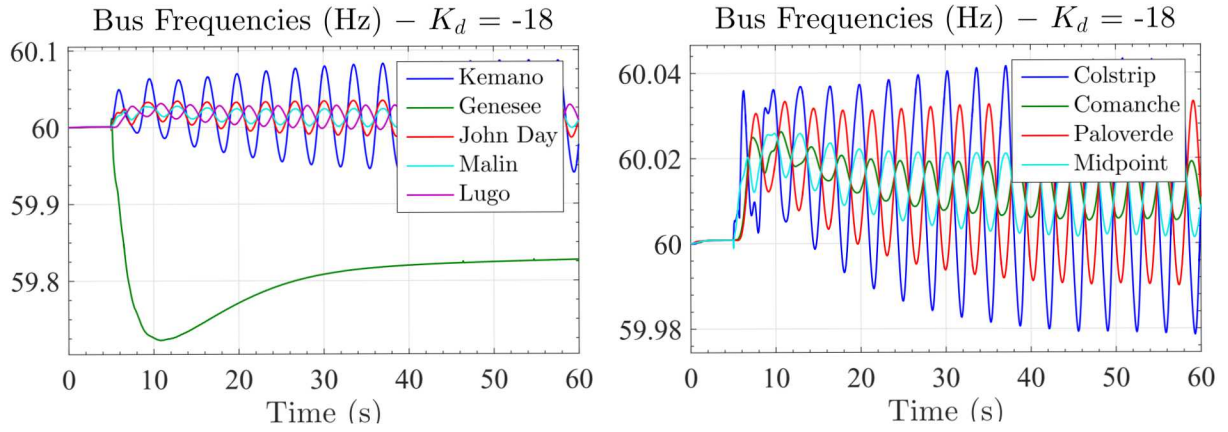
**Figure 46. Bus frequencies. Event: BC-AB Separation**



**Figure 47. Bus frequencies. Event: BC-AB Separation**

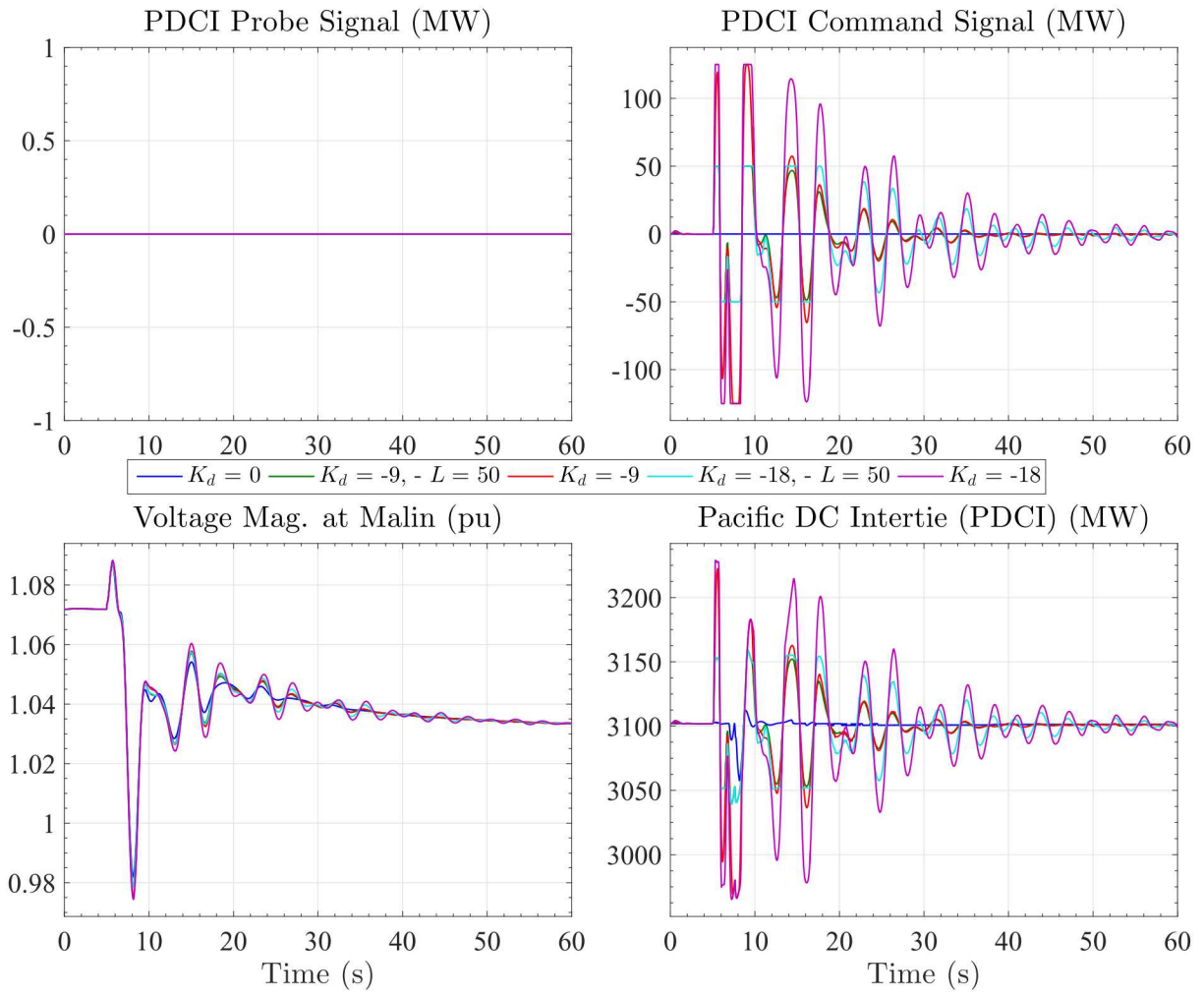


**Figure 48. Bus frequencies. Event: BC-AB Separation**

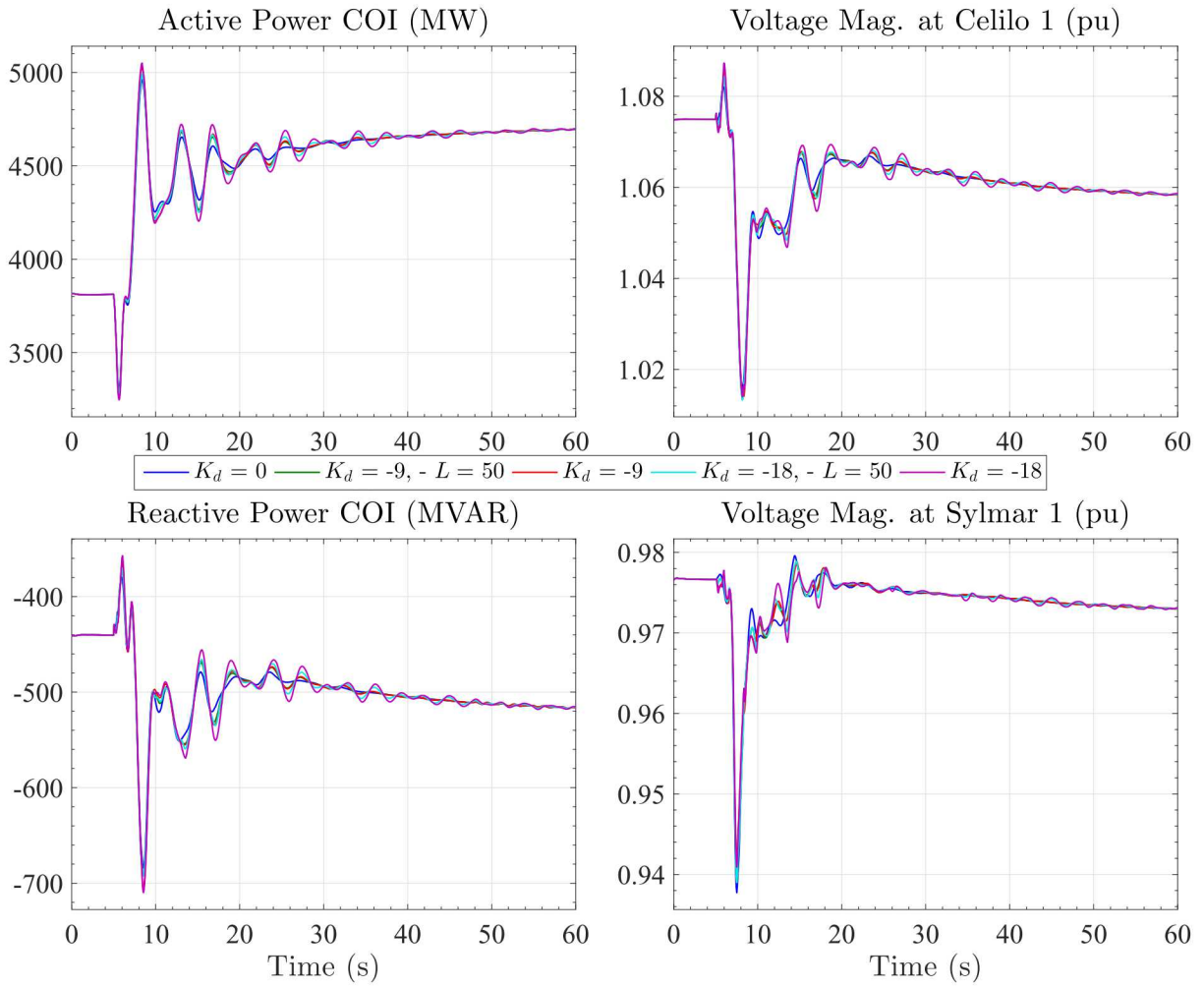


**Figure 49. Bus frequencies. Event: BC-AB Separation**

## 2.5. Test System: Heavy Summer 2016. Event: CJB + 2PV

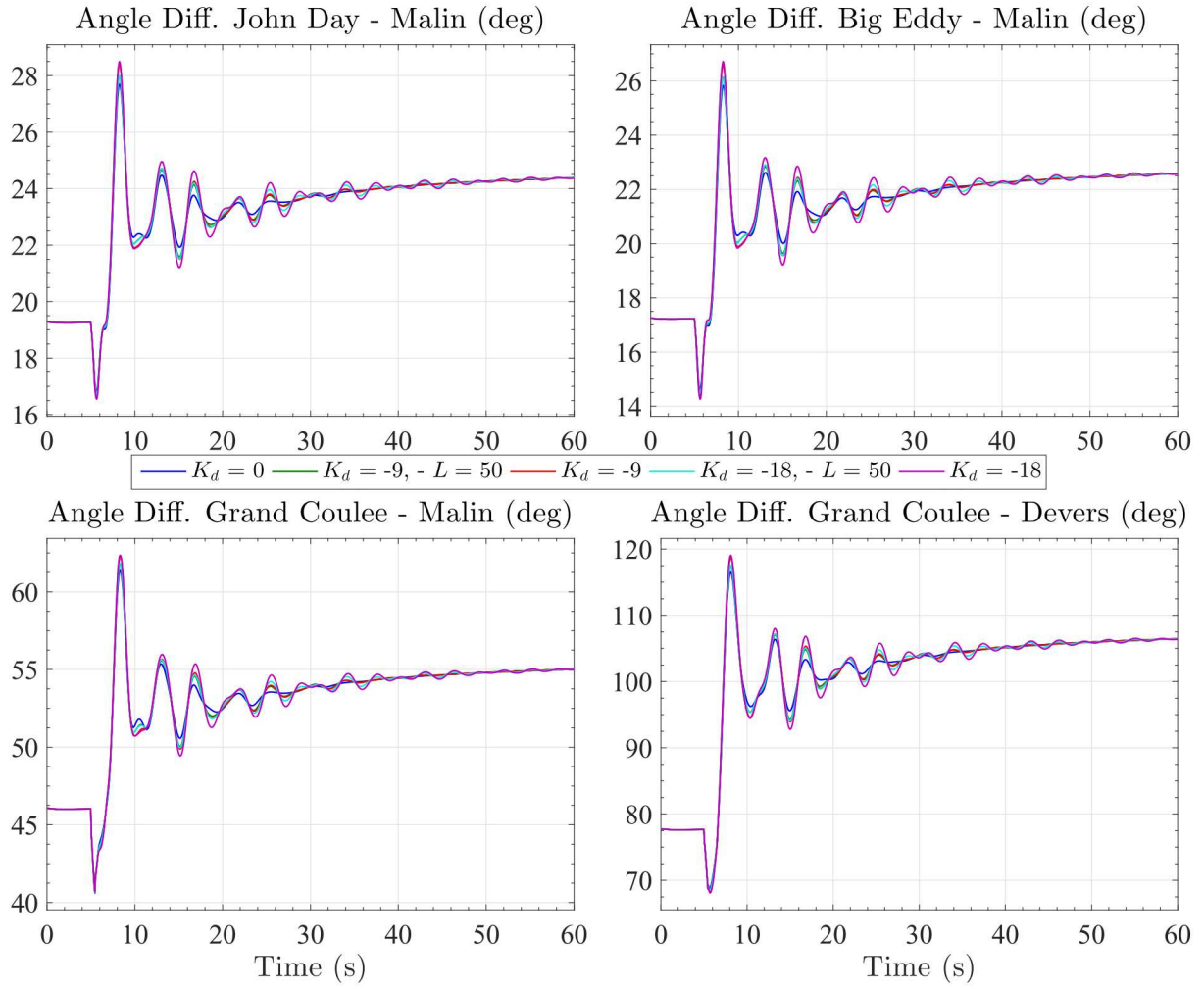


**Figure 50. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + 2PV**

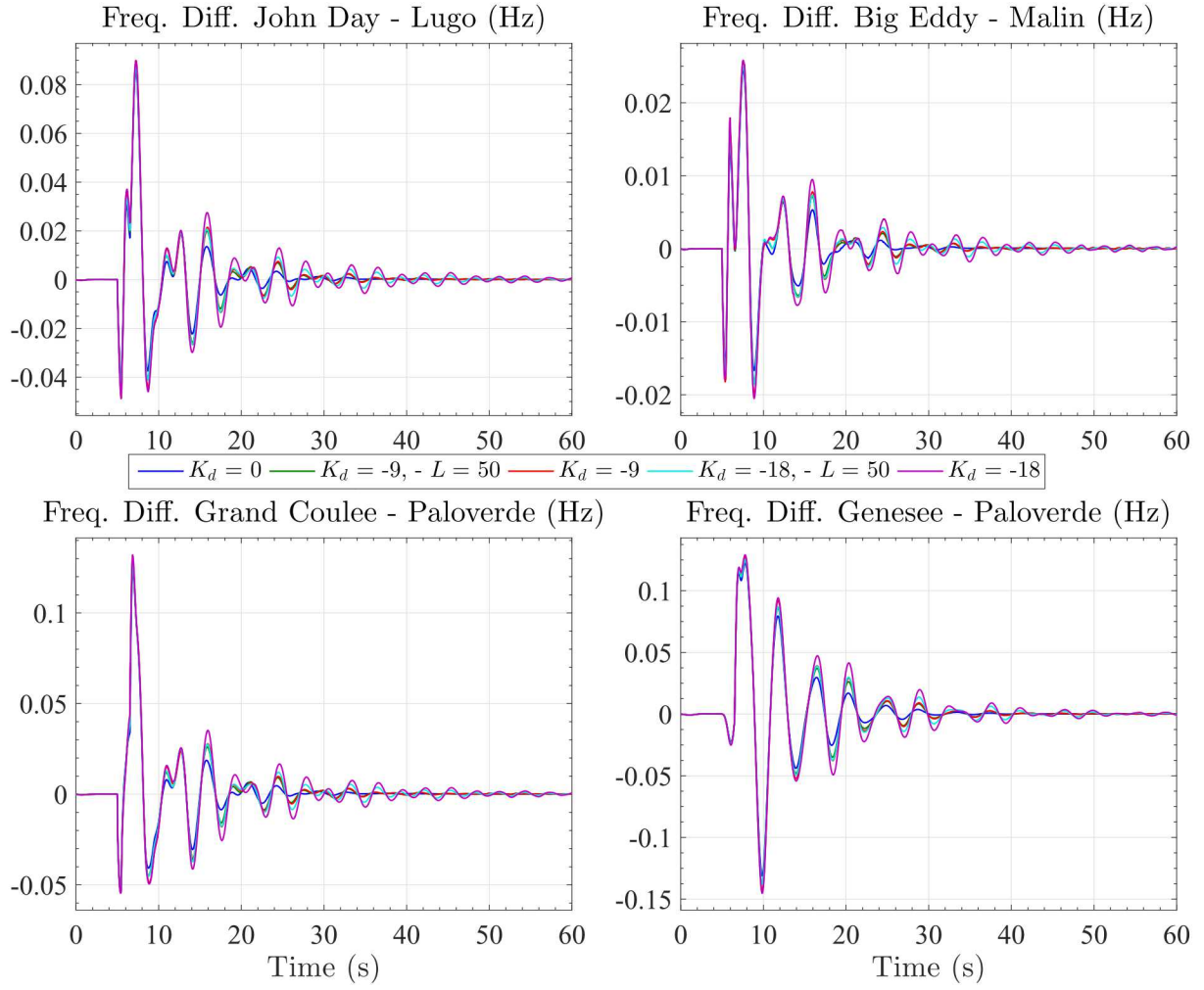


**Figure 51. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + 2PV**

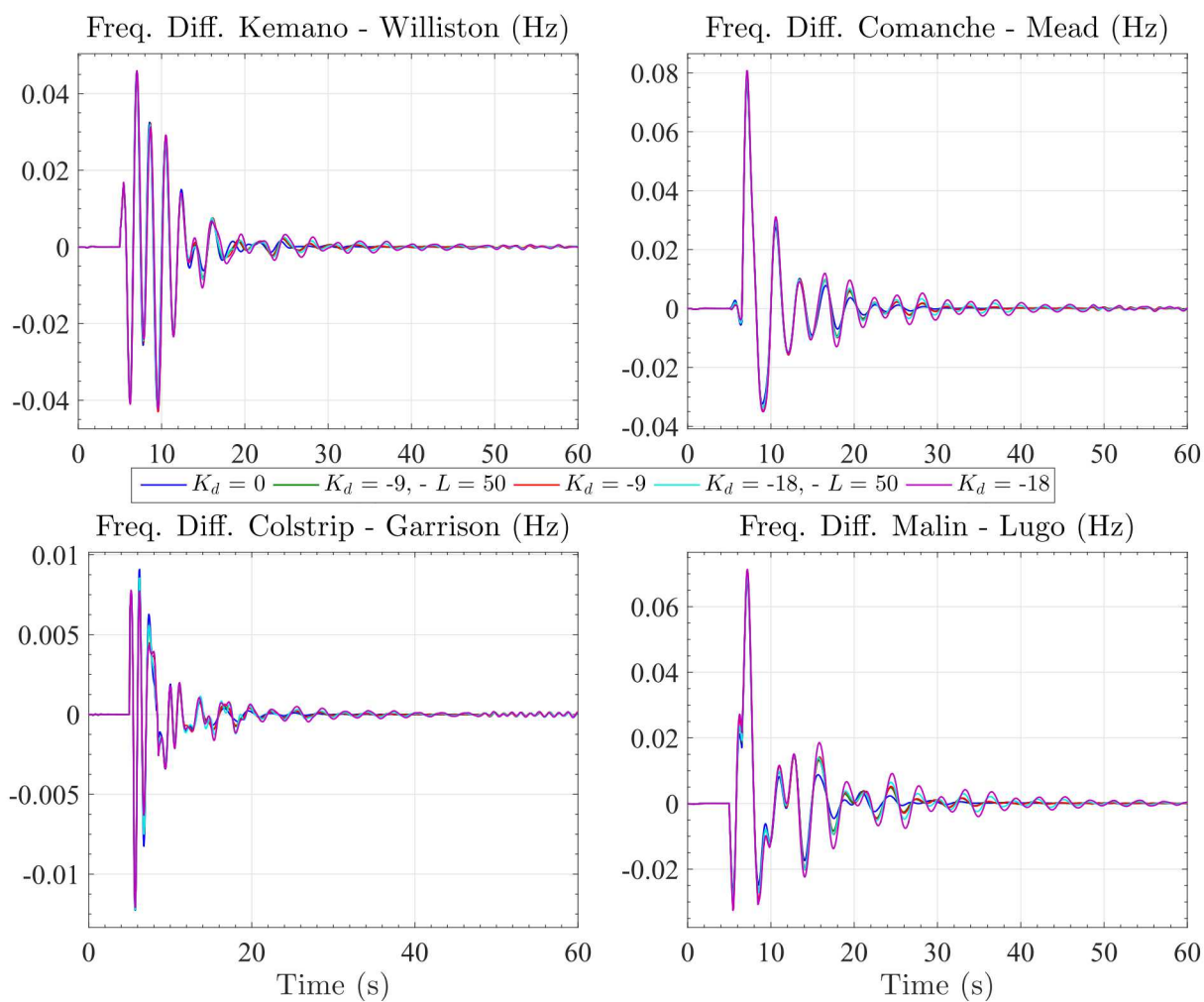




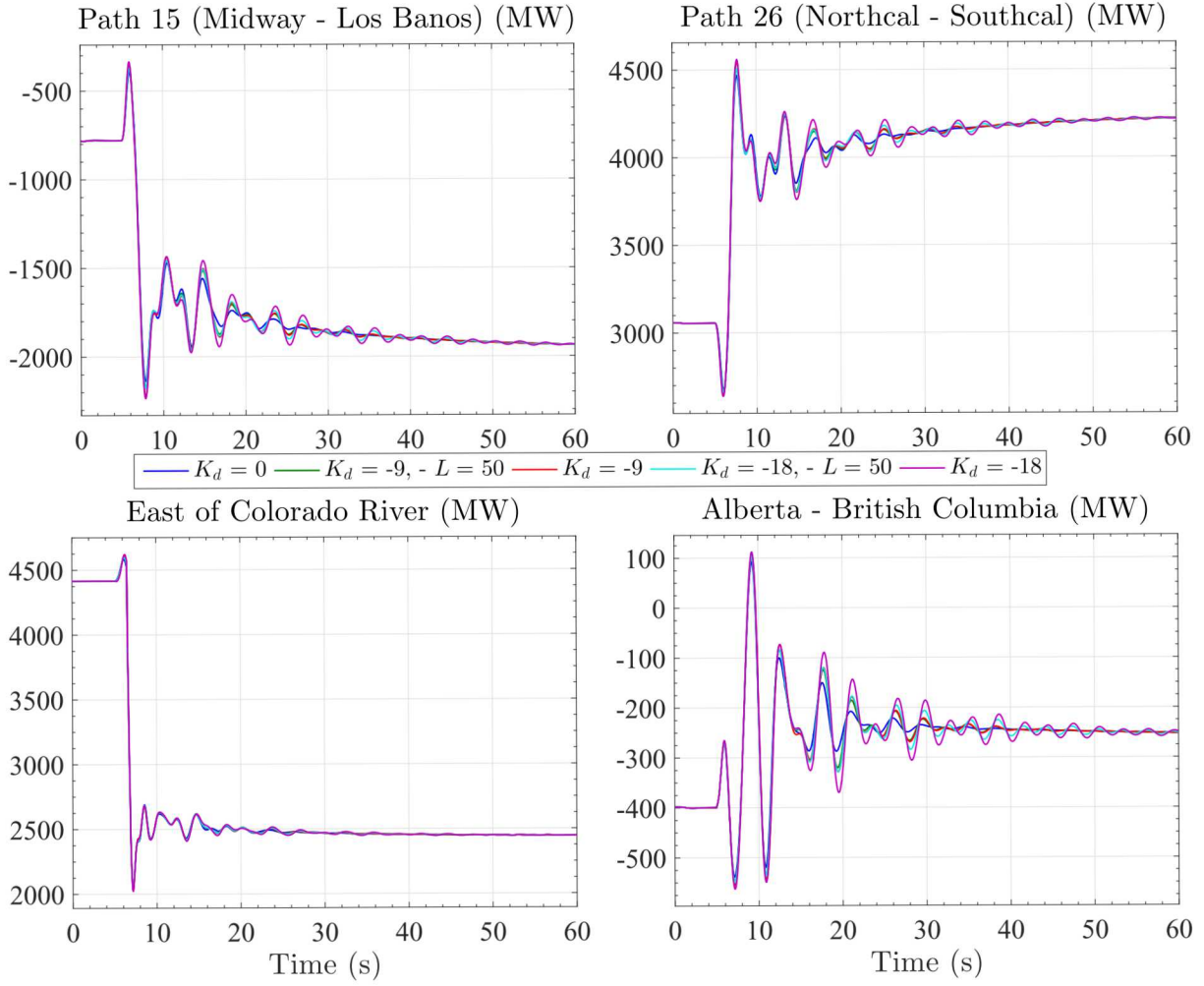
**Figure 52. Angle differences. Event: CJB + 2PV**



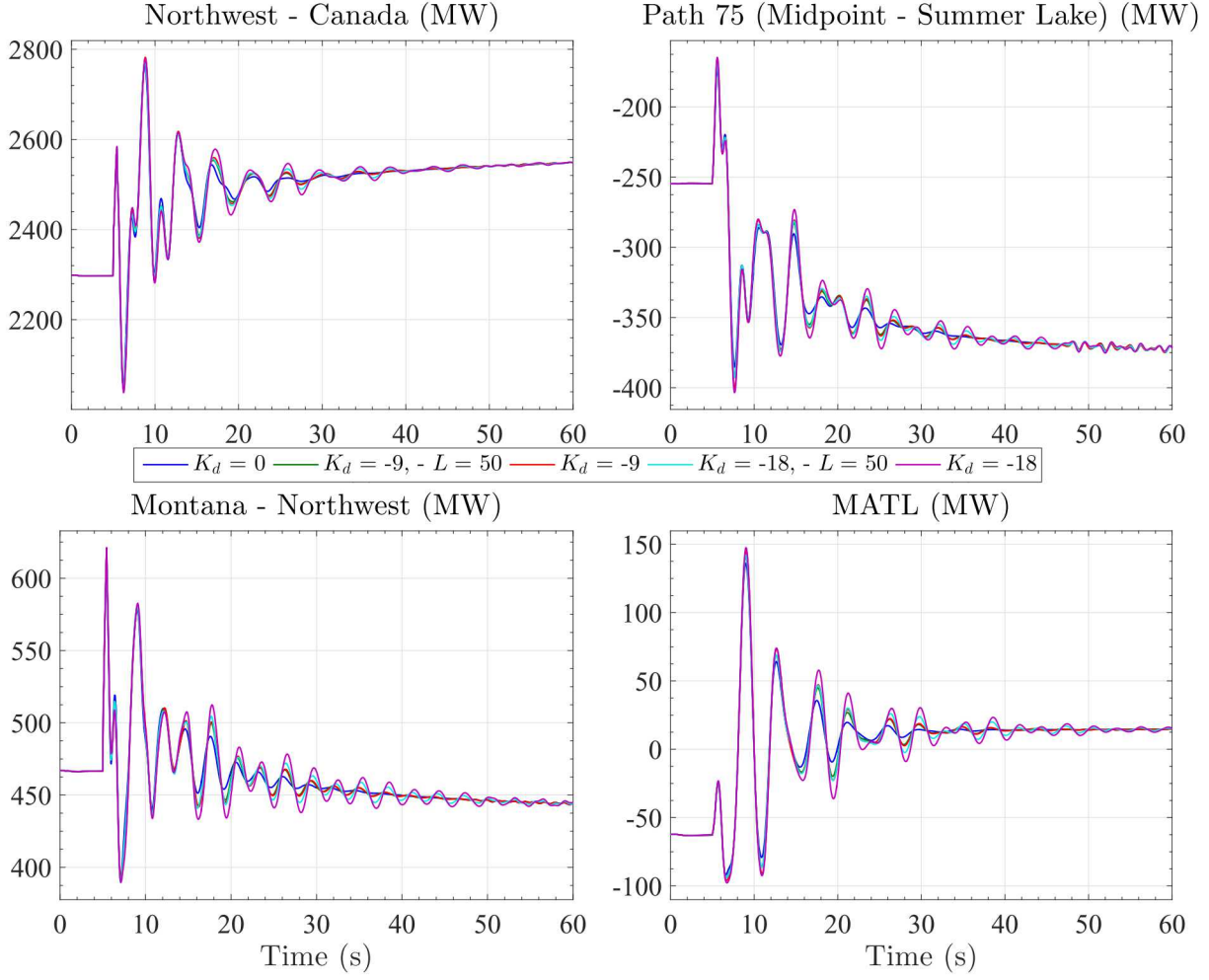
**Figure 53. Frequency differences. Event: CJB + 2PV**



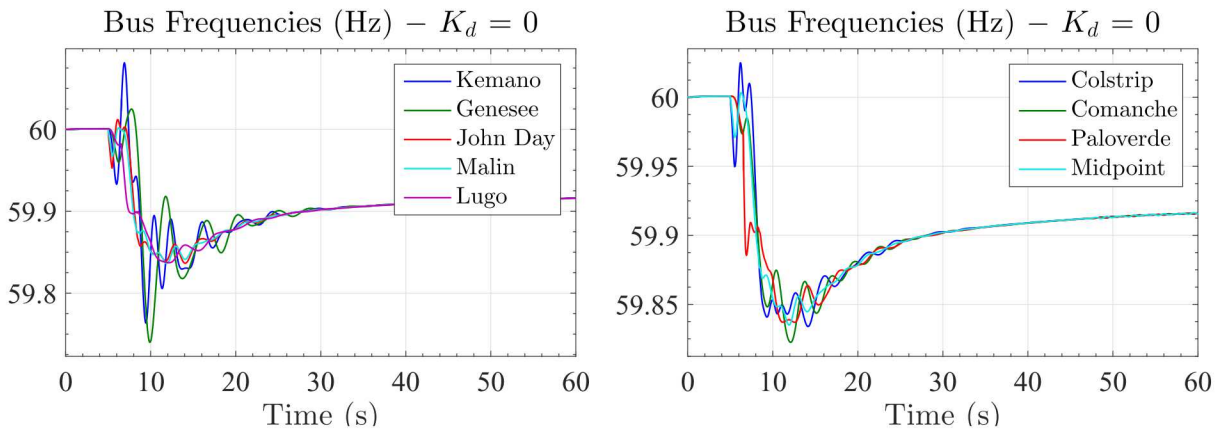
**Figure 54. Frequency differences. Event: CJB + 2PV**



**Figure 55. Active power flows. Event: CJB + 2PV**

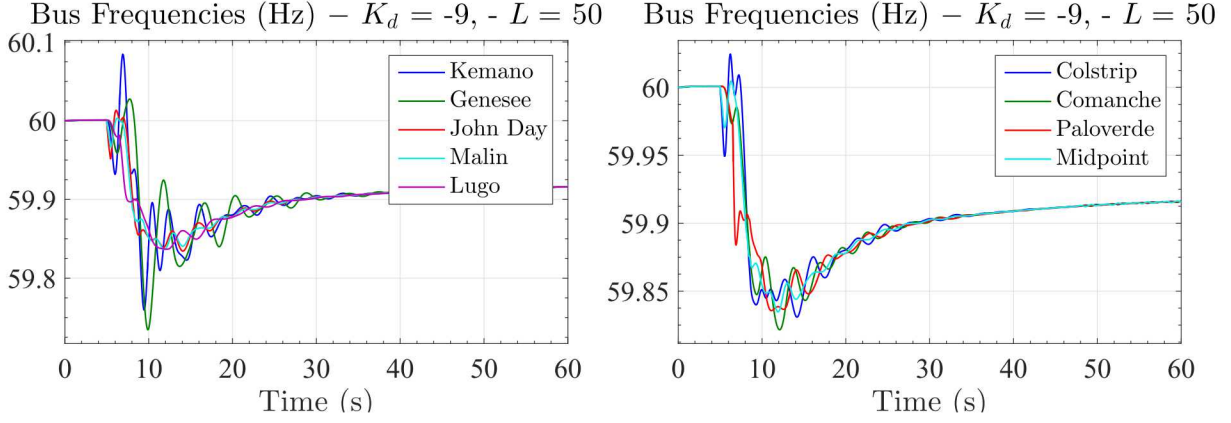


**Figure 56. Active power flows. Event: CJB + 2PV**

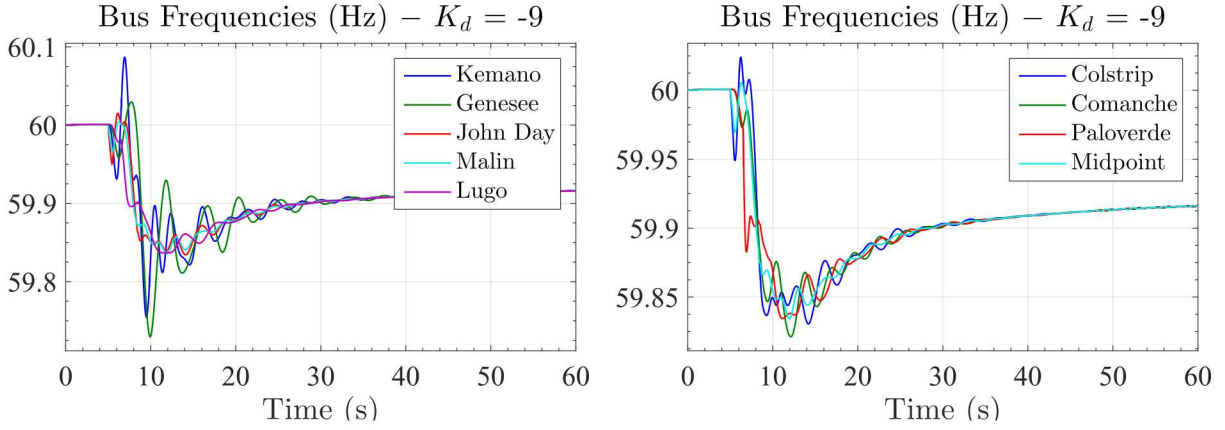


**Figure 57. Bus frequencies. Event: CJB + 2PV**

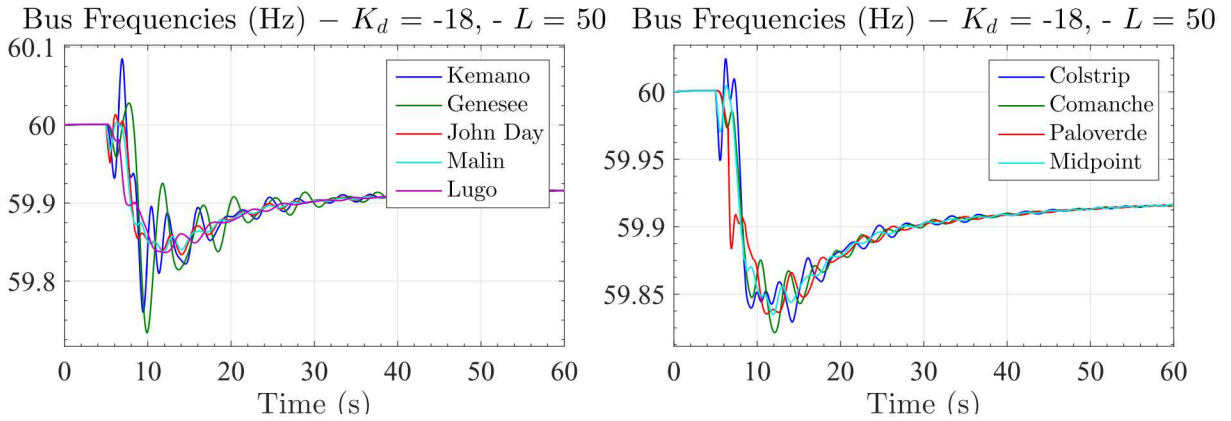




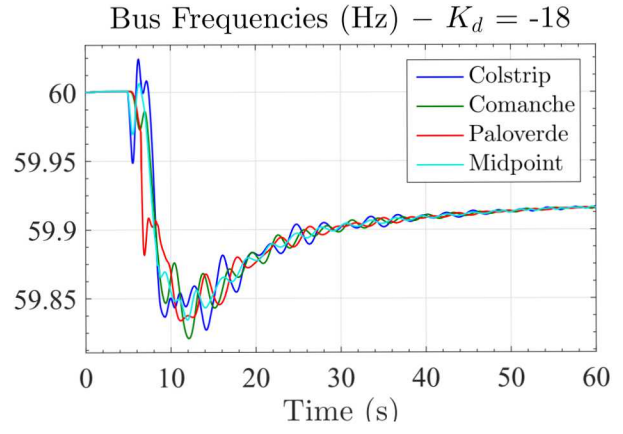
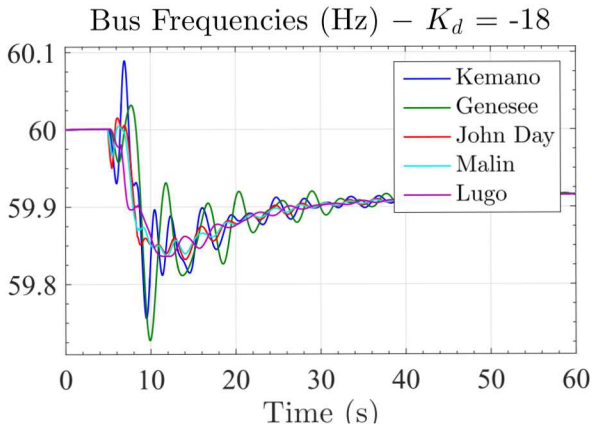
**Figure 58. Bus frequencies. Event: CJB + 2PV**



**Figure 59. Bus frequencies. Event: CJB + 2PV**

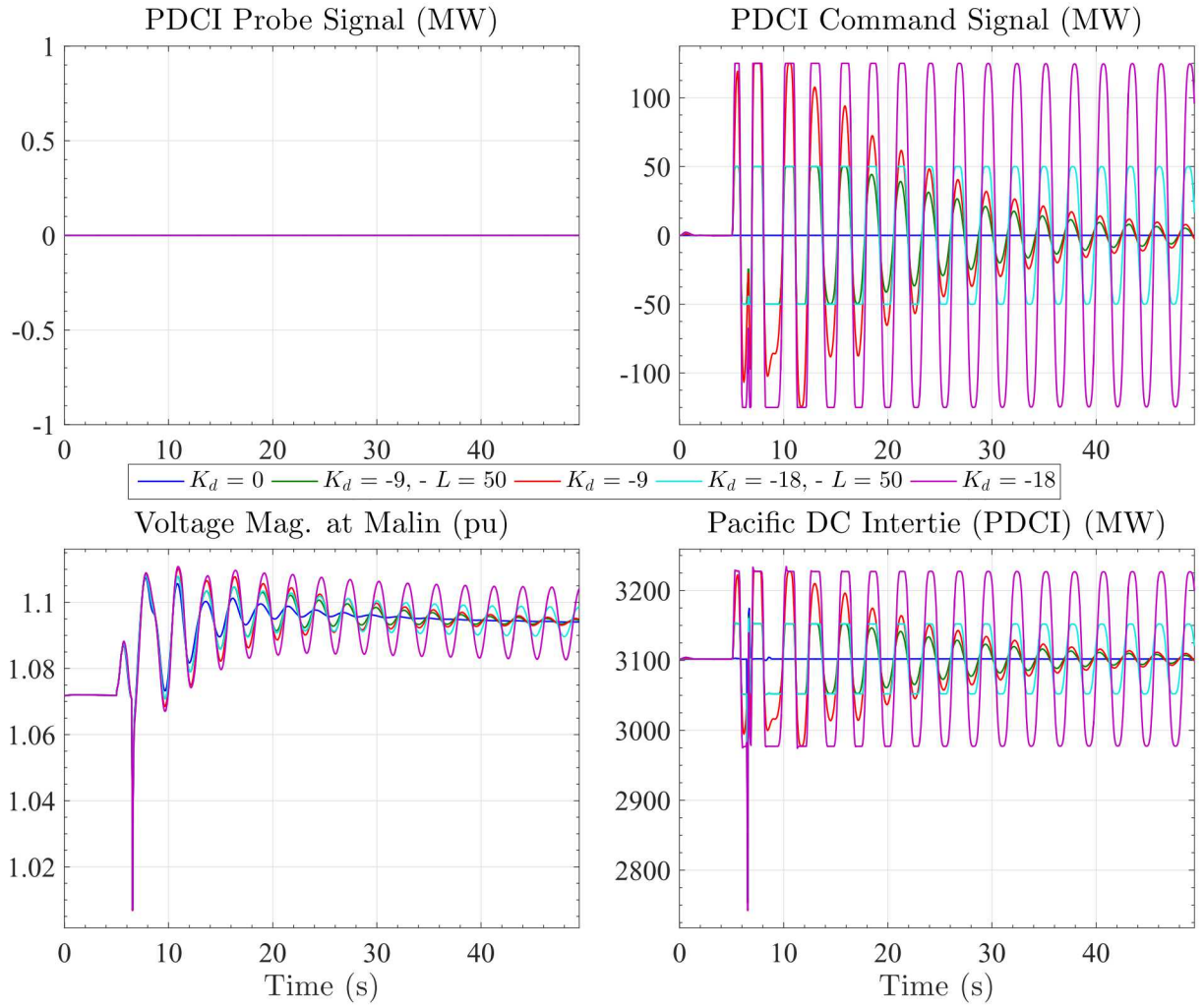


**Figure 60. Bus frequencies. Event: CJB + 2PV**

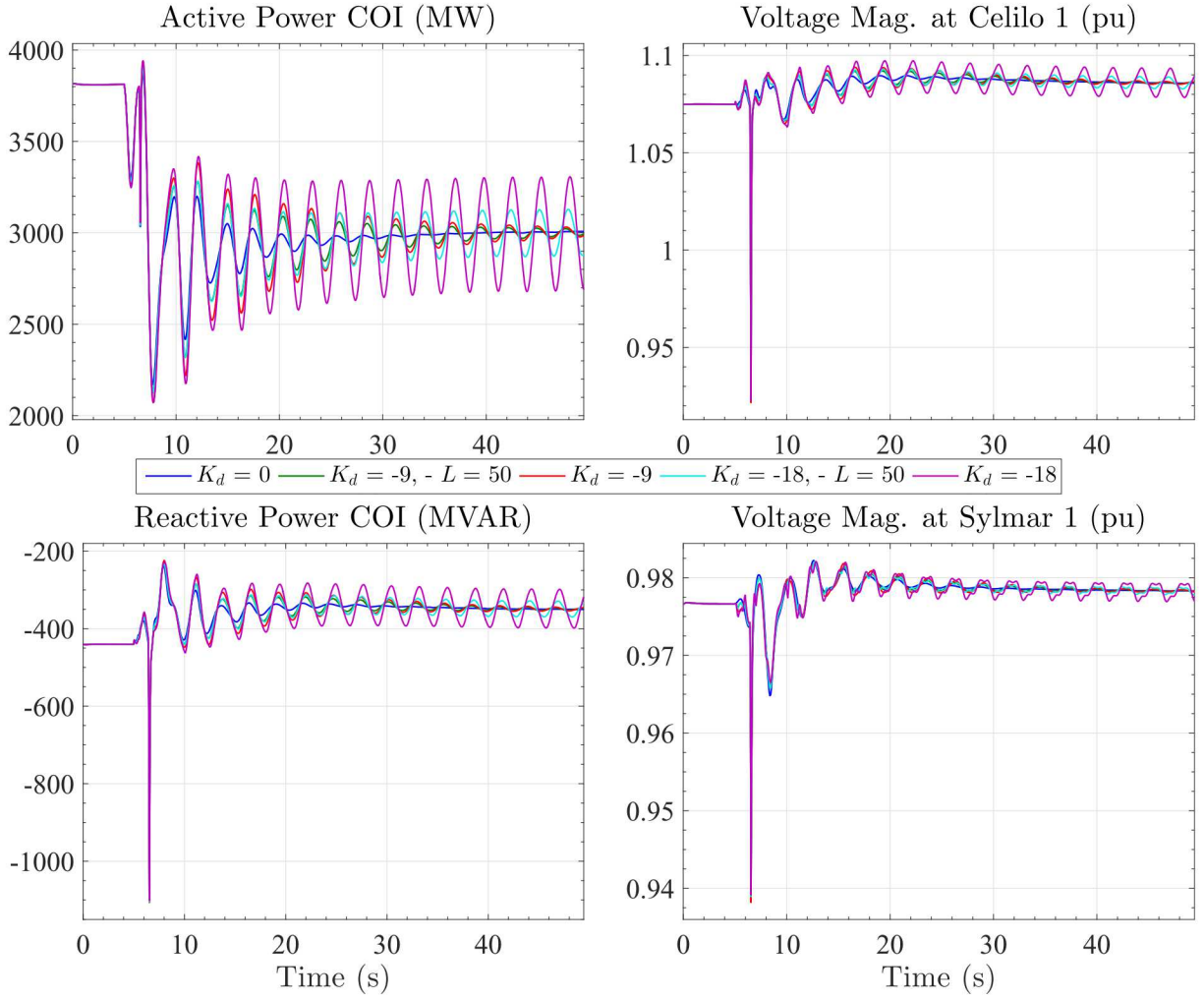


**Figure 61. Bus frequencies. Event: CJB + 2PV**

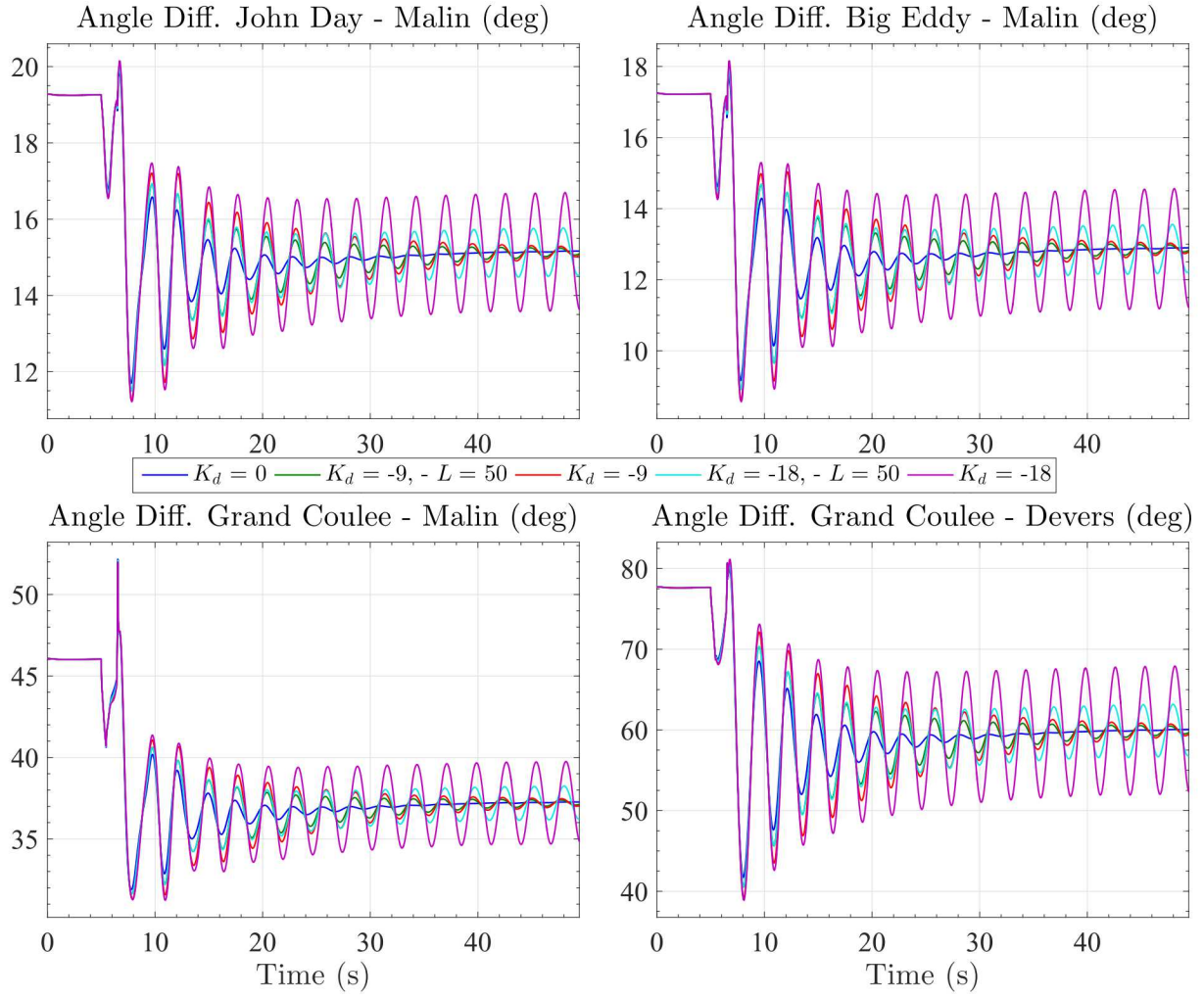
## 2.6. Test System: Heavy Summer 2016. Event: CJB + BCUS Separation



**Figure 62. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCUS Separation**

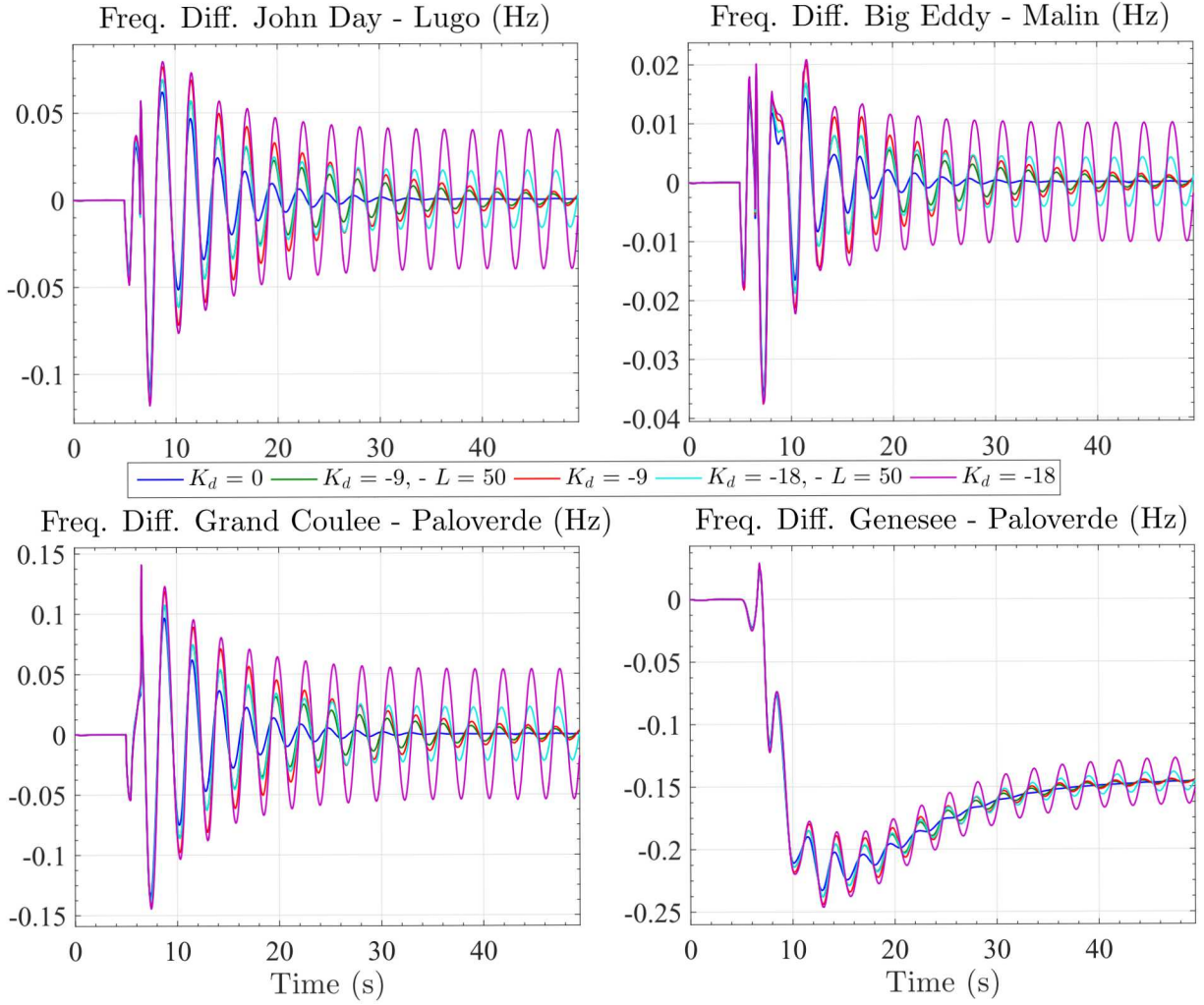


**Figure 63. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCUS Separation**

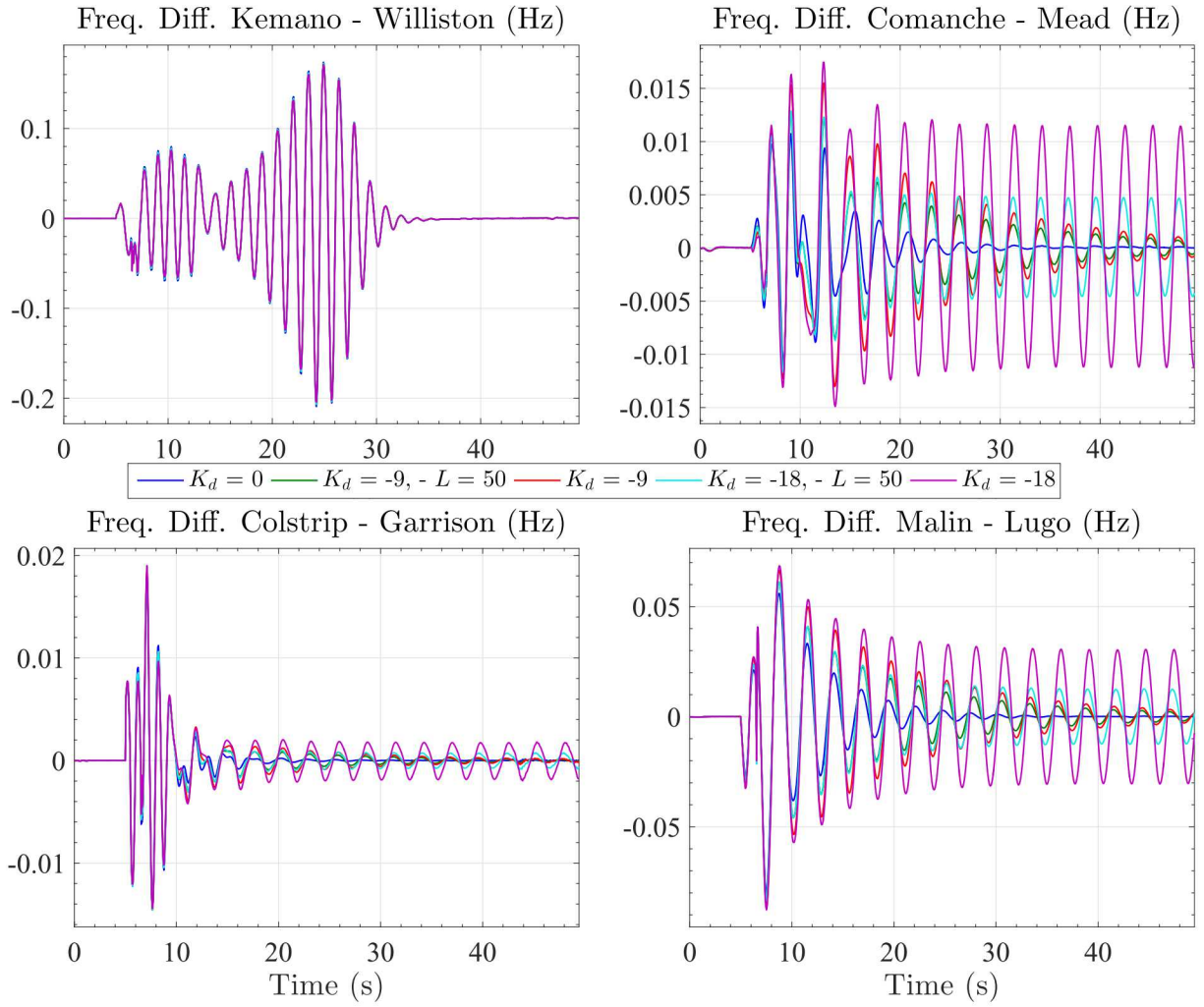


**Figure 64. Angle differences. Event: CJB + BCUS Separation**

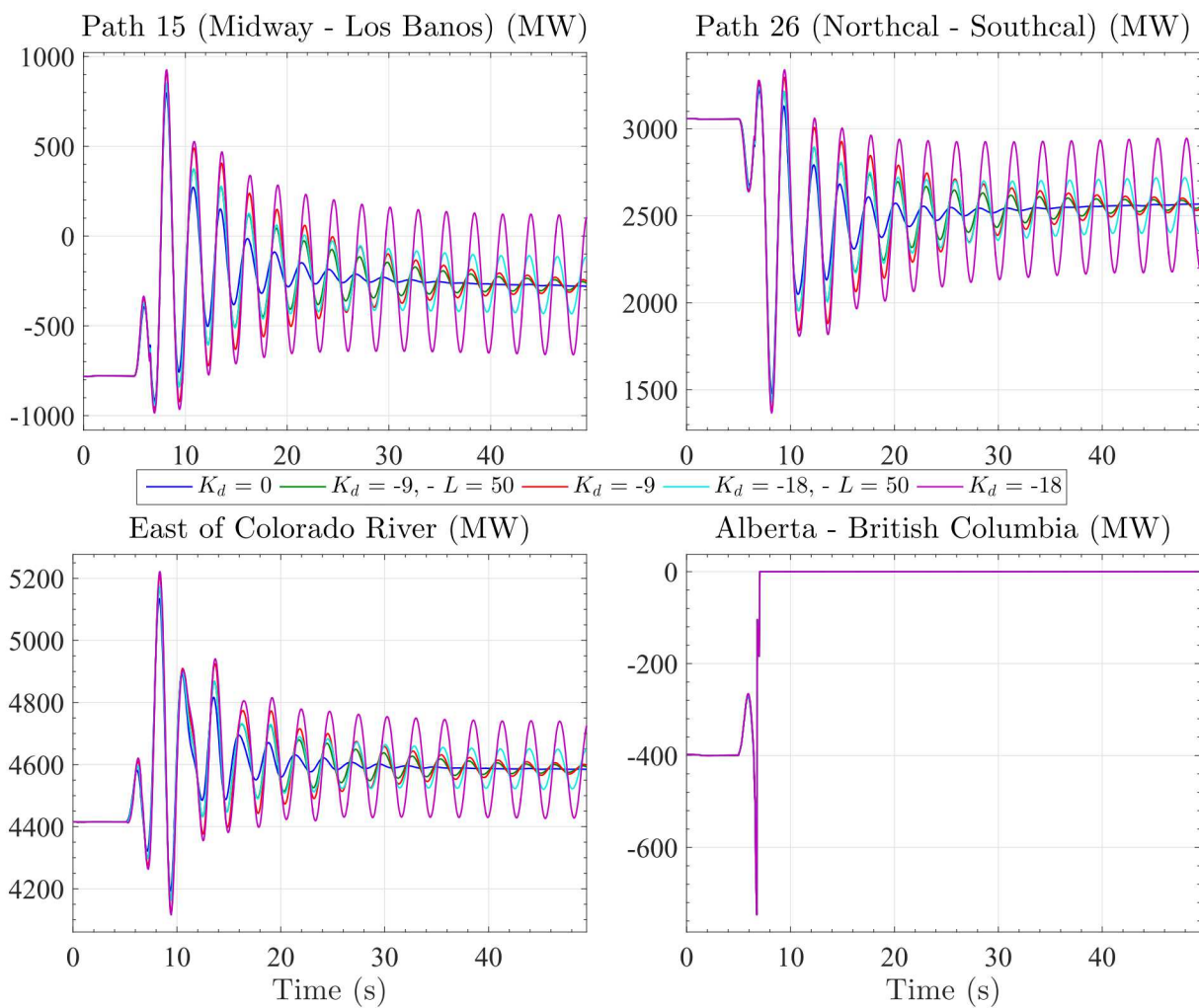




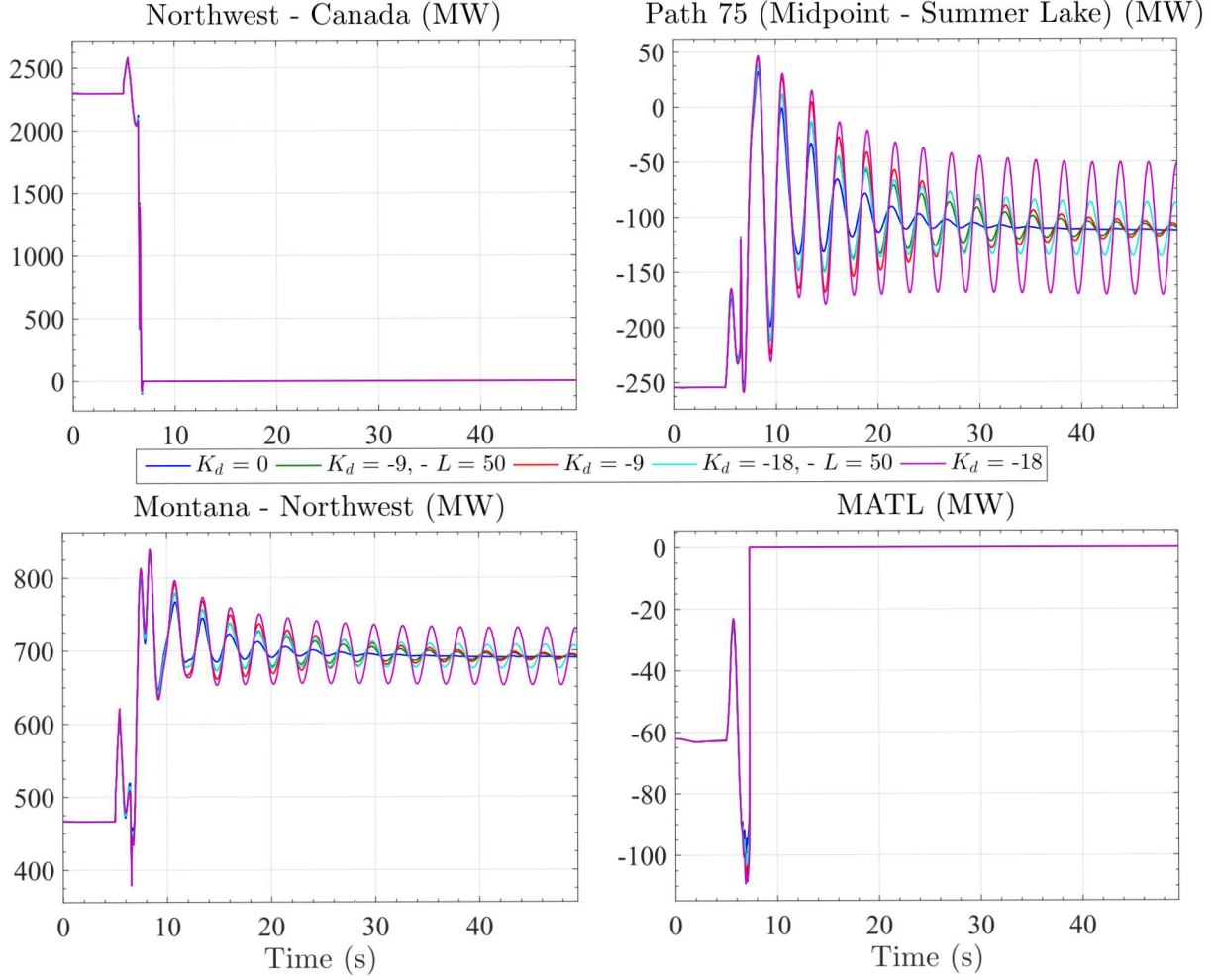
**Figure 65. Frequency differences. Event: CJB + BCUS Separation**



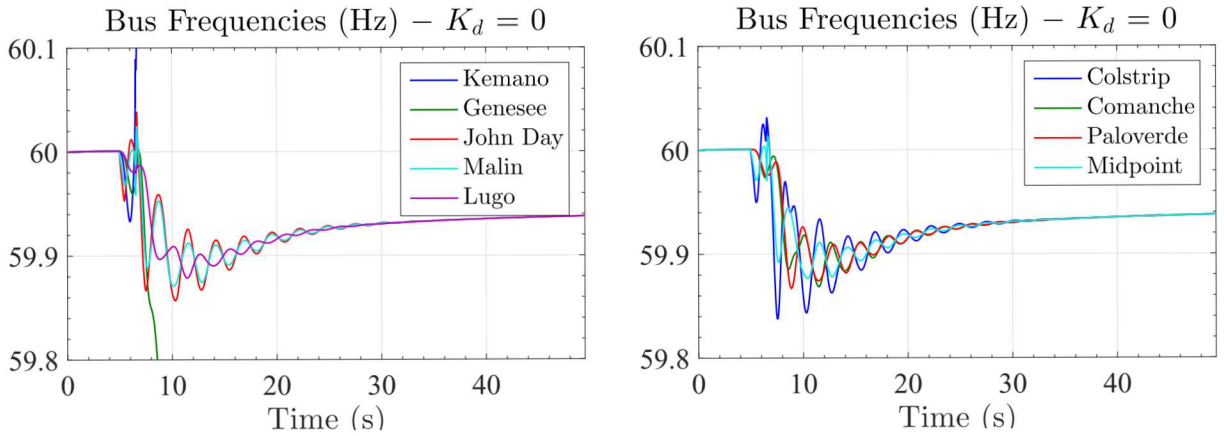
**Figure 66. Frequency differences. Event: CJB + BCUS Separation**



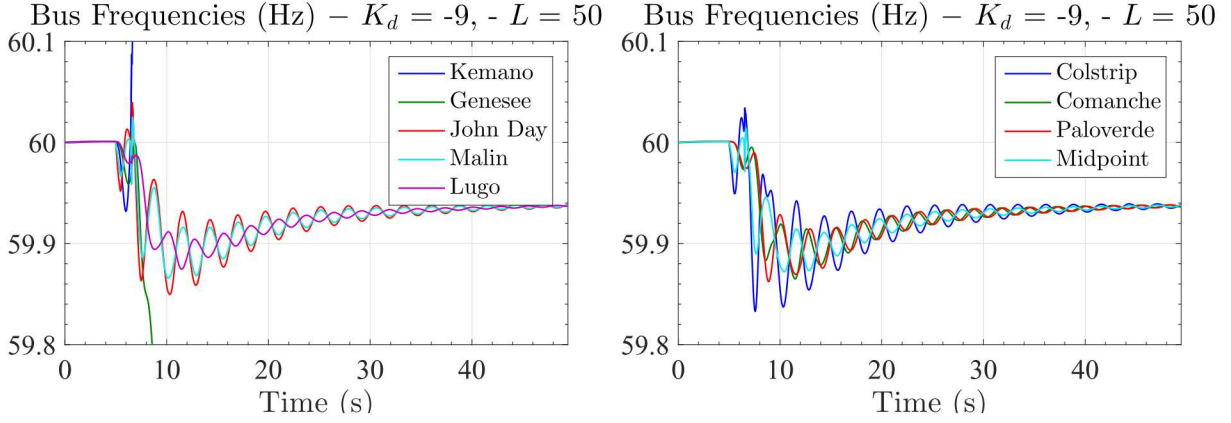
**Figure 67. Active power flows. Event: CJB + BCUS Separation**



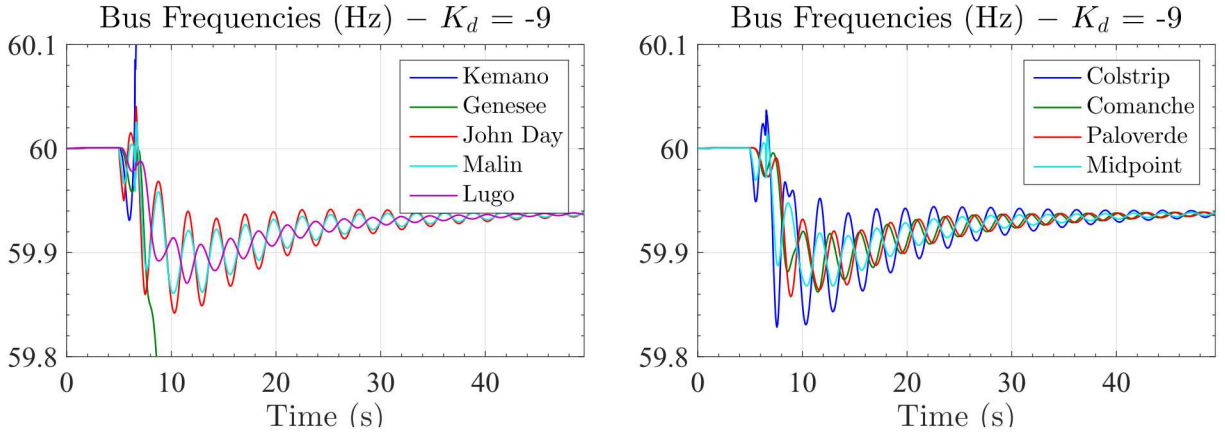
**Figure 68. Active power flows. Event: CJB + BCUS Separation**



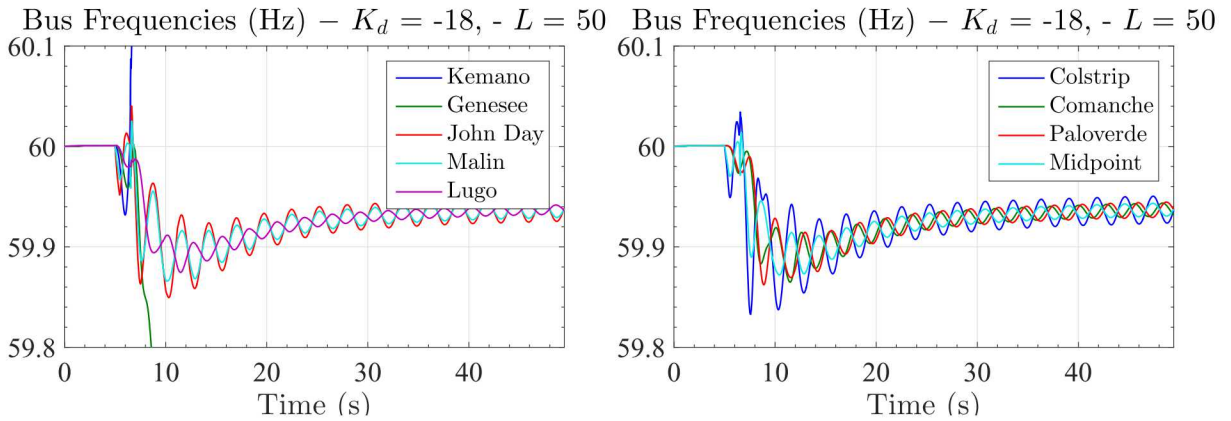
**Figure 69. Bus frequencies. Event: CJB + BCUS Separation**



**Figure 70. Bus frequencies. Event: CJB + BCUS Separation**

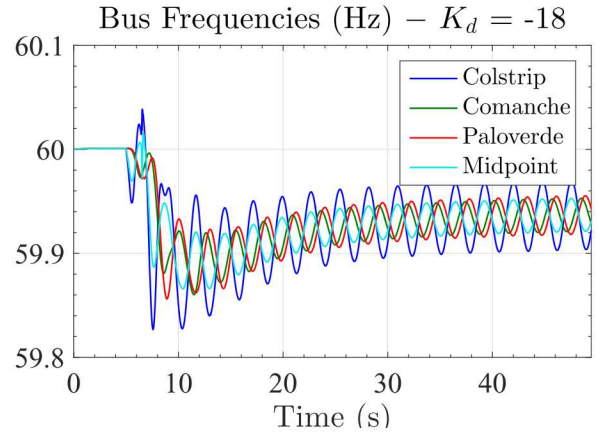
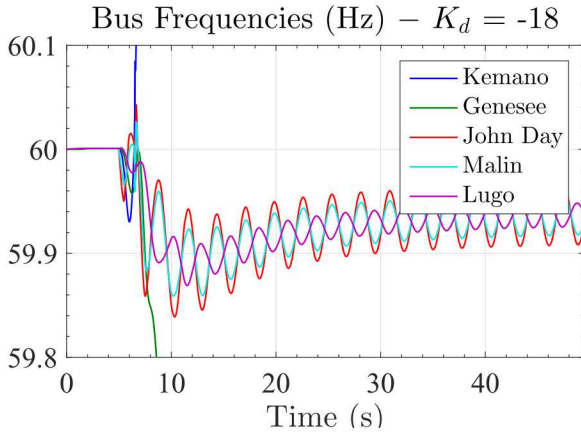


**Figure 71. Bus frequencies. Event: CJB + BCUS Separation**



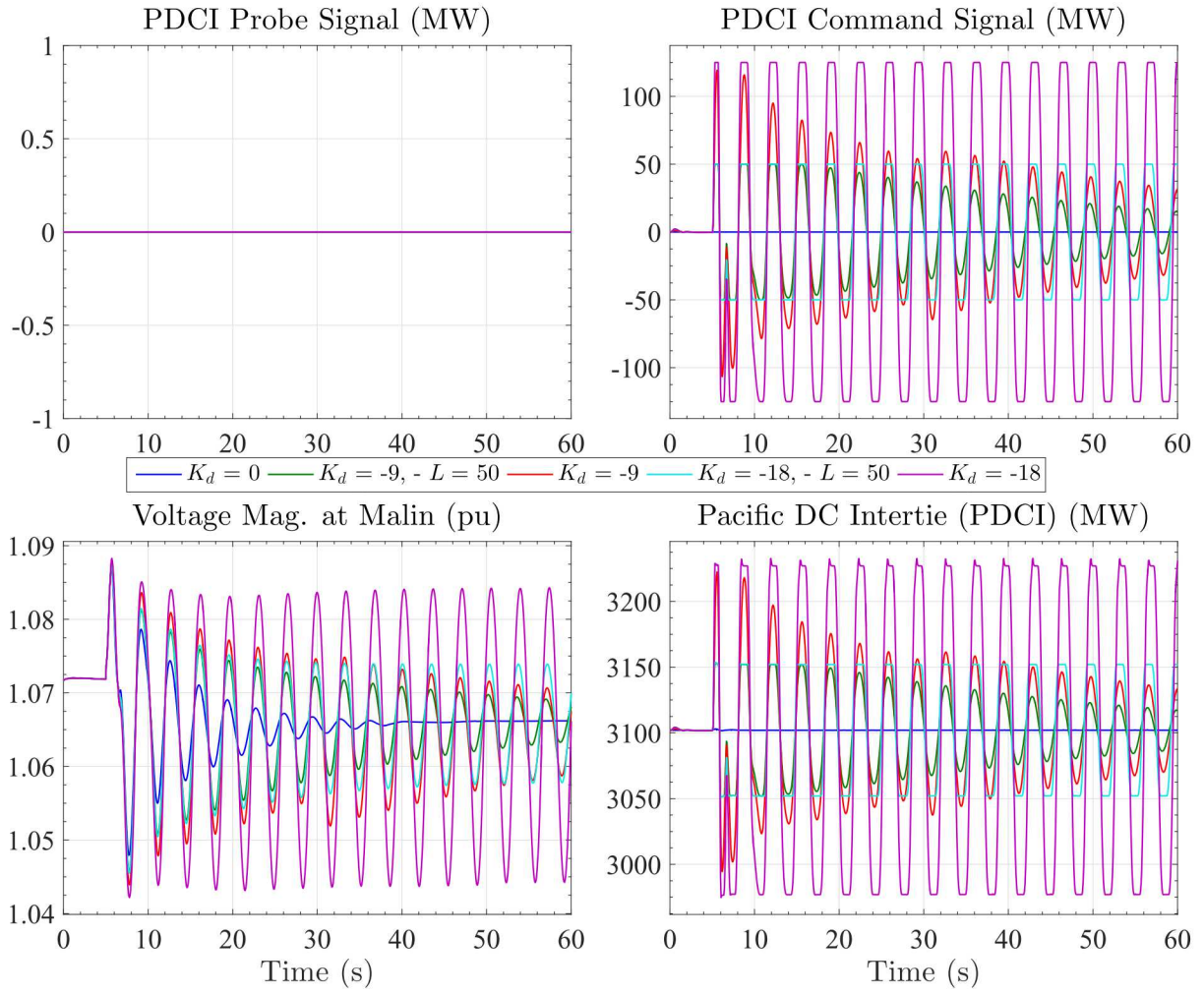
**Figure 72. Bus frequencies. Event: CJB + BCUS Separation**



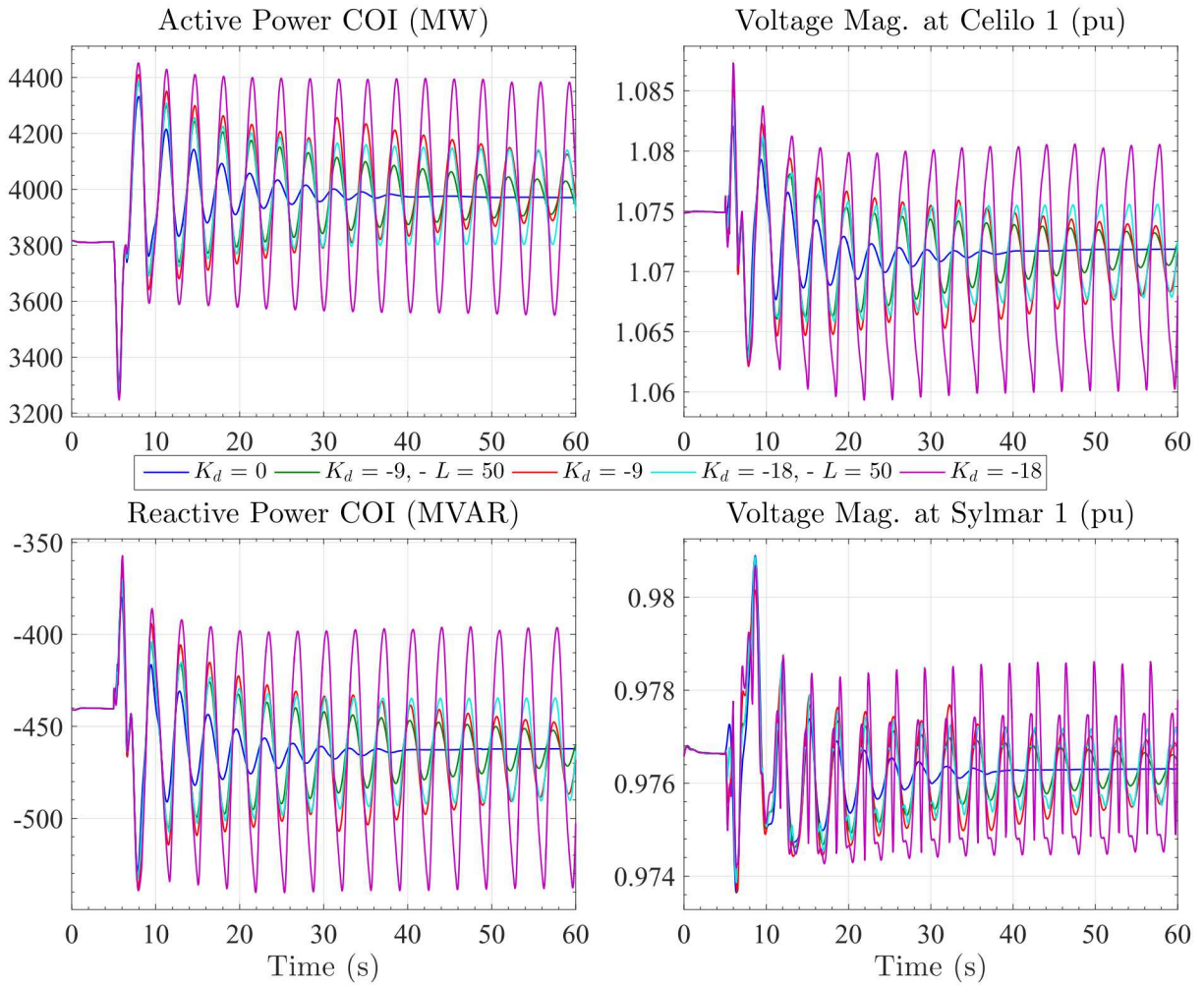


**Figure 73. Bus frequencies. Event: CJB + BCUS Separation**

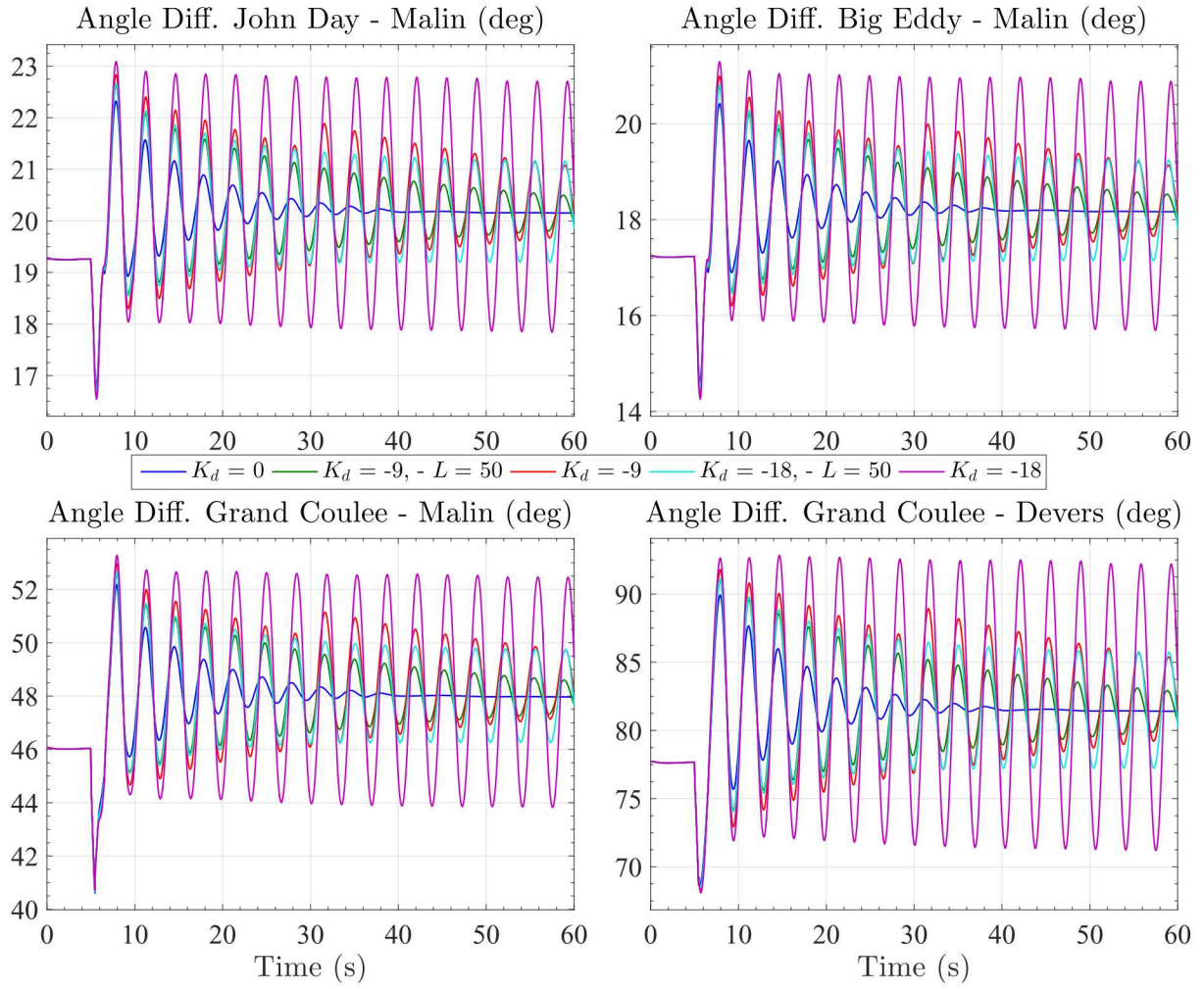
## 2.7. Test System: Heavy Summer 2016. Event: CJB + BCAB Separation



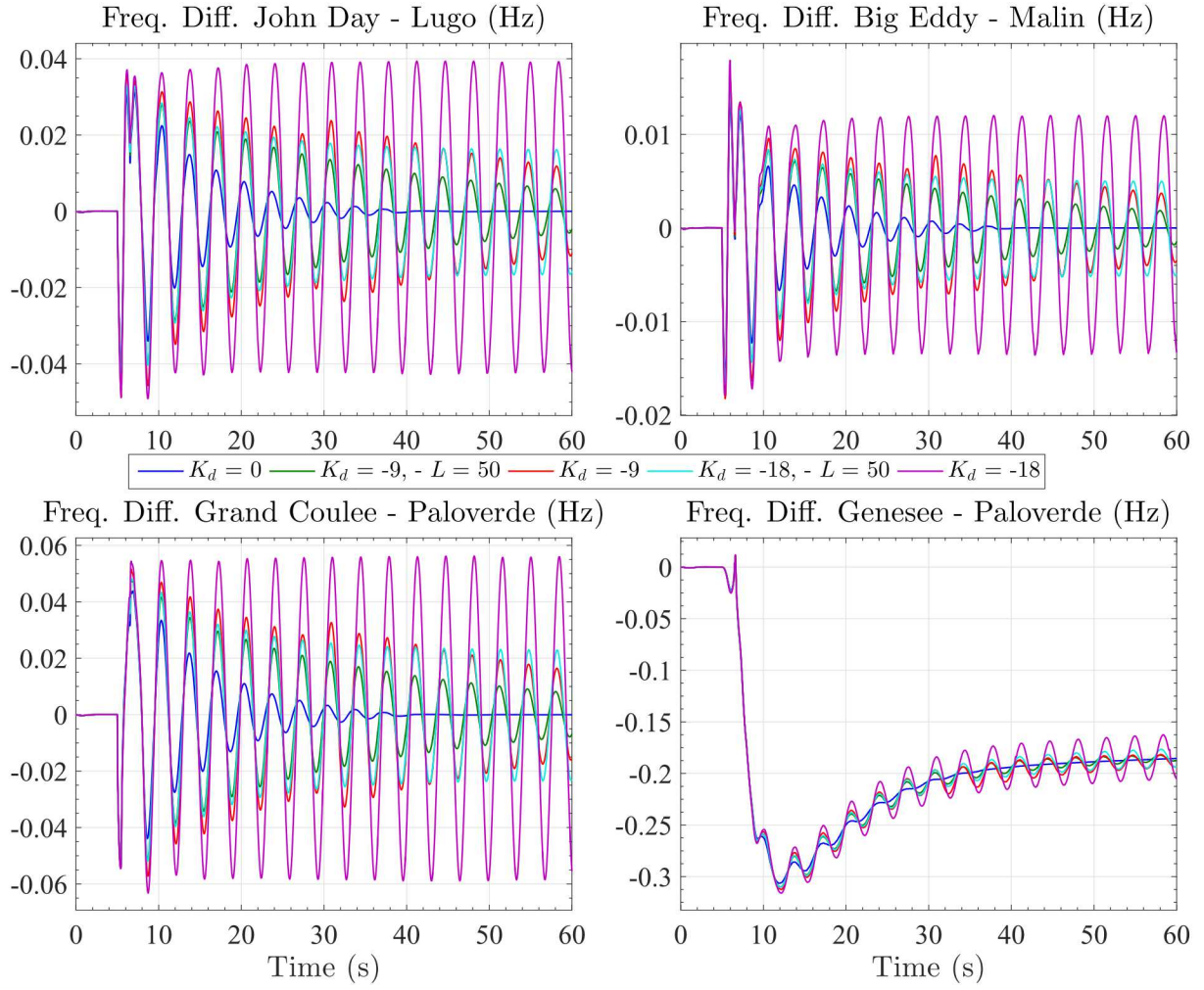
**Figure 74. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCAB Separation**



**Figure 75. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCAB Separation**

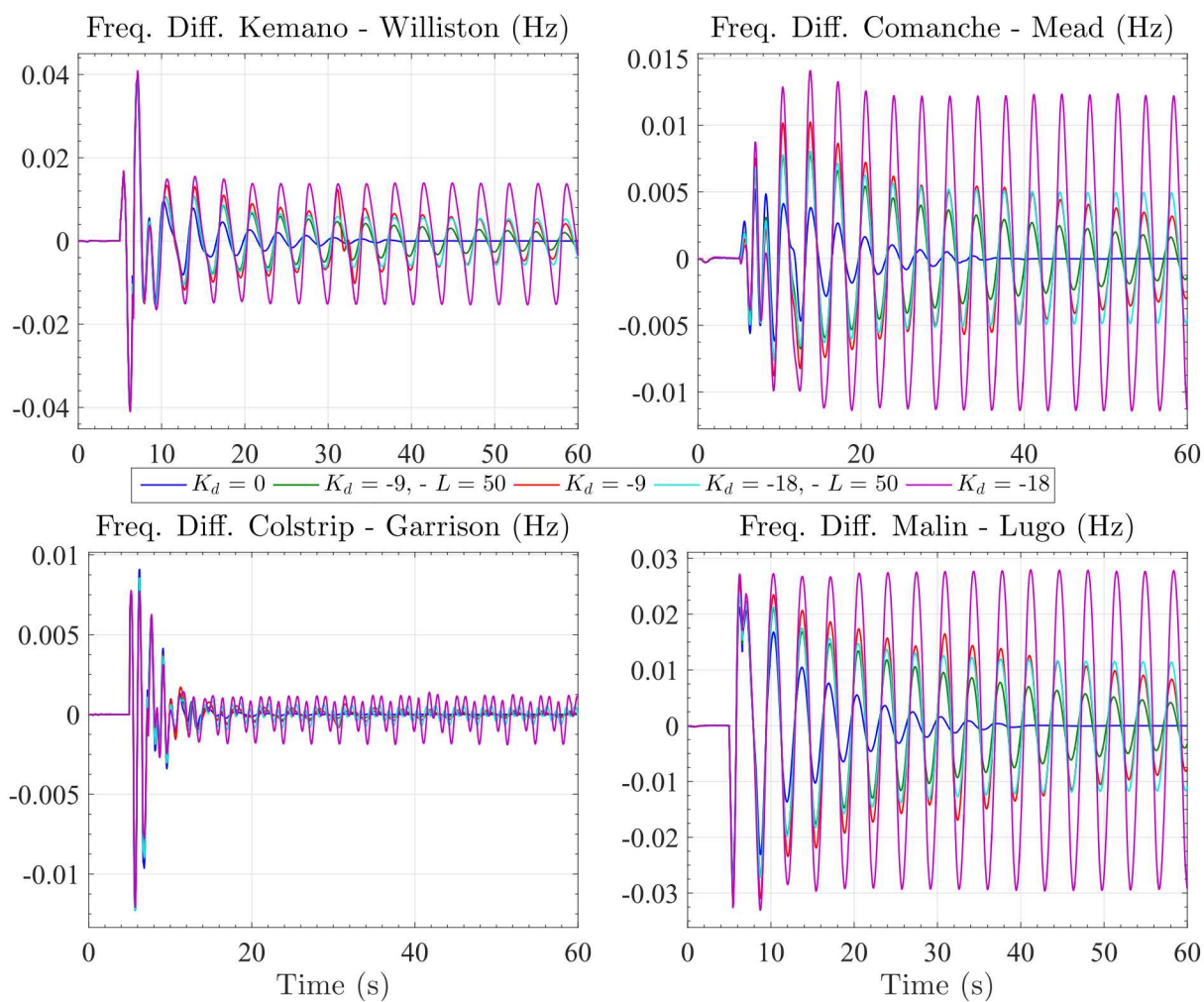


**Figure 76. Angle differences. Event: CJB + BCAB Separation**

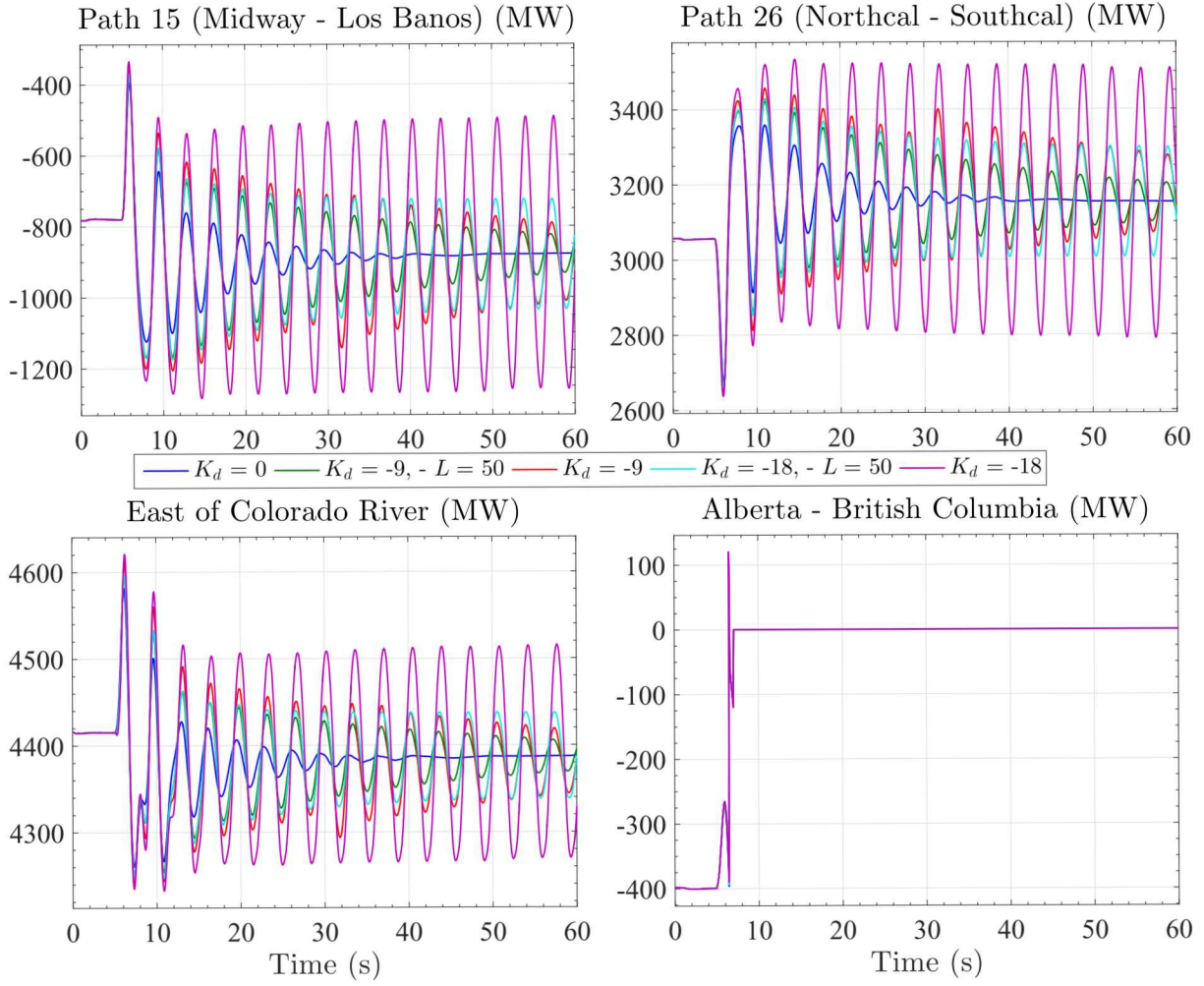


**Figure 77. Frequency differences. Event: CJB + BCAB Separation**

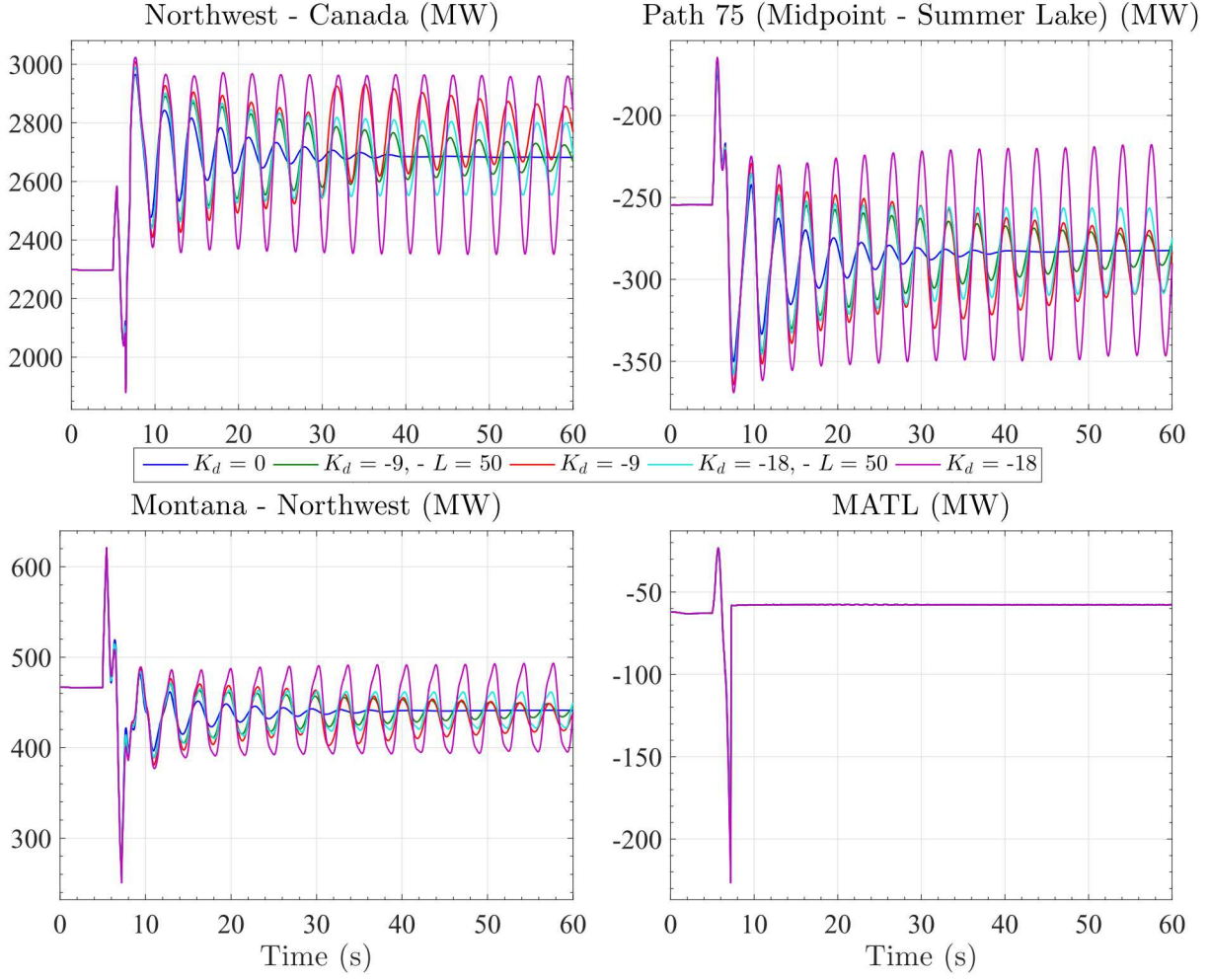




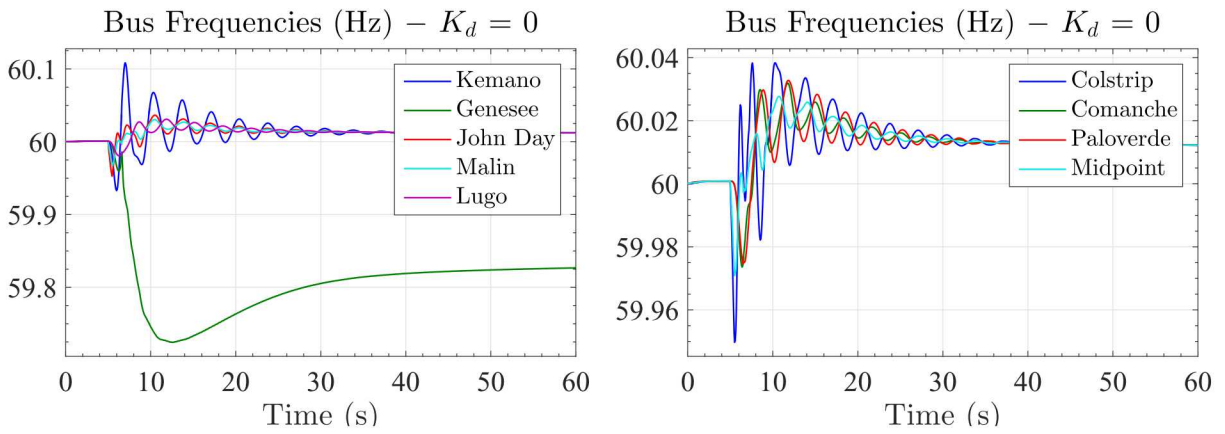
**Figure 78. Frequency differences. Event: CJB + BCAB Separation**



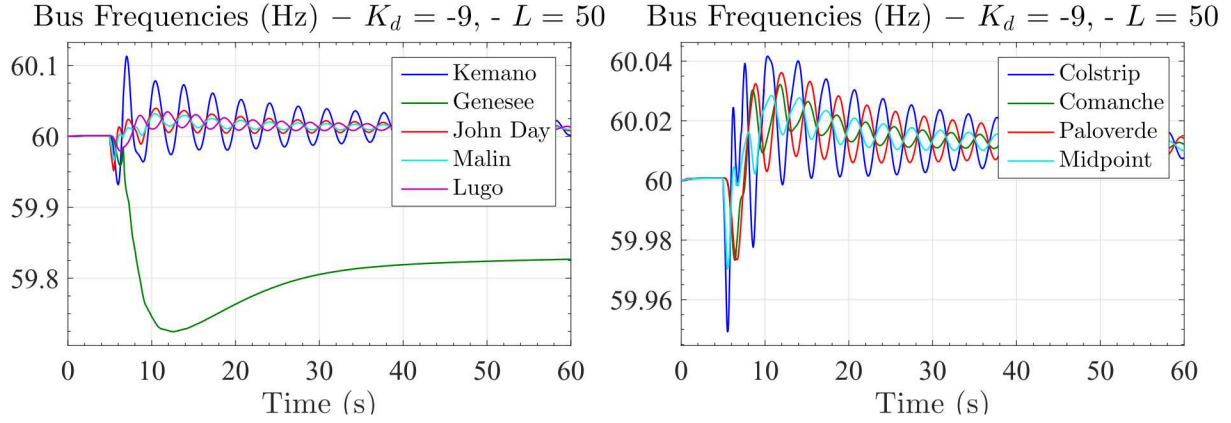
**Figure 79. Active power flows. Event: CJB + BCAB Separation**



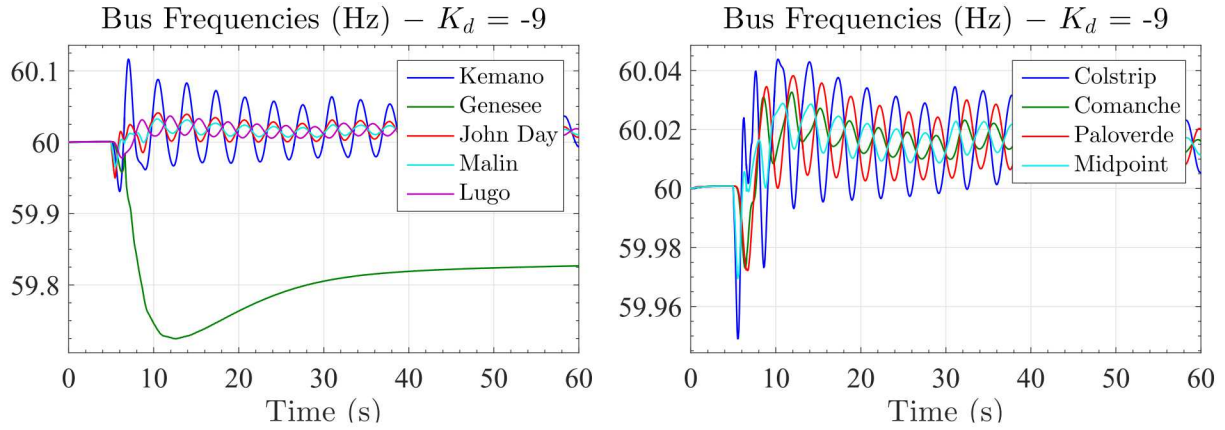
**Figure 80. Active power flows. Event: CJB + BCAB Separation**



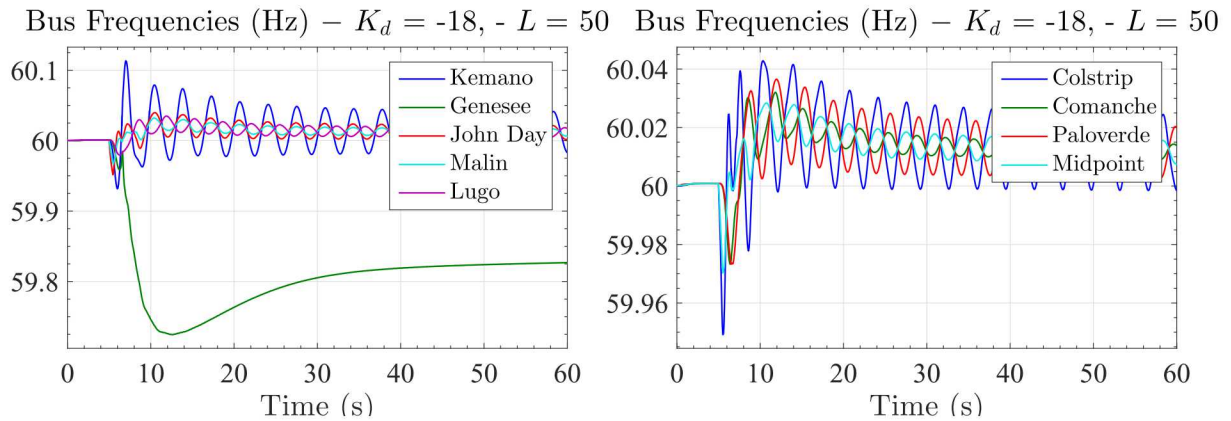
**Figure 81. Bus frequencies. Event: CJB + BCAB Separation**



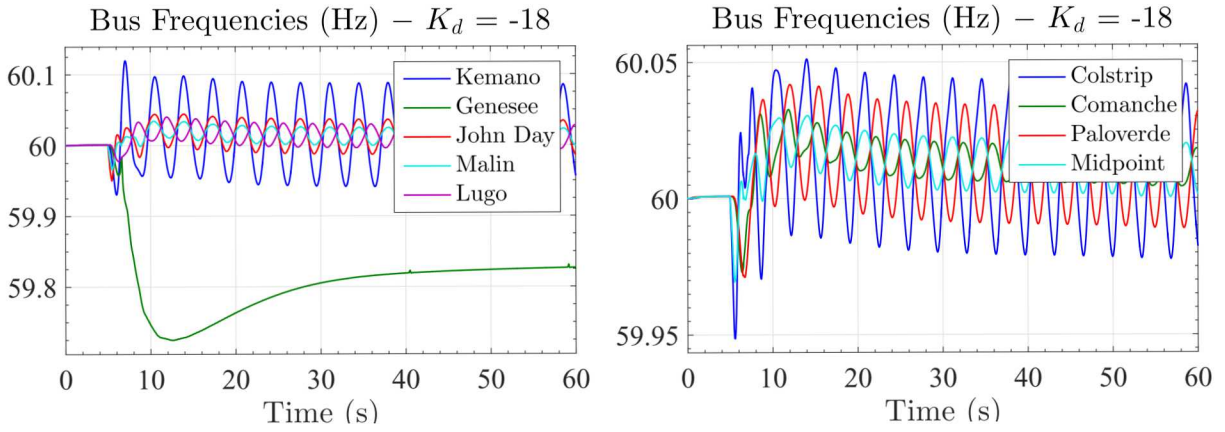
**Figure 82. Bus frequencies. Event: CJB + BCAB Separation**



**Figure 83. Bus frequencies. Event: CJB + BCAB Separation**



**Figure 84. Bus frequencies. Event: CJB + BCAB Separation**



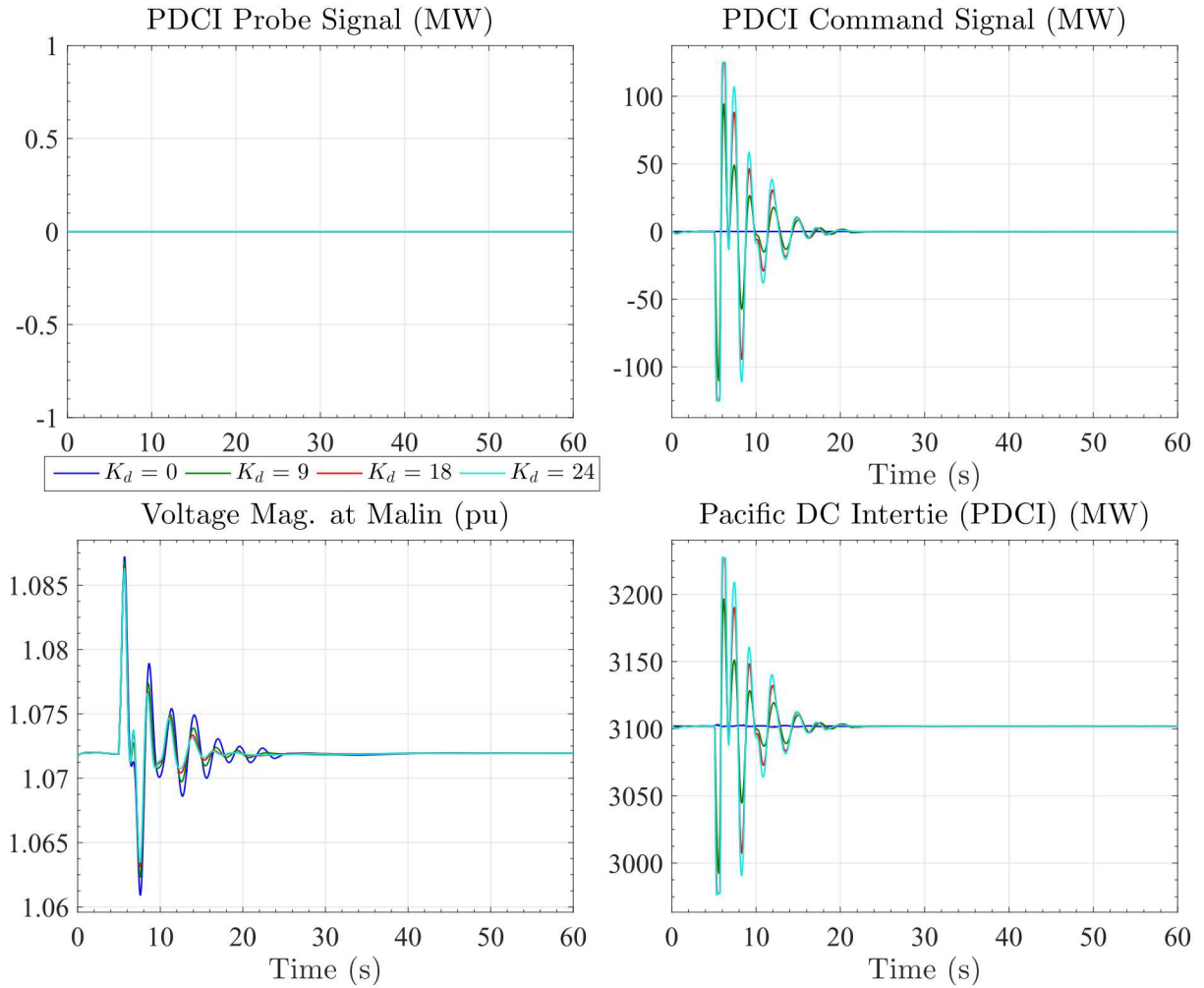
**Figure 85. Bus frequencies. Event: CJB + BCAB Separation**



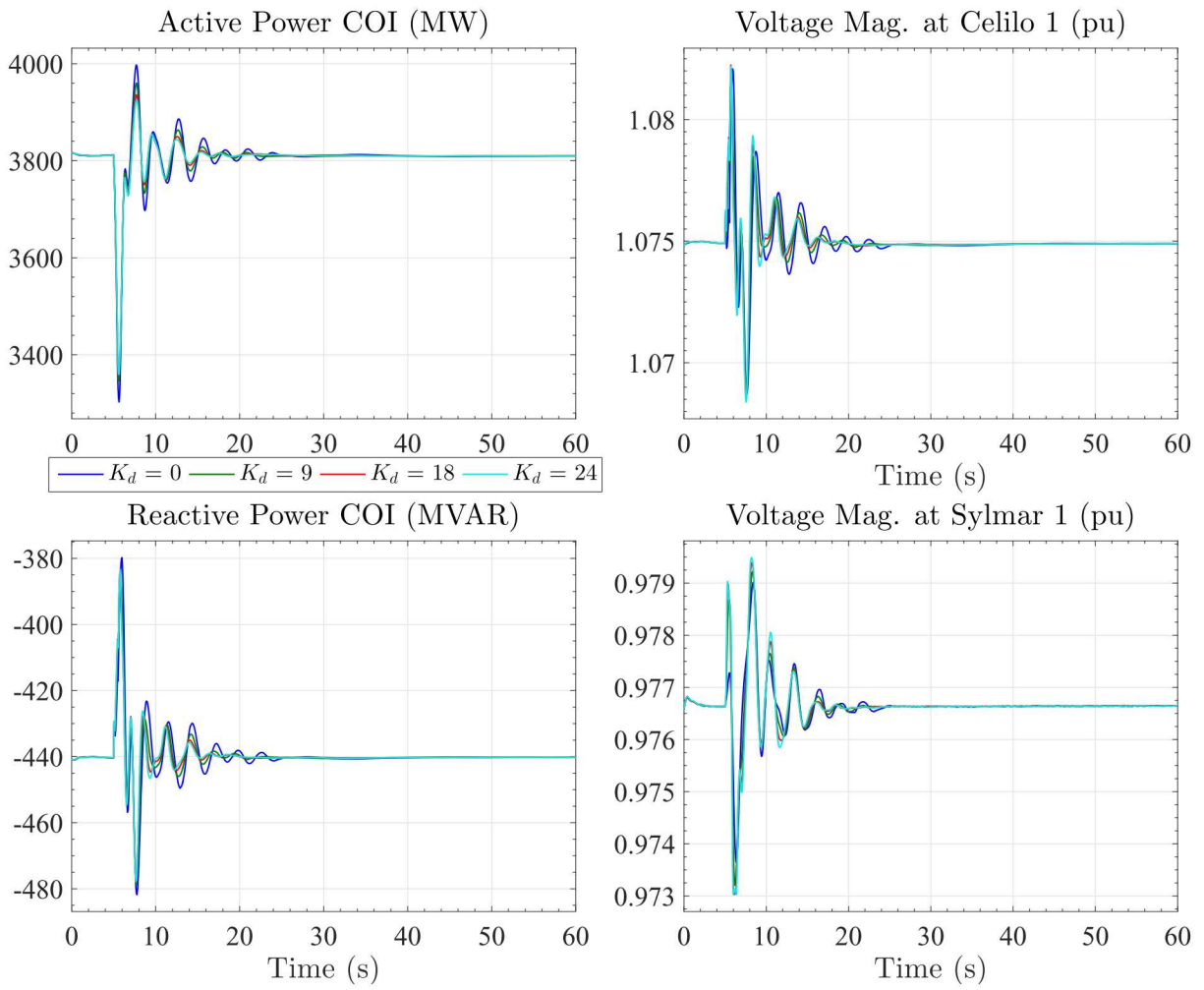


### 3. CONTROLLER LIMITS WITH LARGE GAIN VALUES

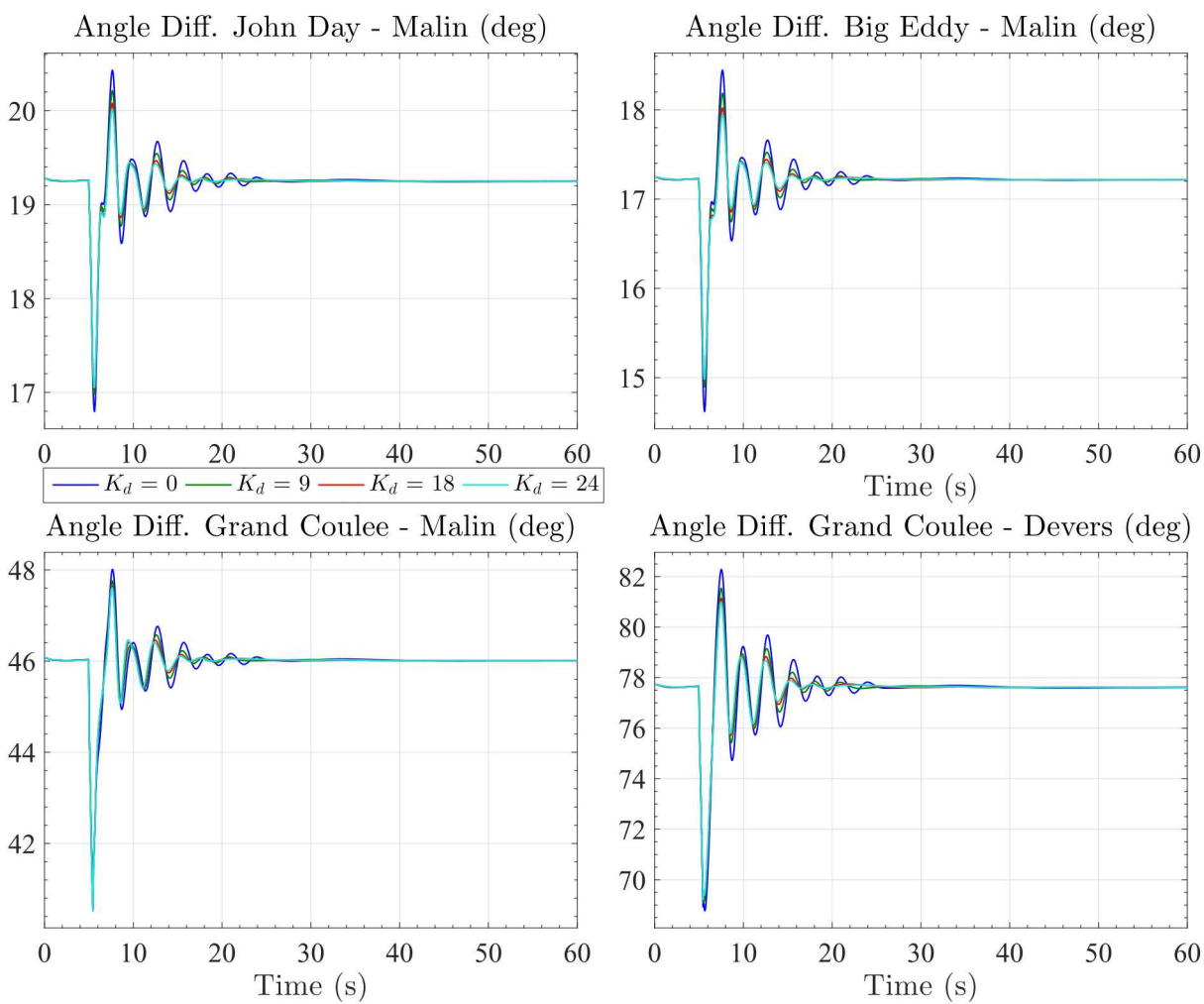
#### 3.1. Test System: Heavy Summer 2016. Event: Chief Joe Brake



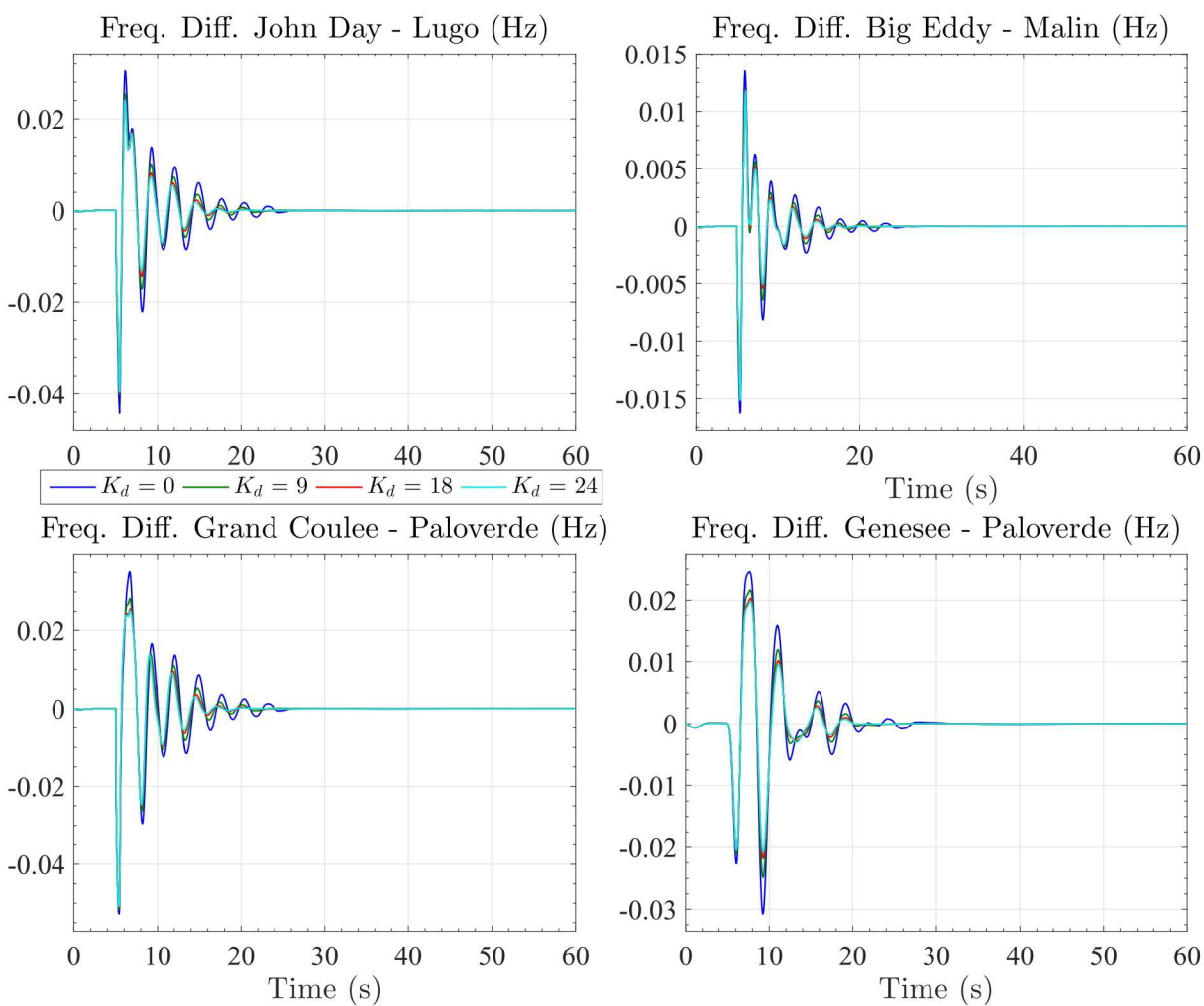
**Figure 86. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake**



**Figure 87. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake**

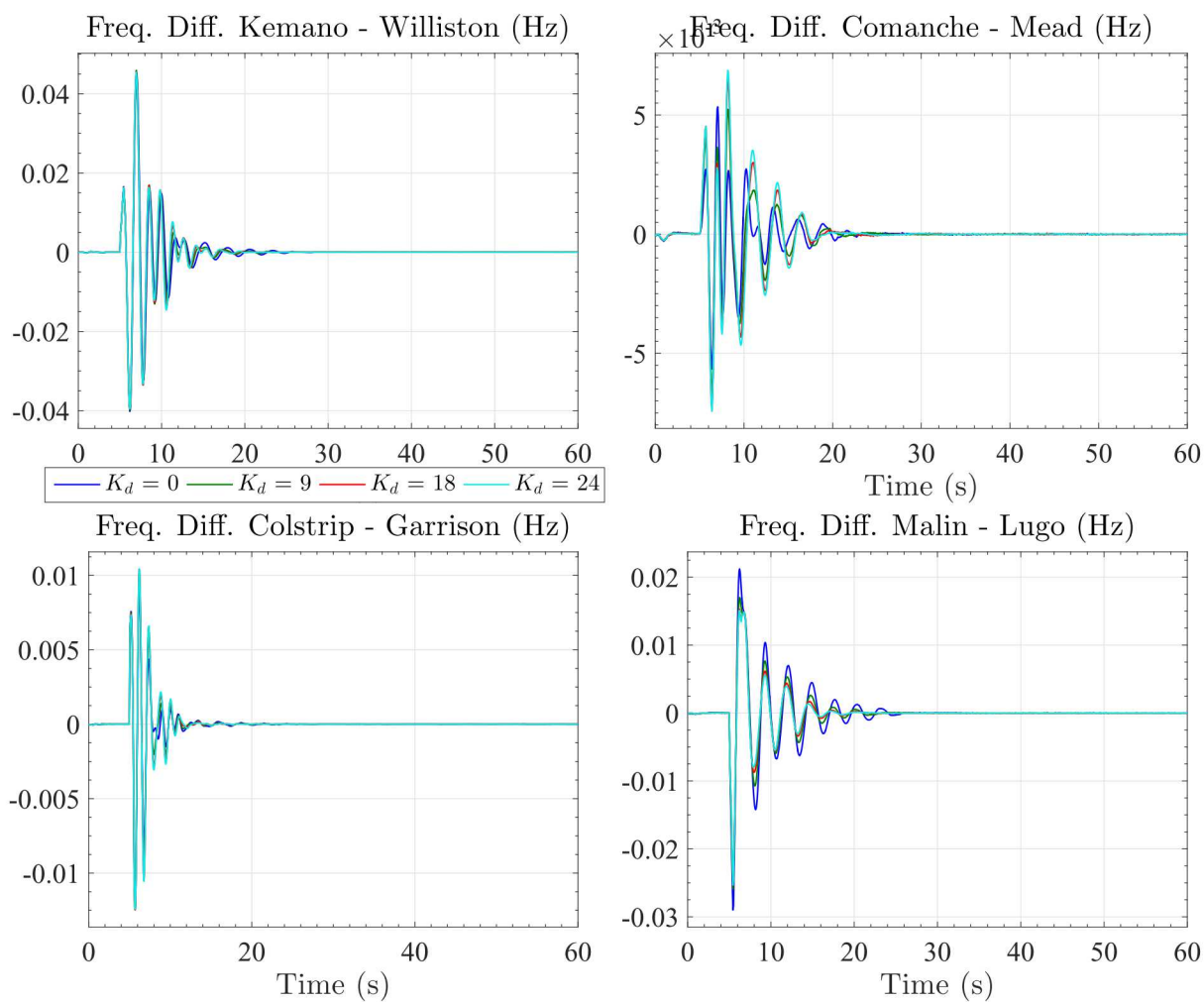


**Figure 88. Angle differences. Event: Chief Joe Brake**

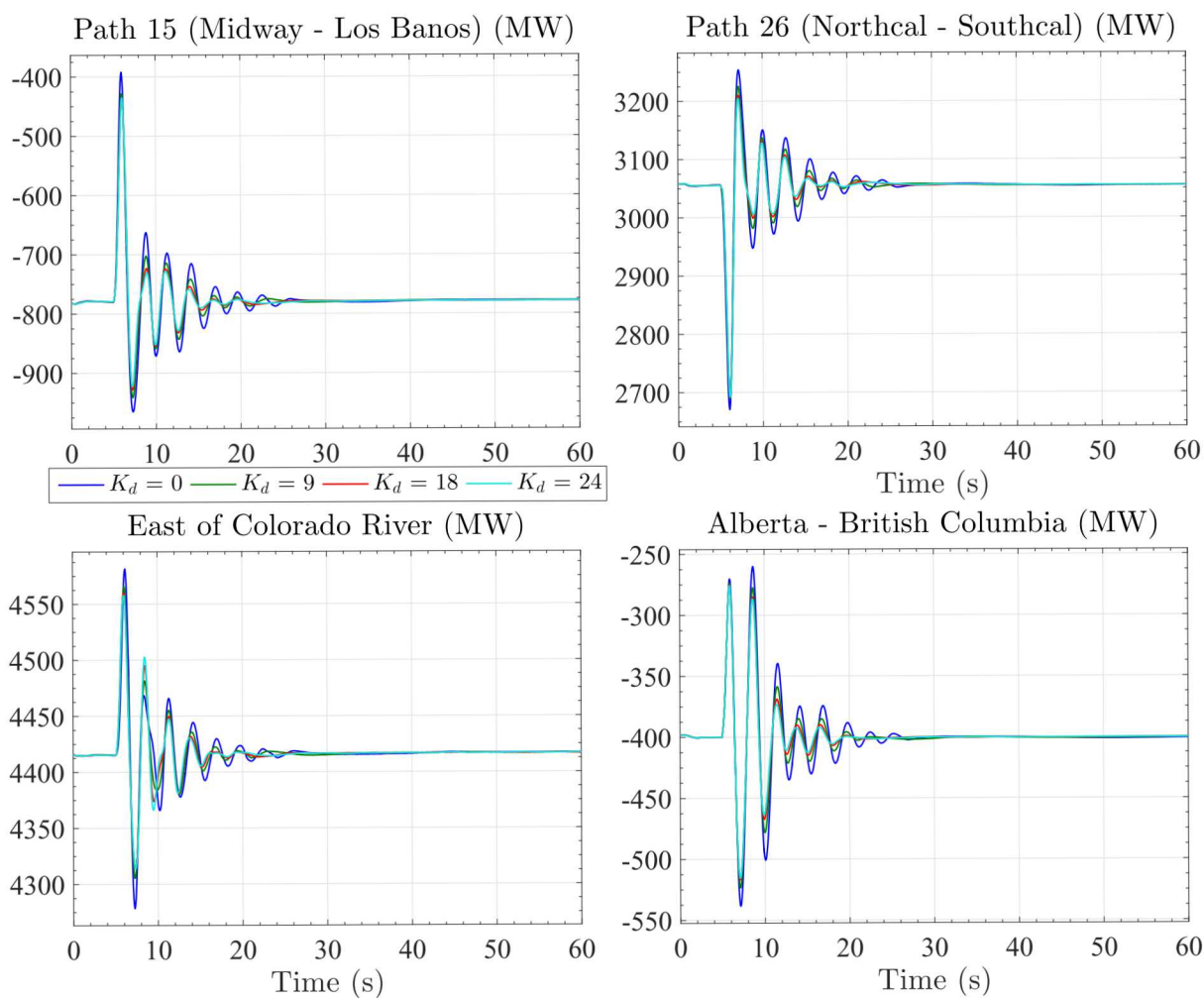


**Figure 89. Frequency differences. Event: Chief Joe Brake**

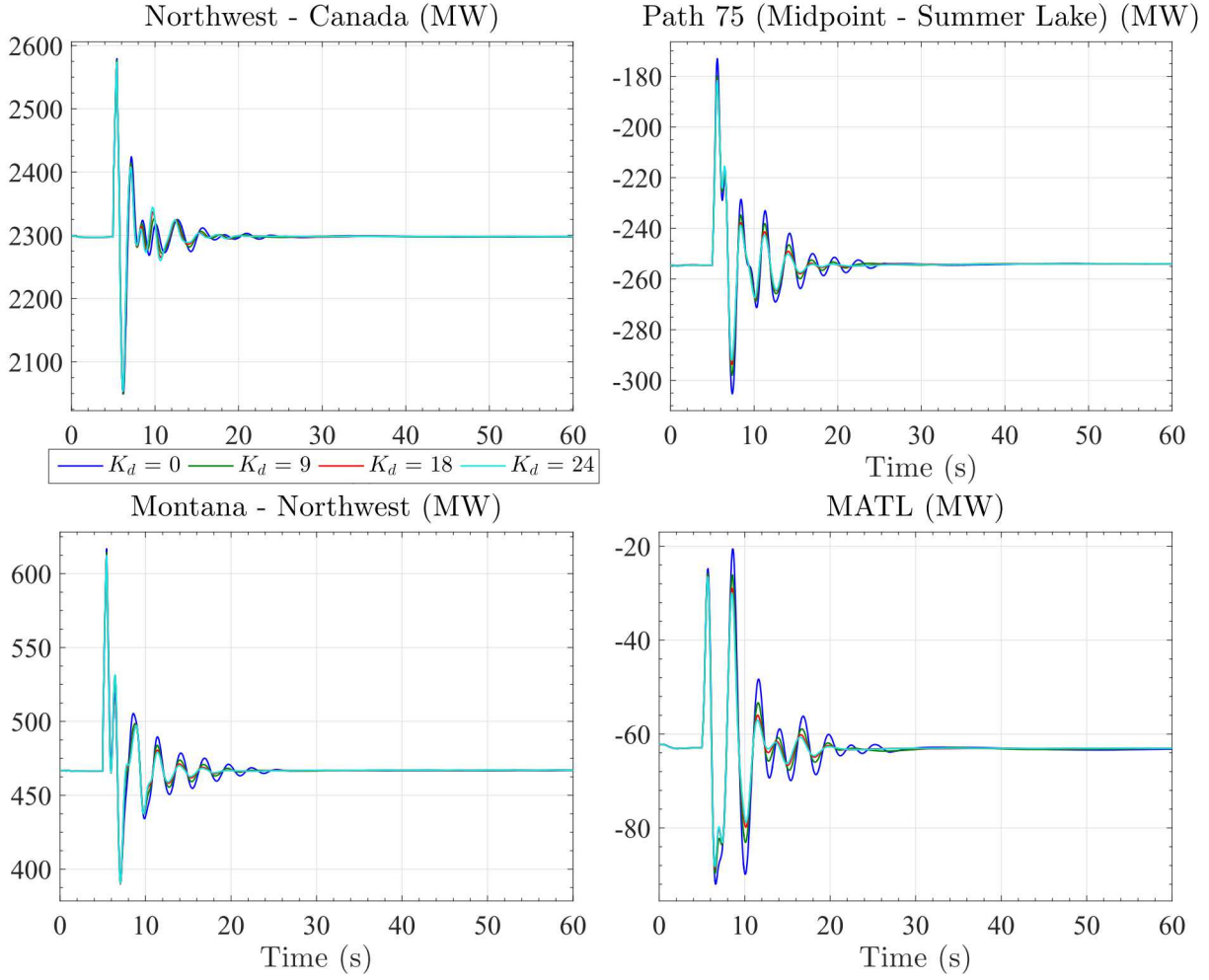




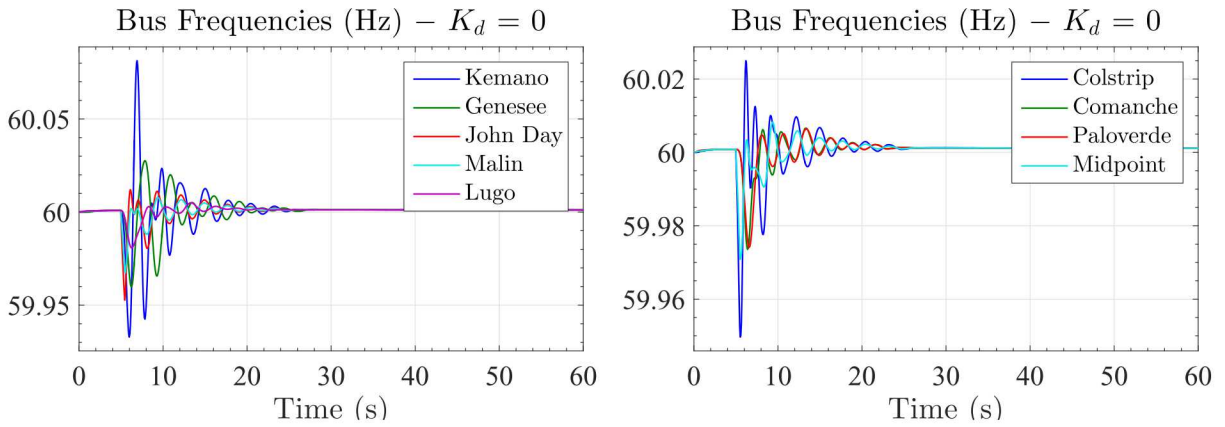
**Figure 90. Frequency differences. Event: Chief Joe Brake**



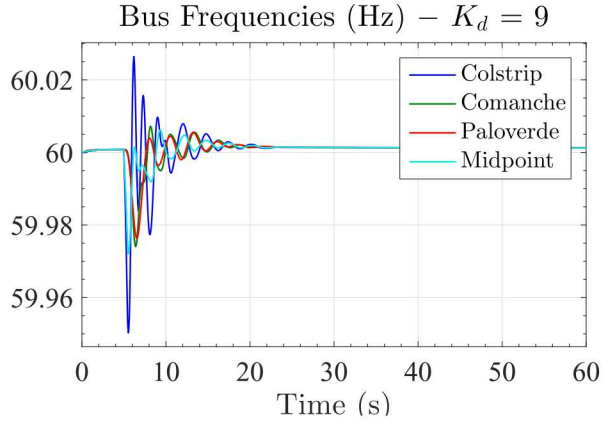
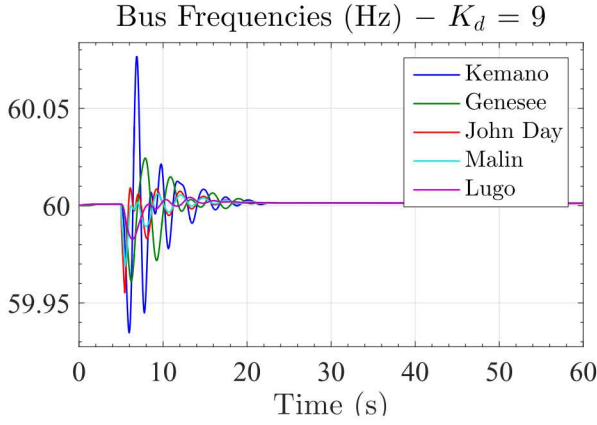
**Figure 91. Active power flows. Event: Chief Joe Brake**



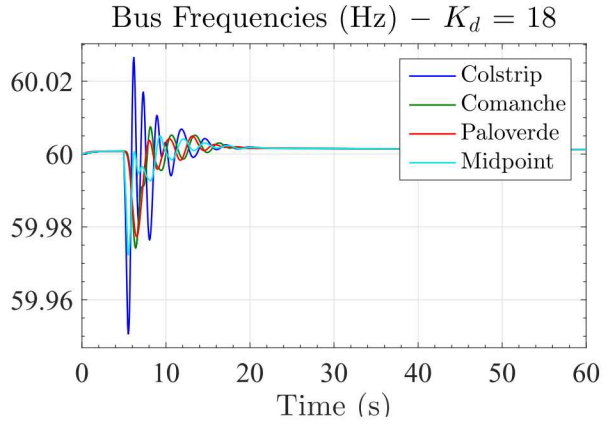
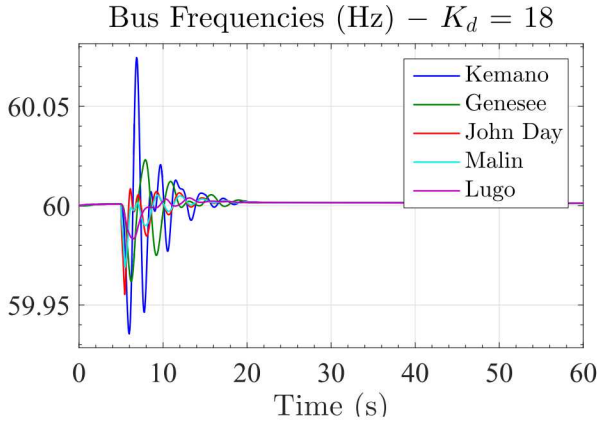
**Figure 92. Active power flows. Event: Chief Joe Brake**



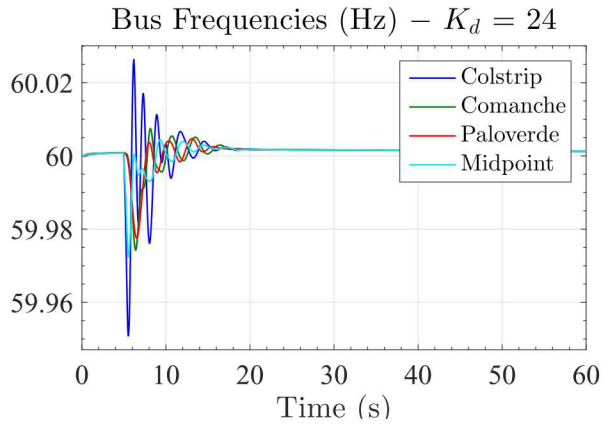
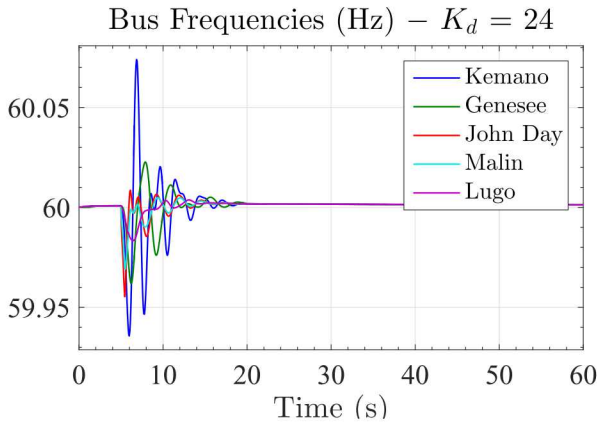
**Figure 93. Bus frequencies. Event: Chief Joe Brake**



**Figure 94. Bus frequencies. Event: Chief Joe Brake**

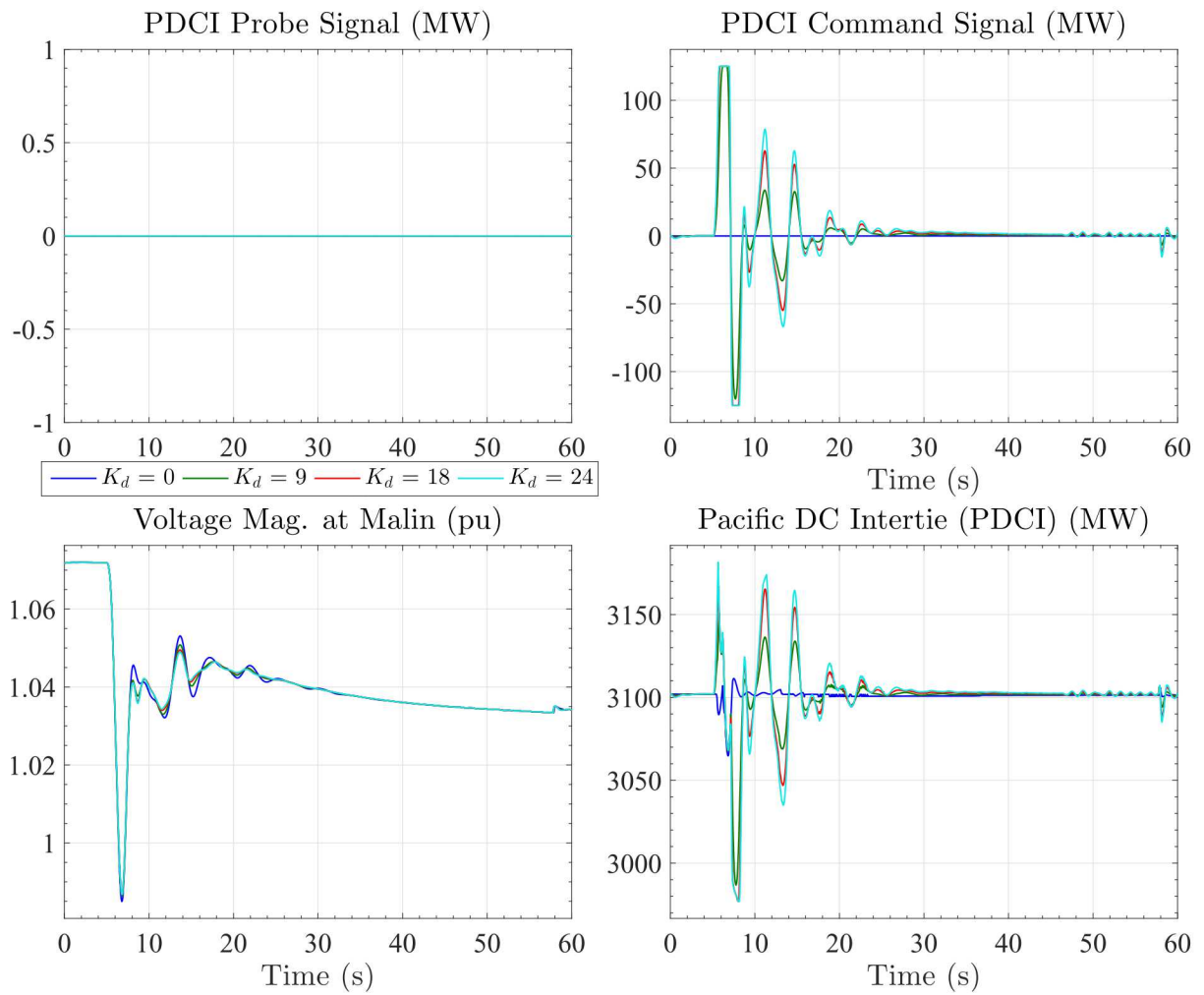


**Figure 95. Bus frequencies. Event: Chief Joe Brake**



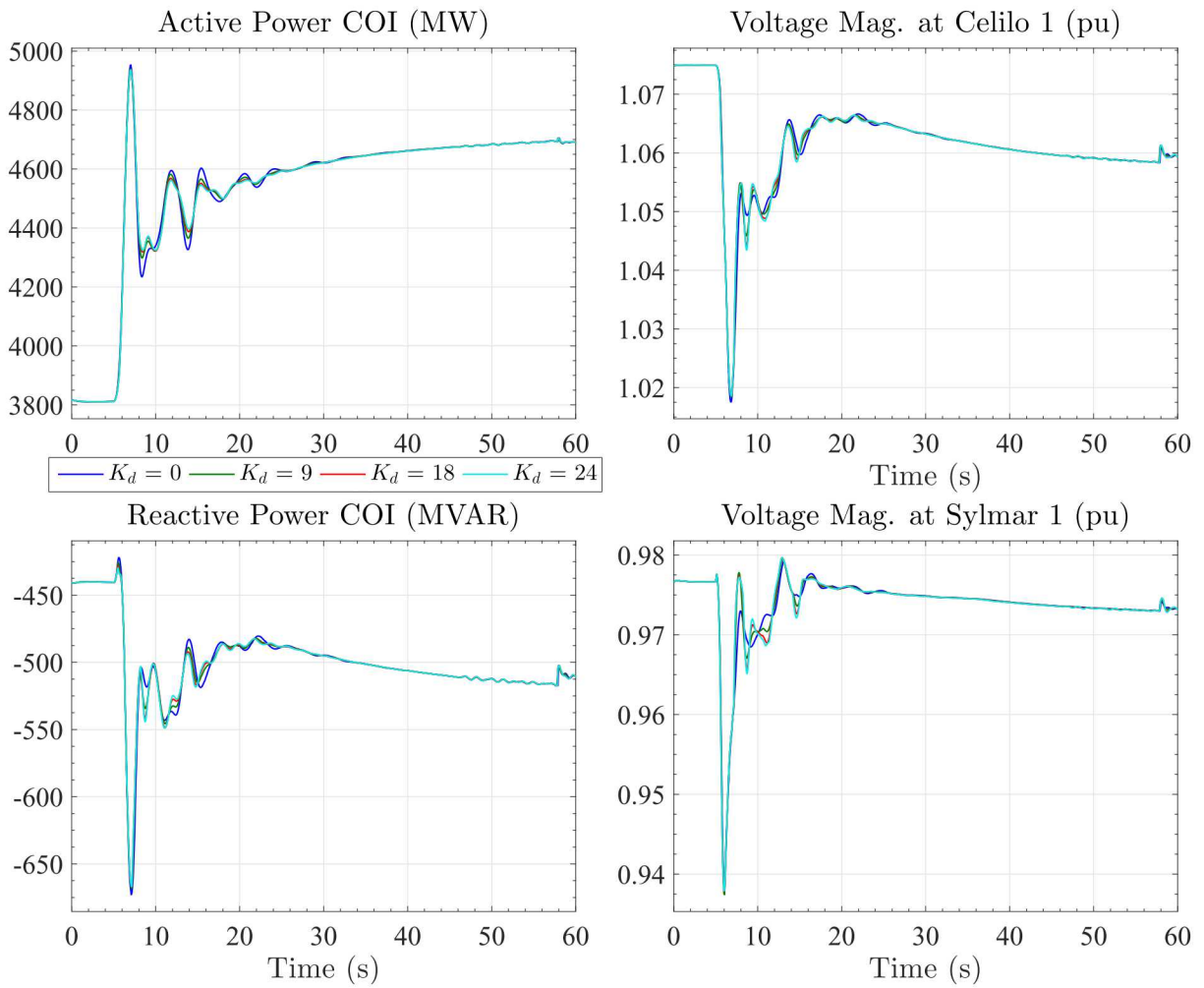
**Figure 96. Bus frequencies. Event: Chief Joe Brake**

### 3.2. Test System: Heavy Summer 2016. Event: Double Palo Verde Trip

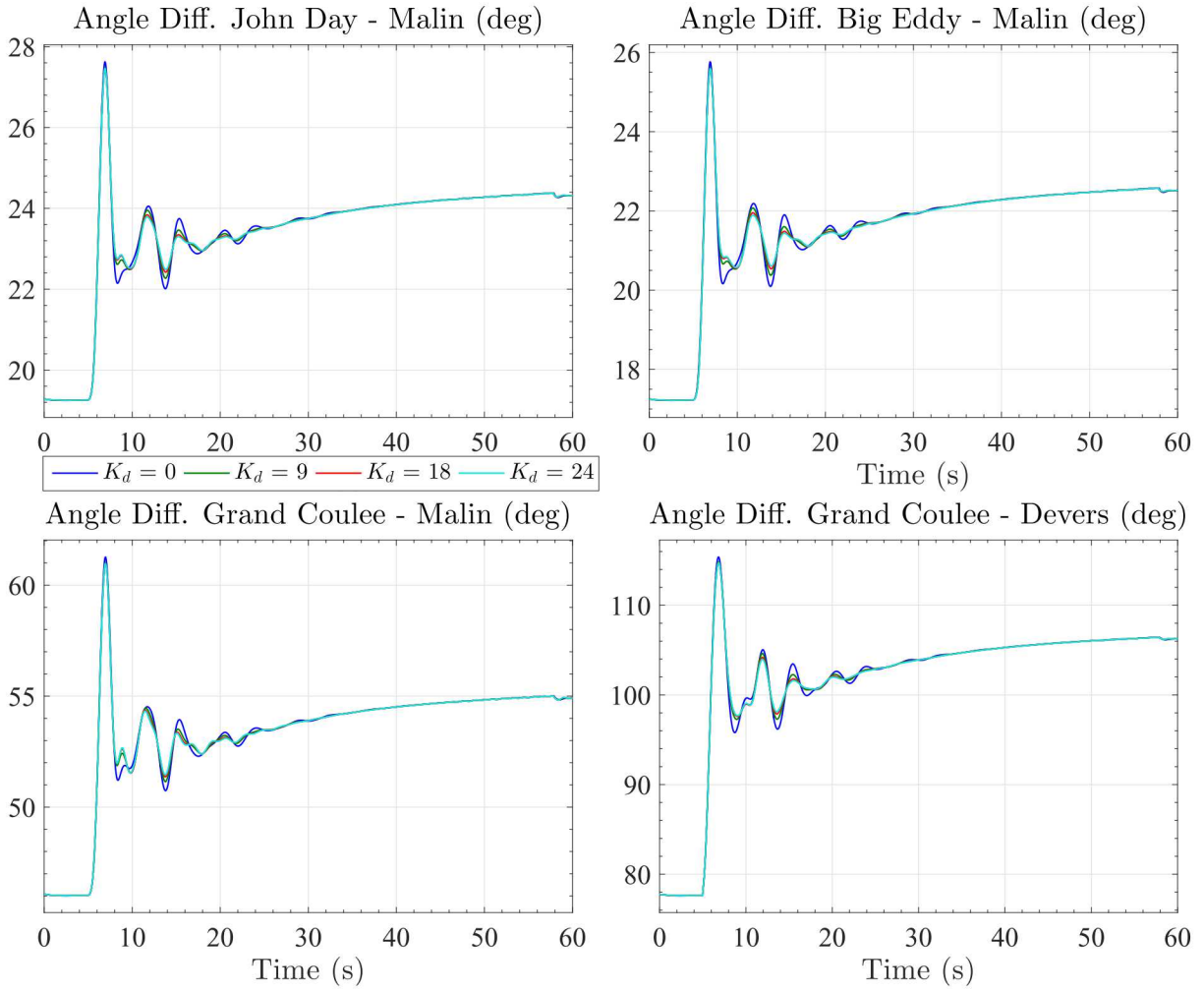


**Figure 97. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Double Palo Verde Trip**

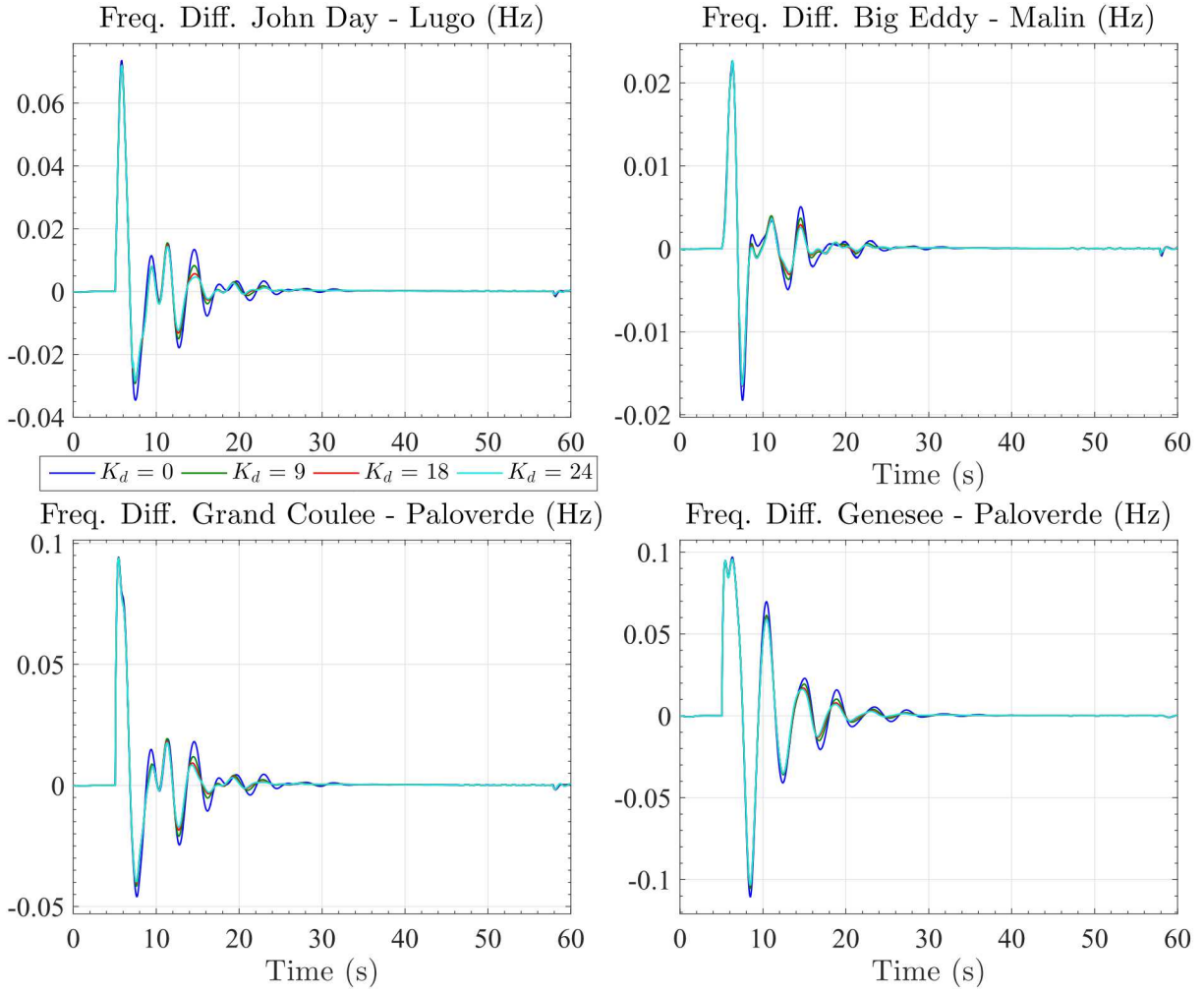




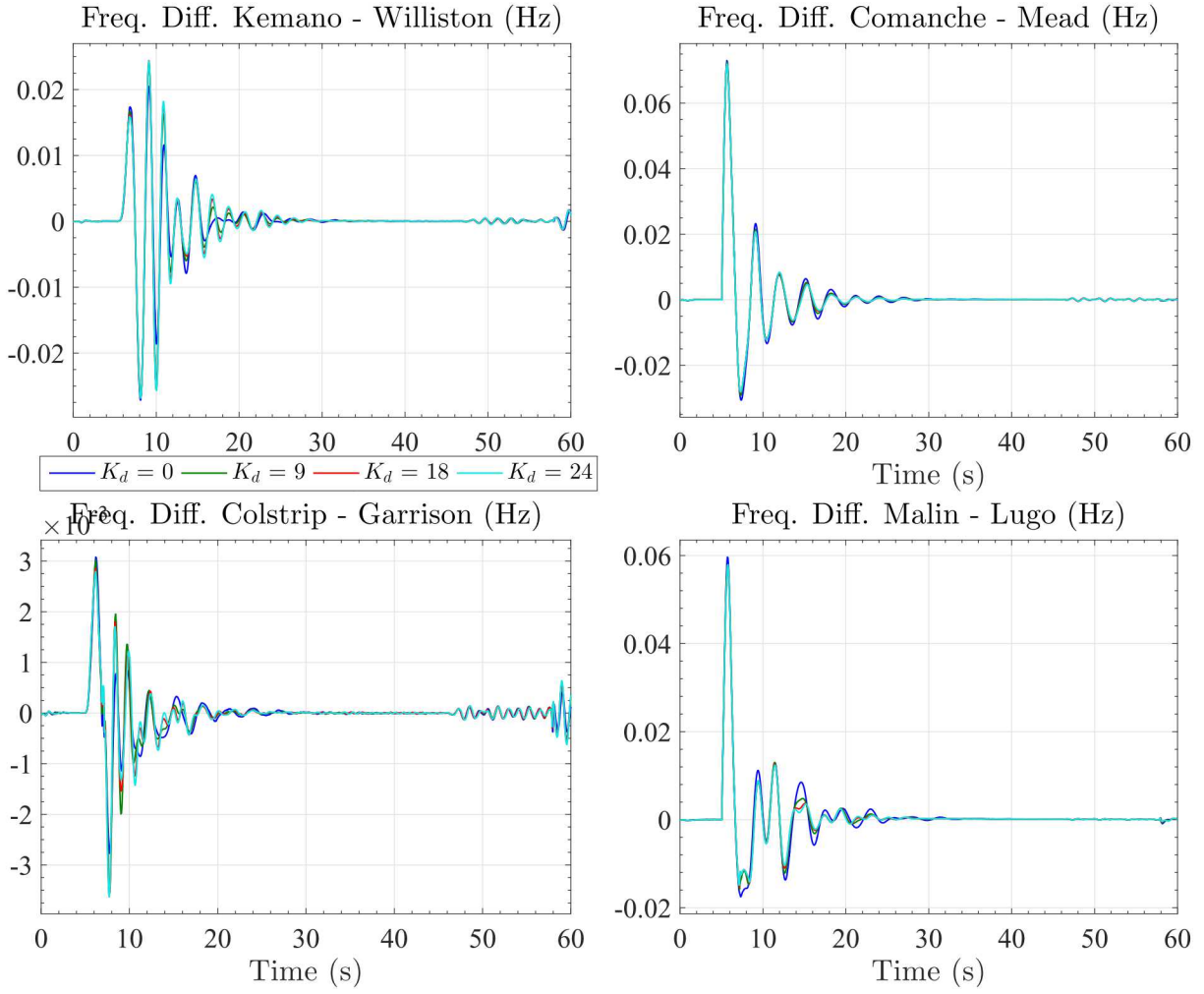
**Figure 98. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Double Palo Verde Trip**



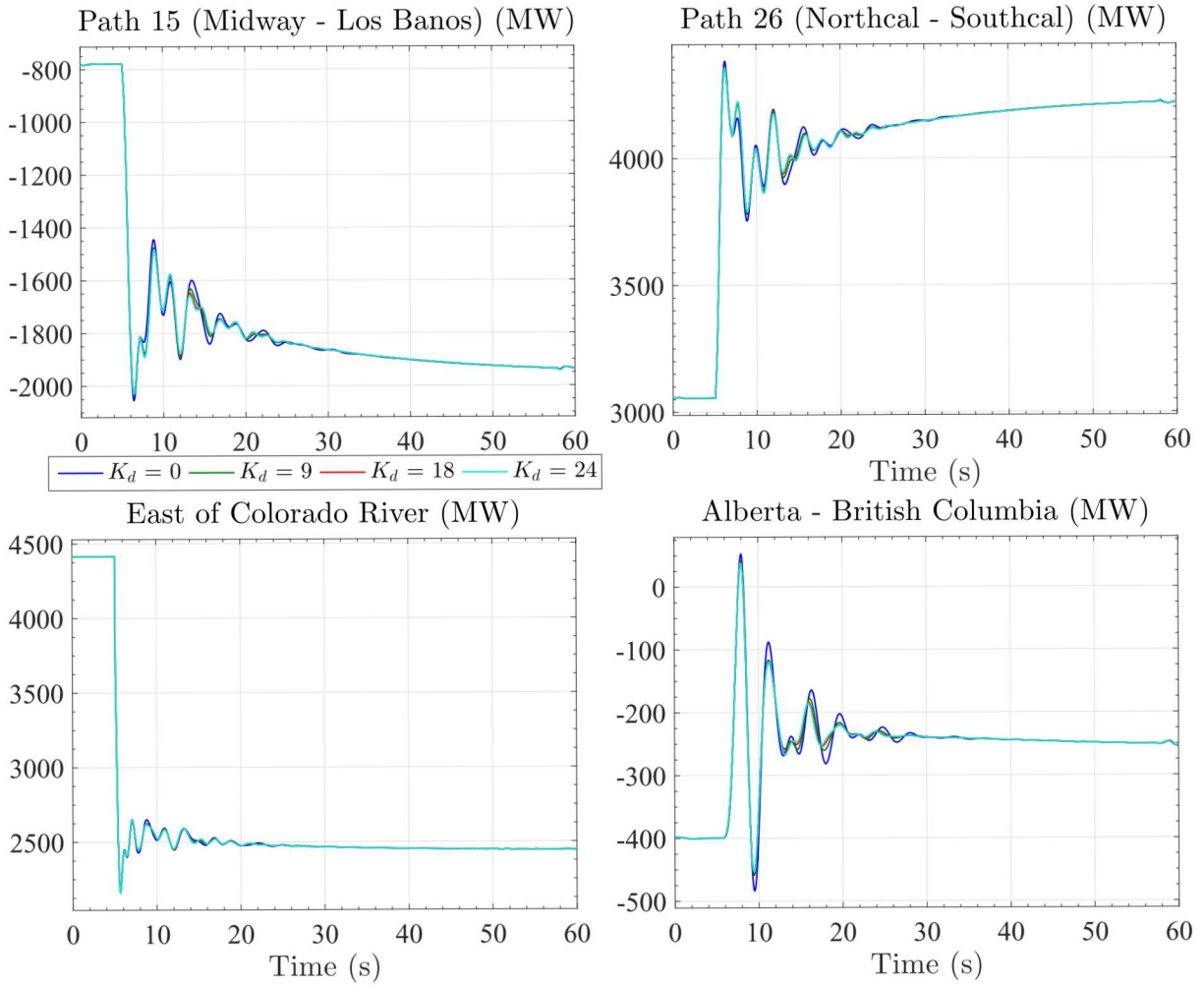
**Figure 99. Angle differences. Event: Double Palo Verde Trip**



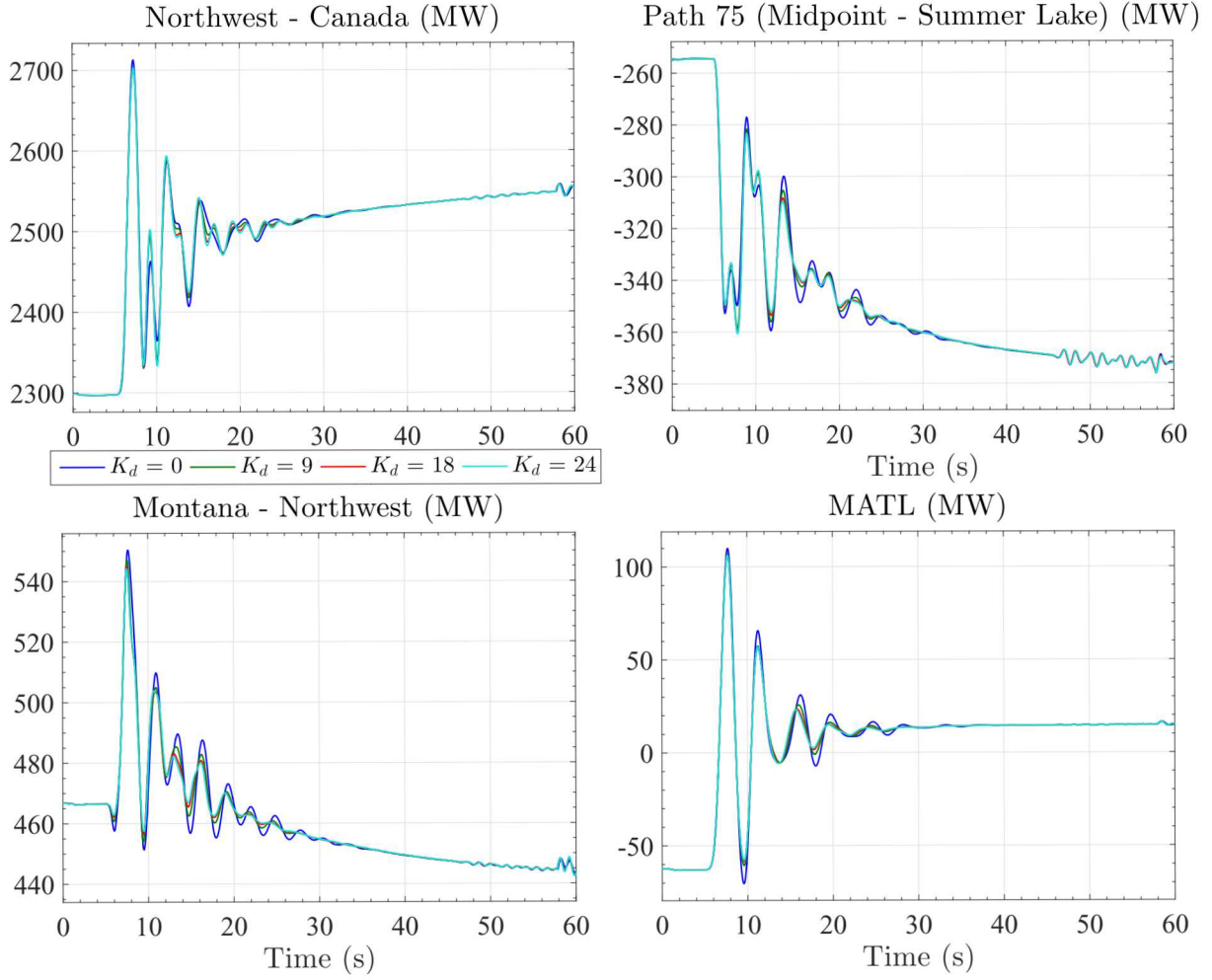
**Figure 100. Frequency differences. Event: Double Palo Verde Trip**



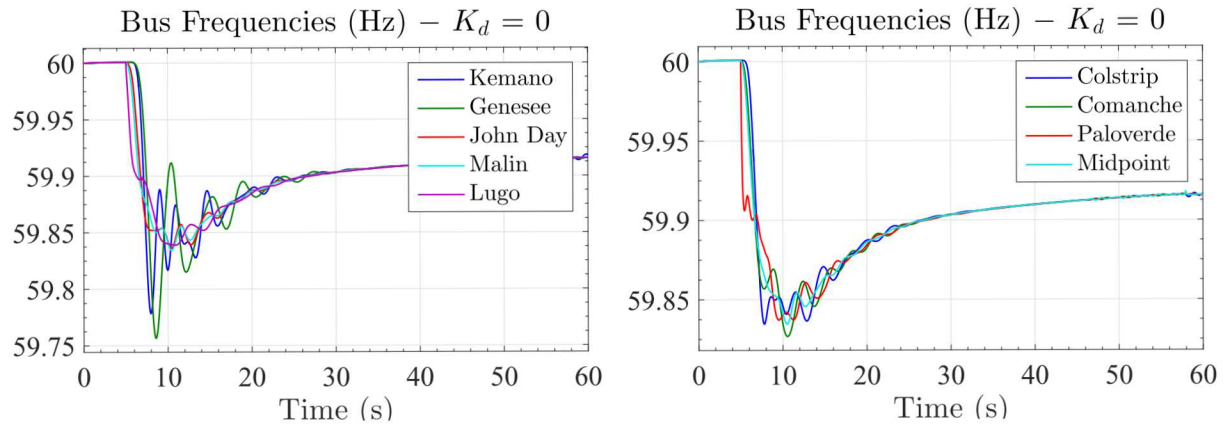
**Figure 101. Frequency differences. Event: Double Palo Verde Trip**



**Figure 102. Active power flows. Event: Double Palo Verde Trip**

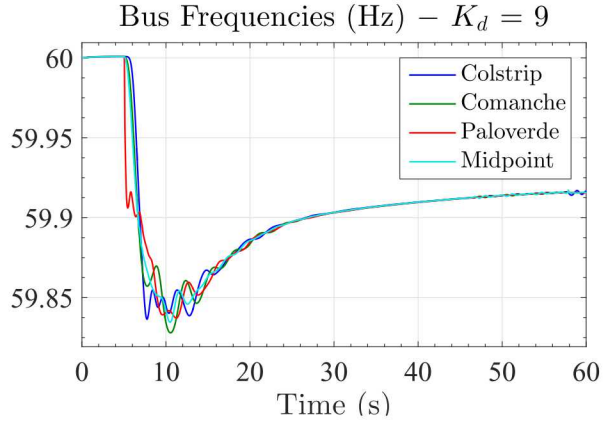
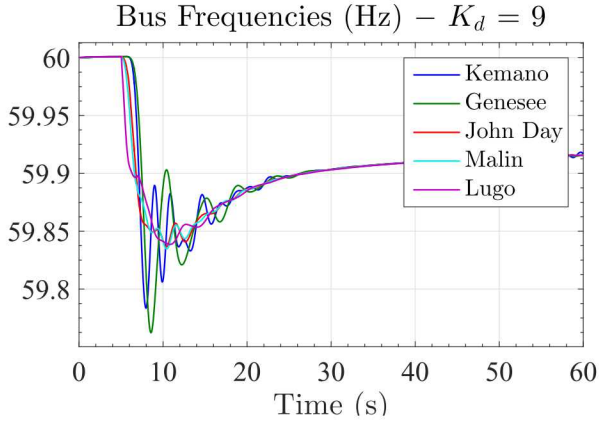


**Figure 103. Active power flows. Event: Double Palo Verde Trip**

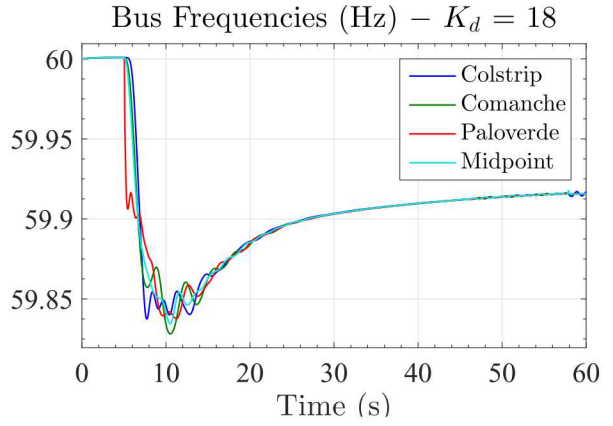
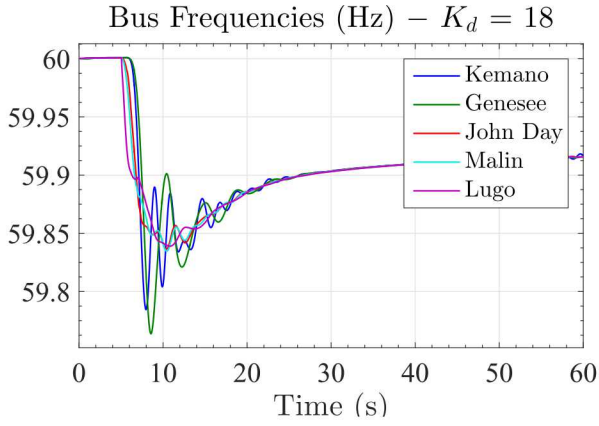


**Figure 104. Bus frequencies. Event: Double Palo Verde Trip**

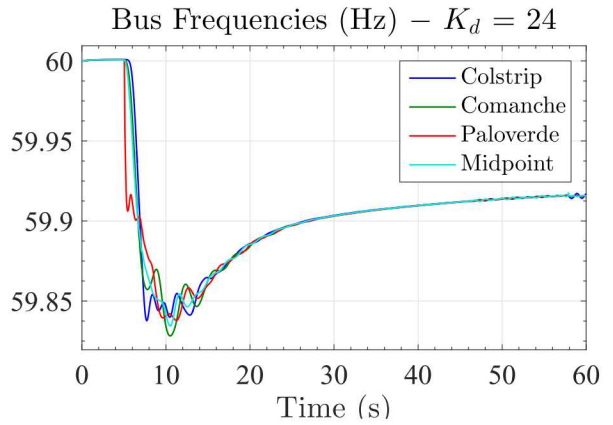
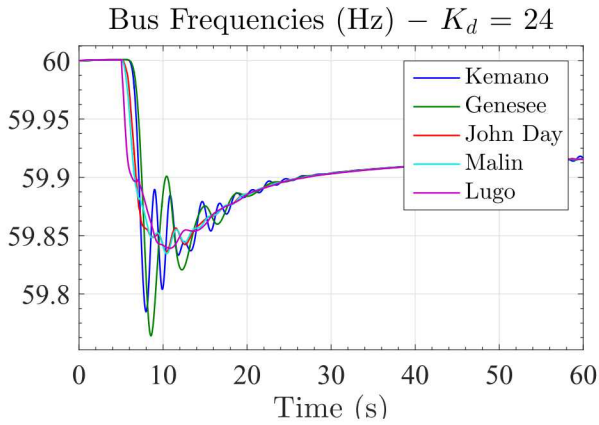




**Figure 105. Bus frequencies. Event: Double Palo Verde Trip**



**Figure 106. Bus frequencies. Event: Double Palo Verde Trip**



**Figure 107. Bus frequencies. Event: Double Palo Verde Trip**

### 3.3. Test System: Heavy Summer 2016. Event: BC-US Separation

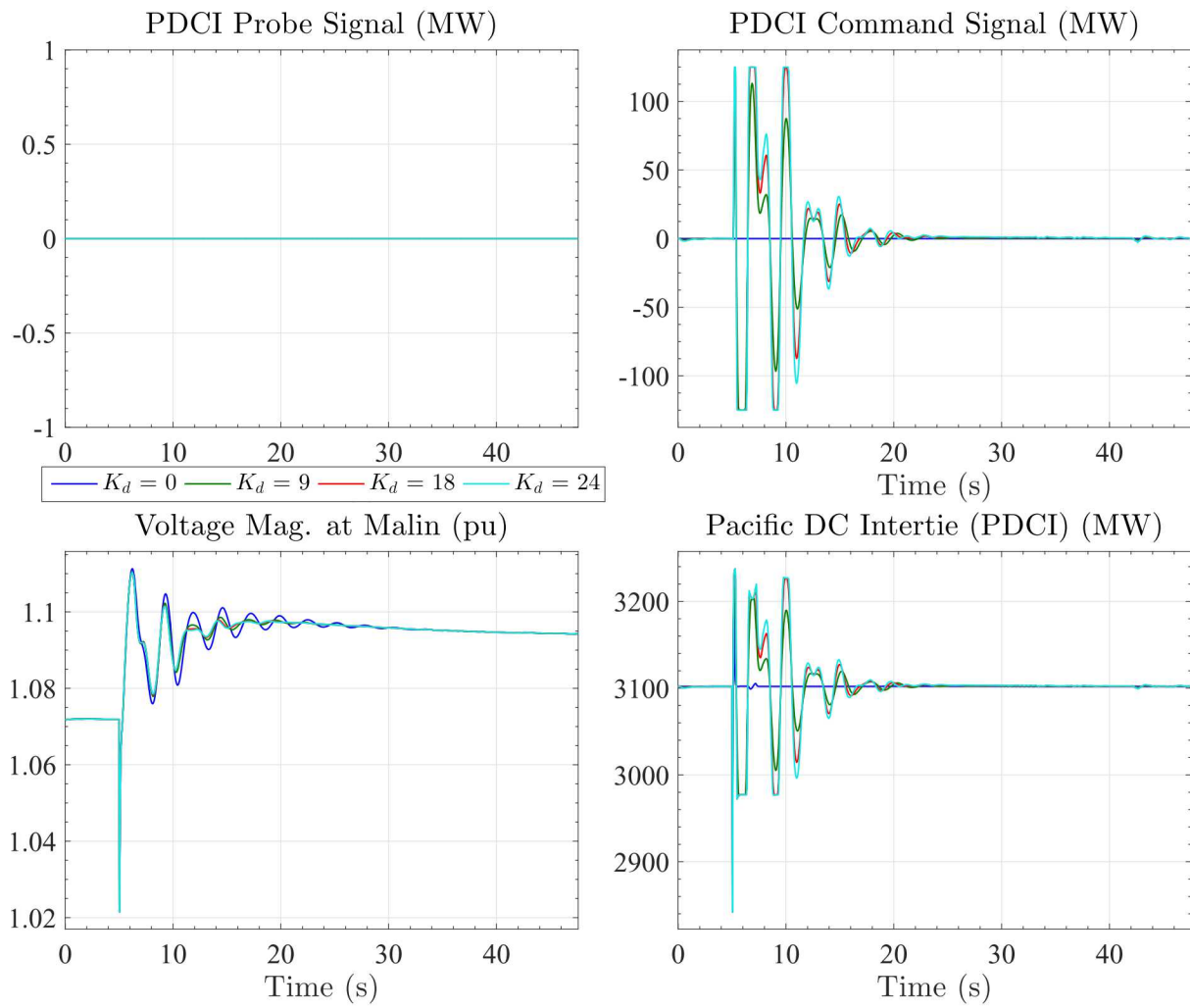
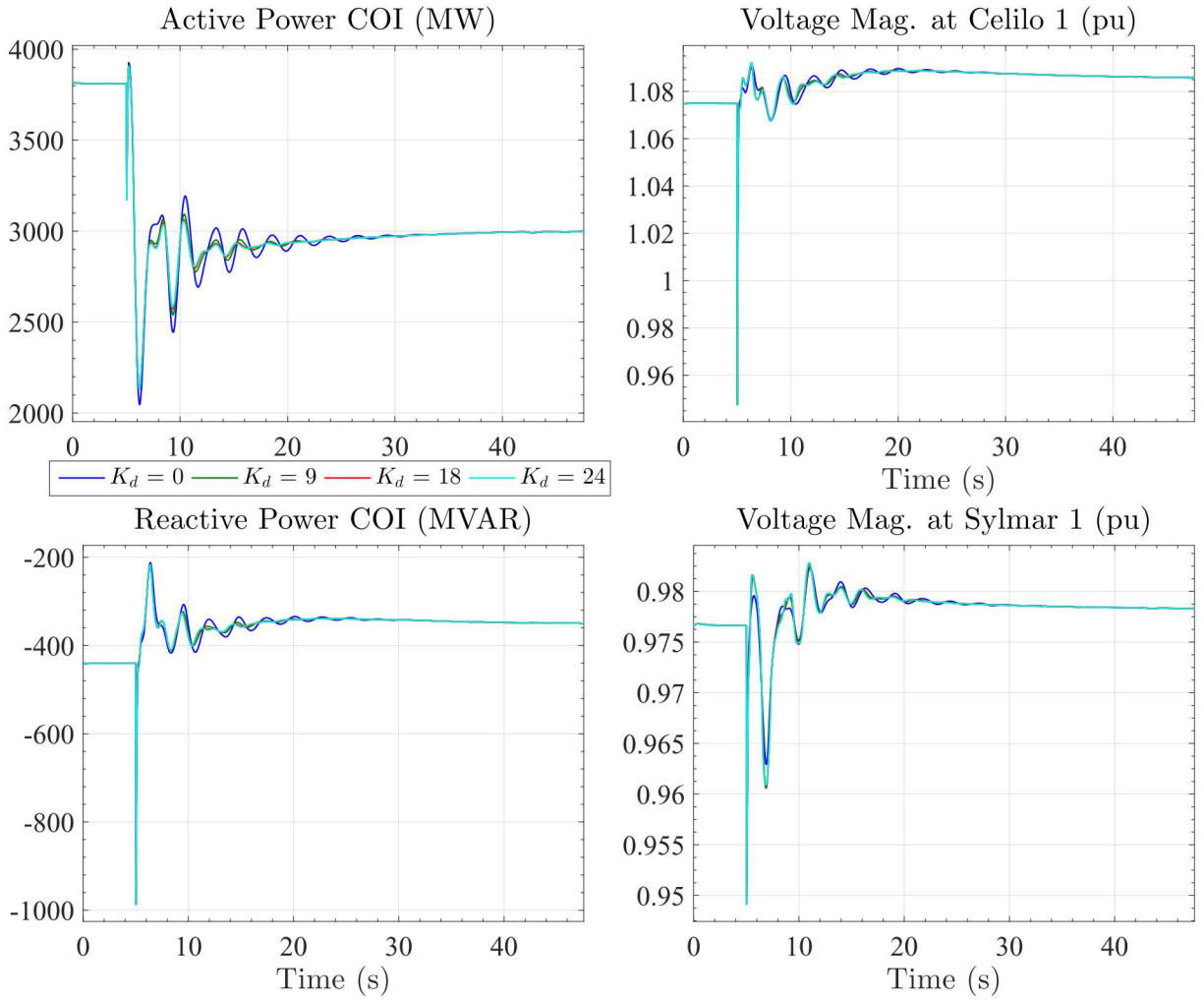
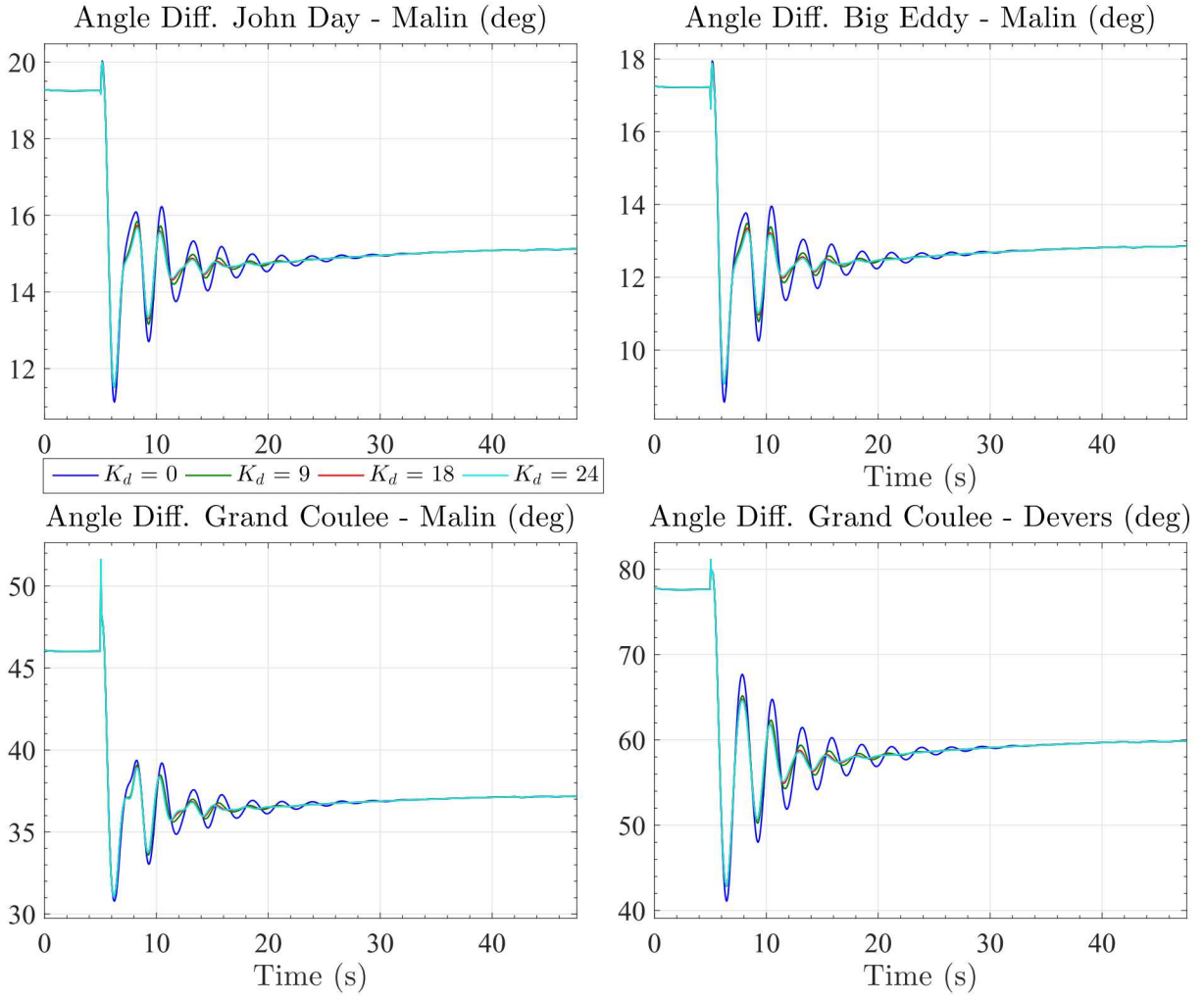


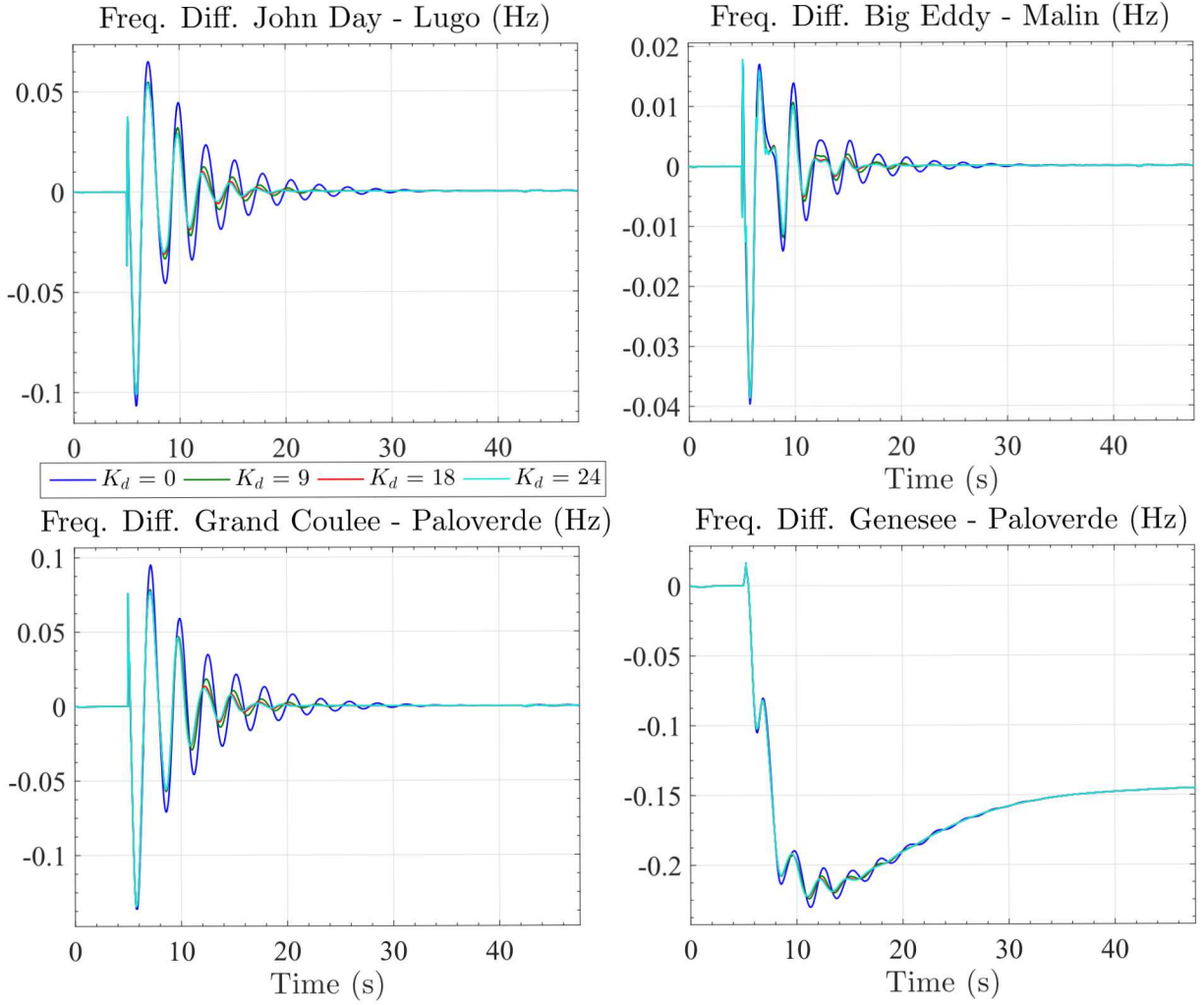
Figure 108. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-US Separation



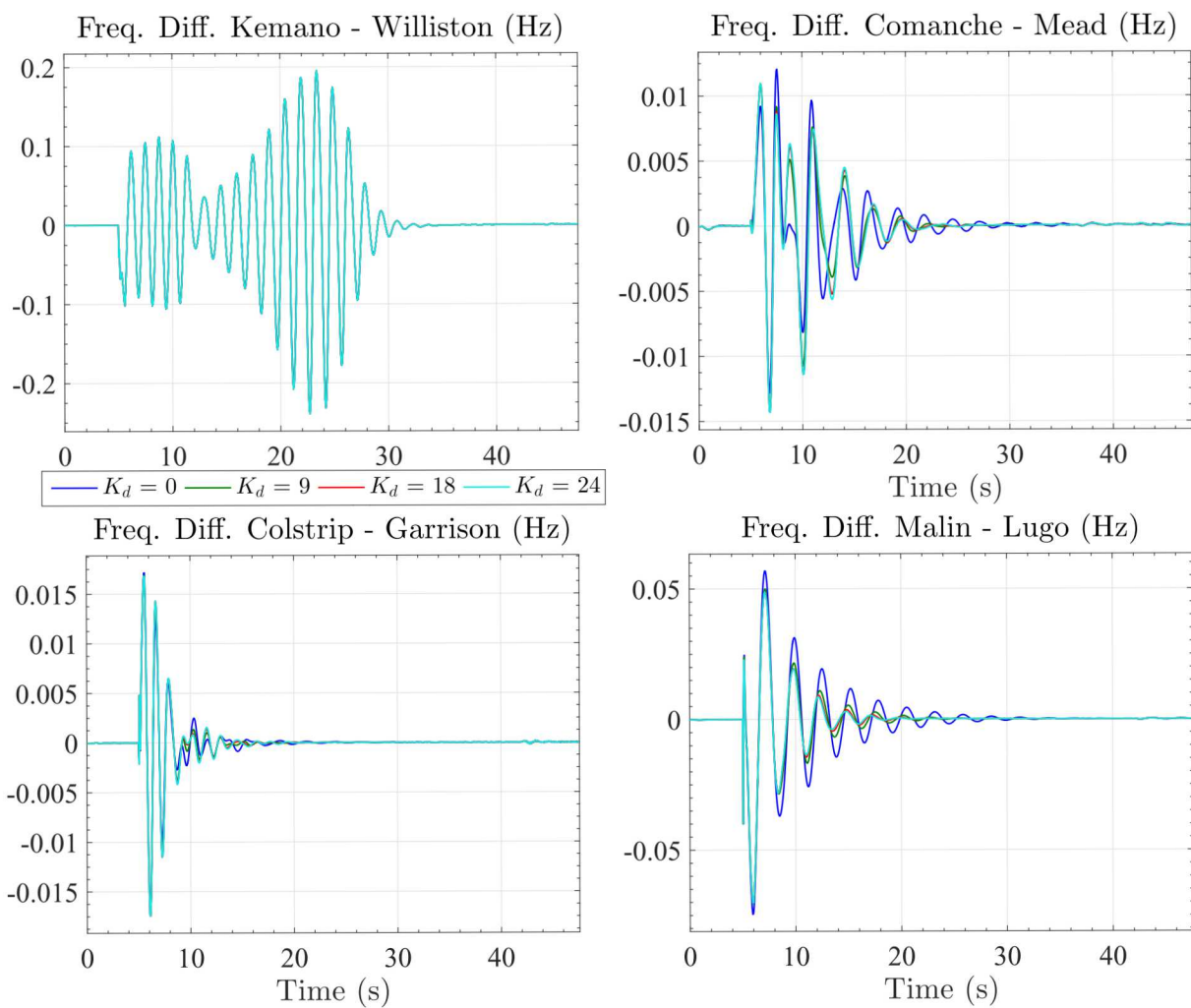
**Figure 109. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-US Separation**



**Figure 110. Angle differences. Event: BC-US Separation**

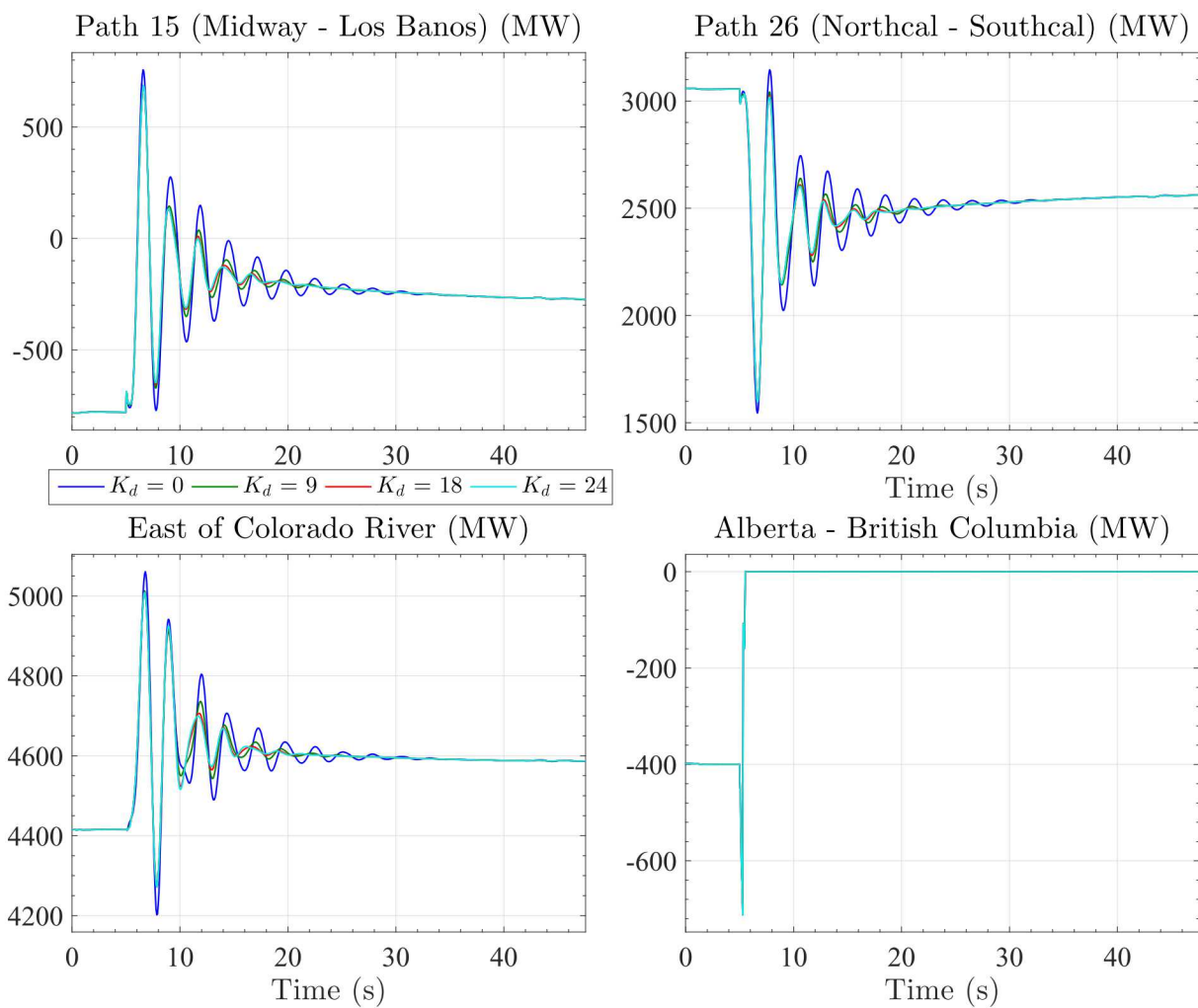


**Figure 111. Frequency differences. Event: BC-US Separation**

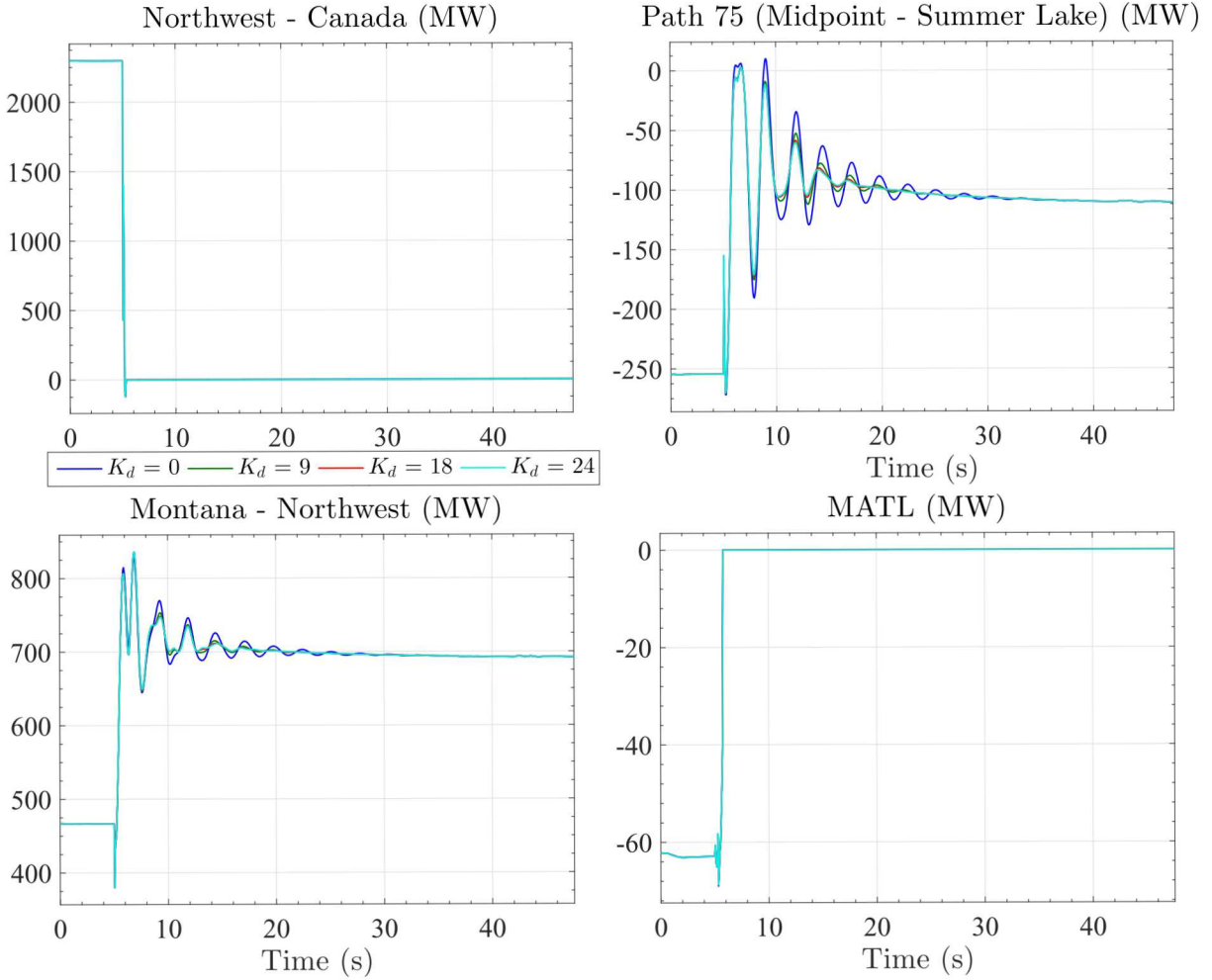


**Figure 112. Frequency differences. Event: BC-US Separation**

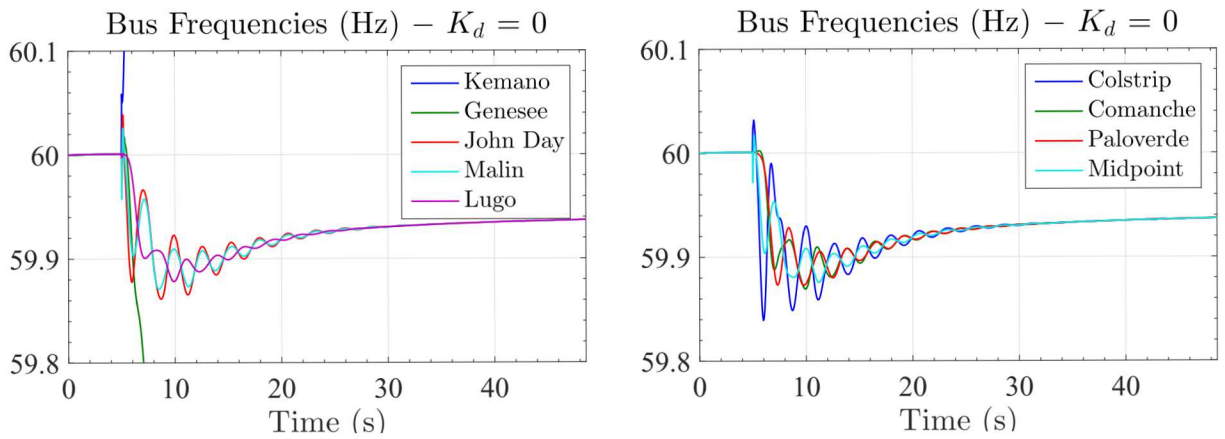




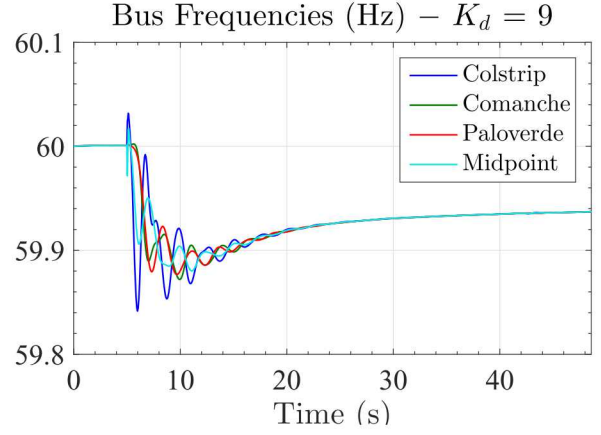
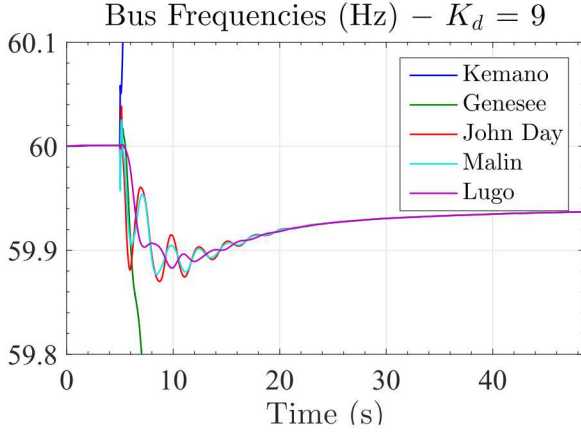
**Figure 113. Active power flows. Event: BC-US Separation**



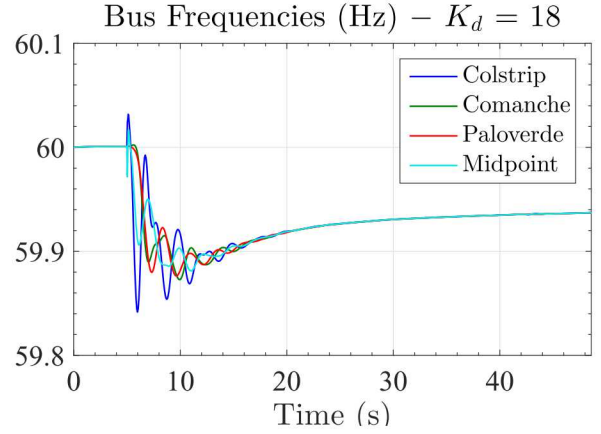
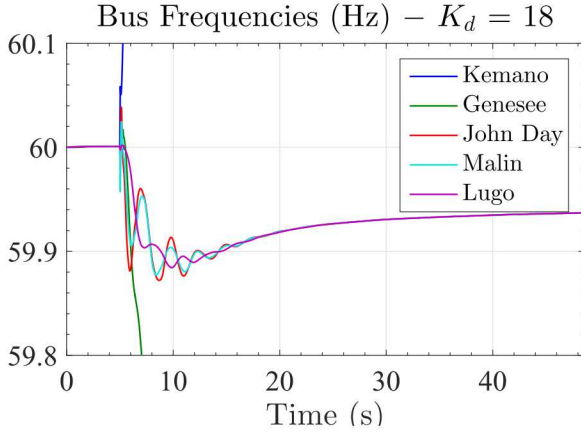
**Figure 114. Active power flows. Event: BC-US Separation**



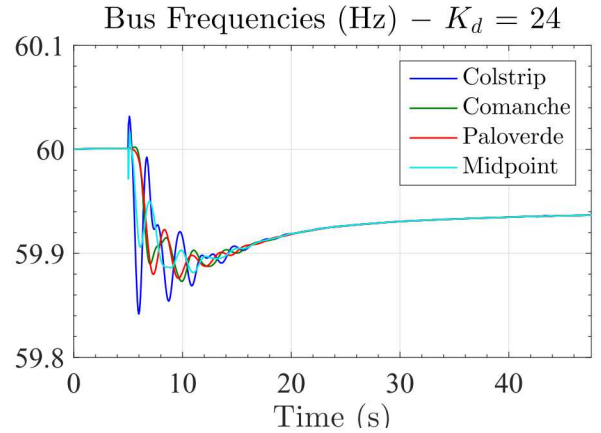
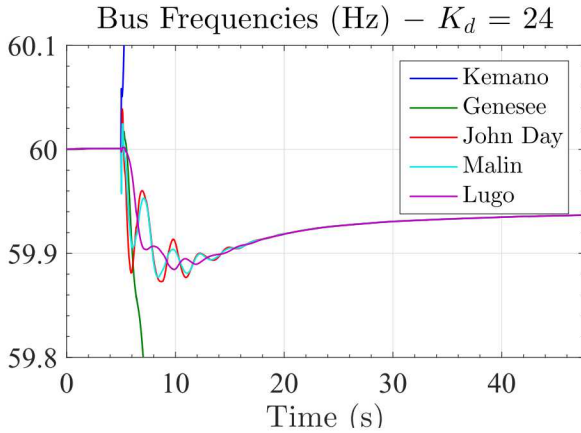
**Figure 115. Bus frequencies. Event: BC-US Separation**



**Figure 116. Bus frequencies. Event: BC-US Separation**

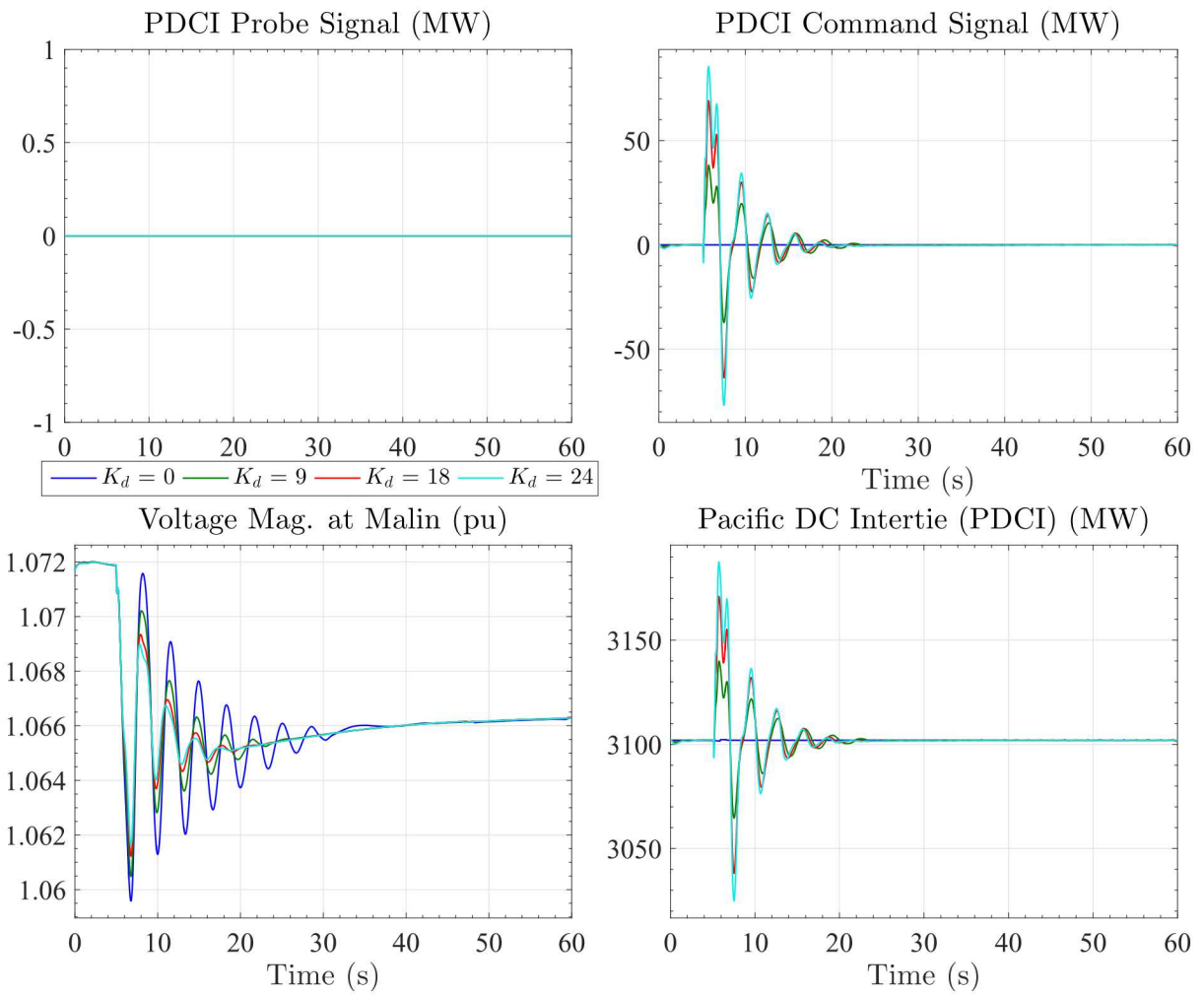


**Figure 117. Bus frequencies. Event: BC-US Separation**

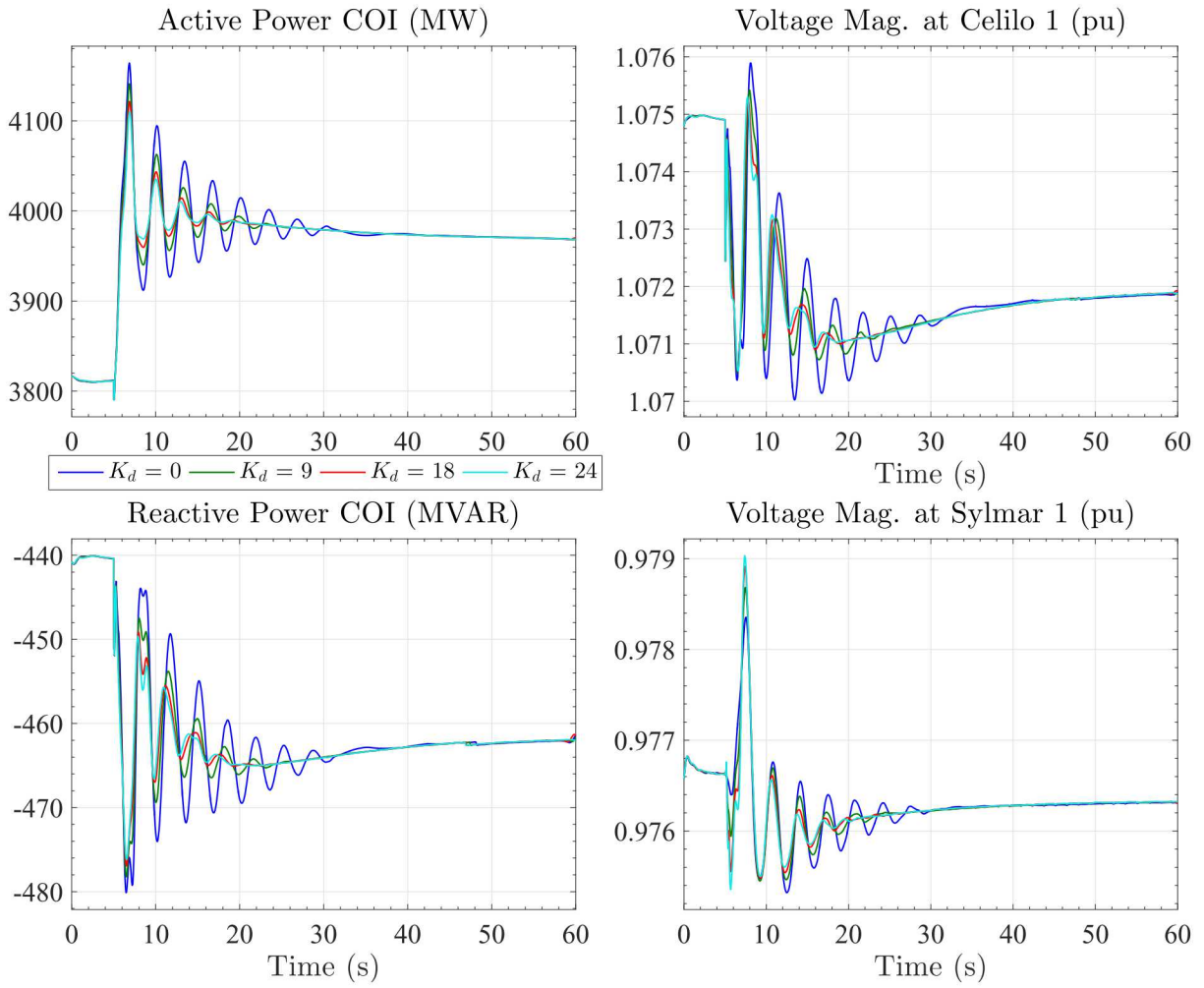


**Figure 118. Bus frequencies. Event: BC-US Separation**

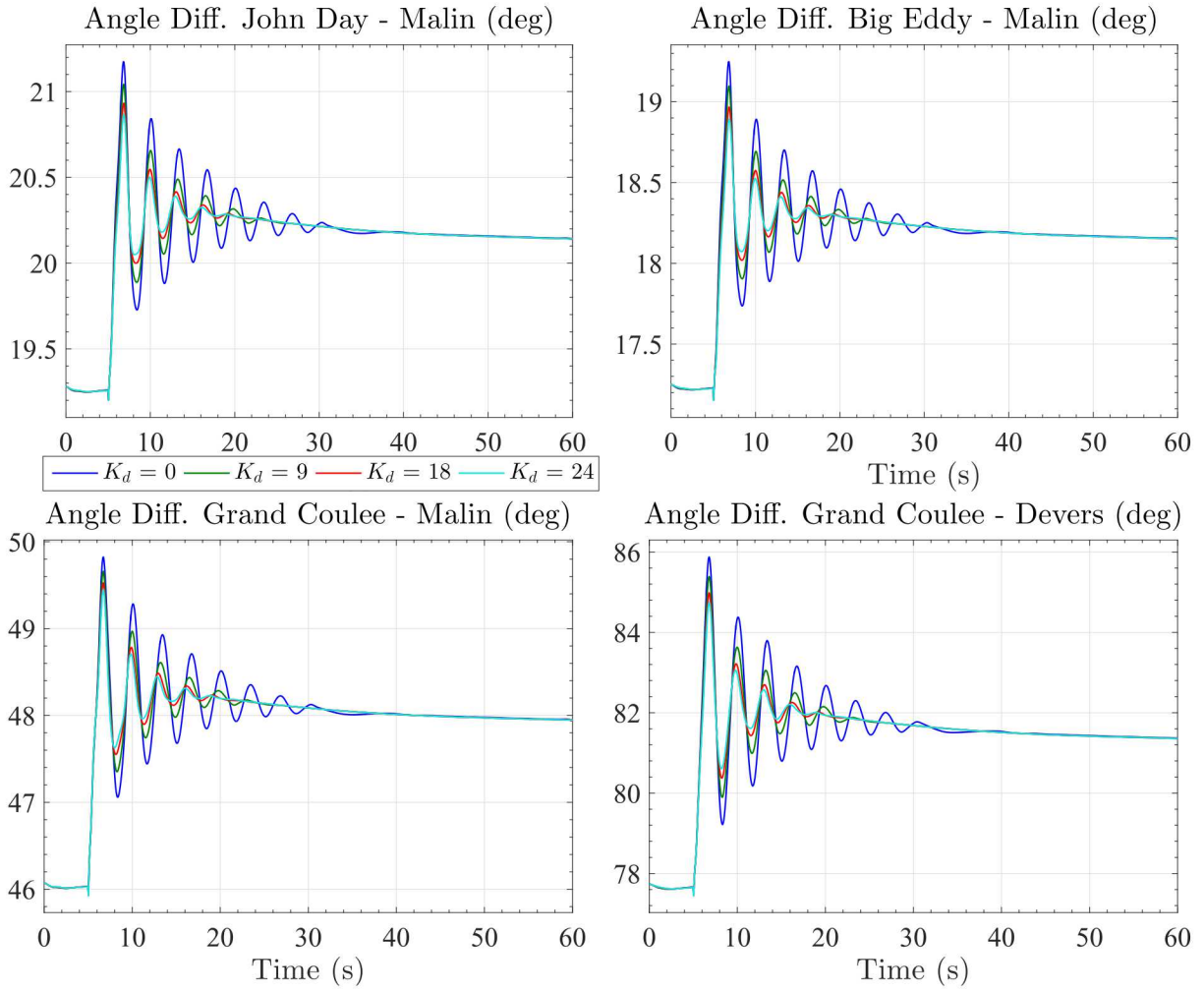
### 3.4. Test System: Heavy Summer 2016. Event: BC-AB Separation



**Figure 119. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-AB Separation**

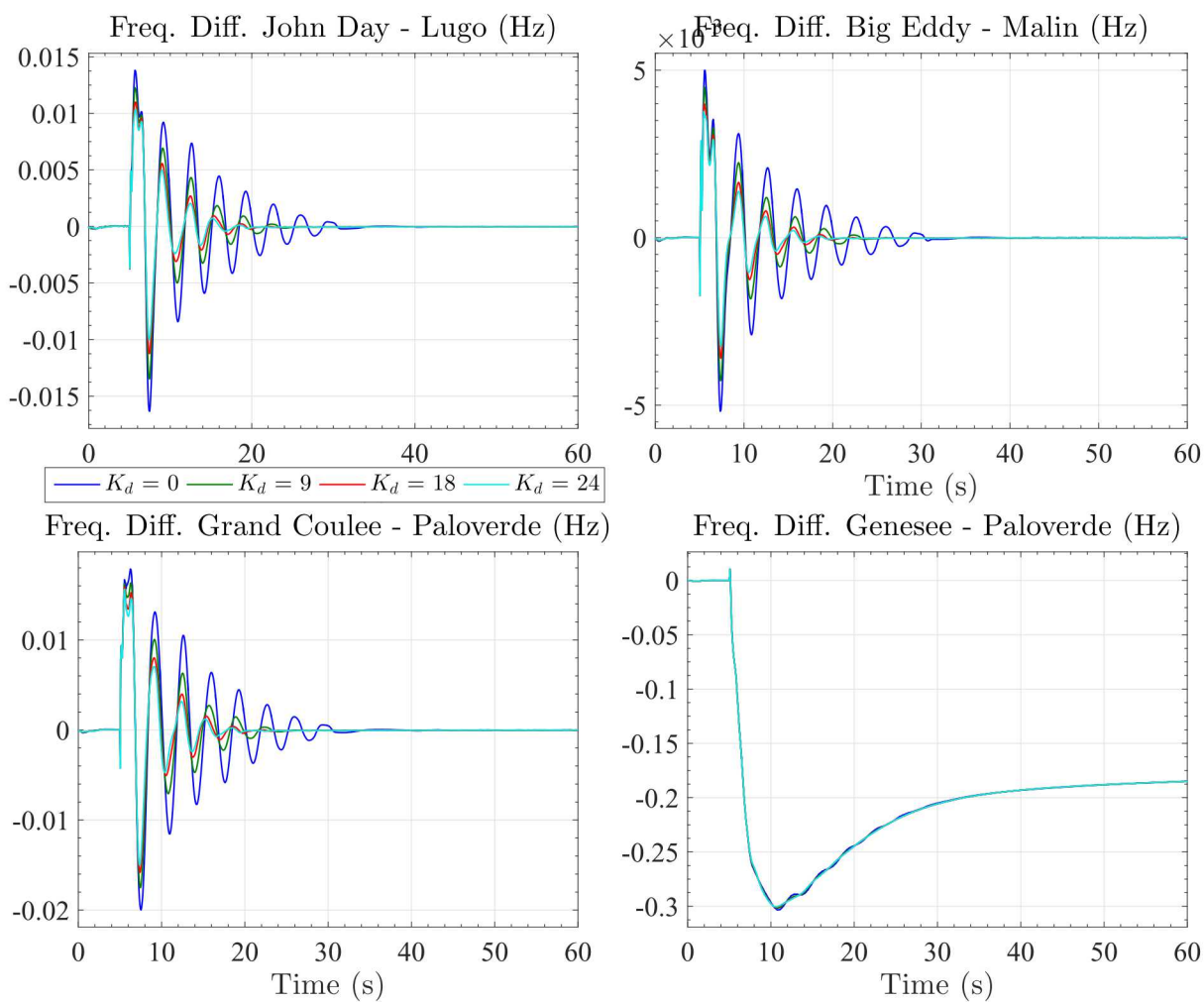


**Figure 120. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-AB Separation**

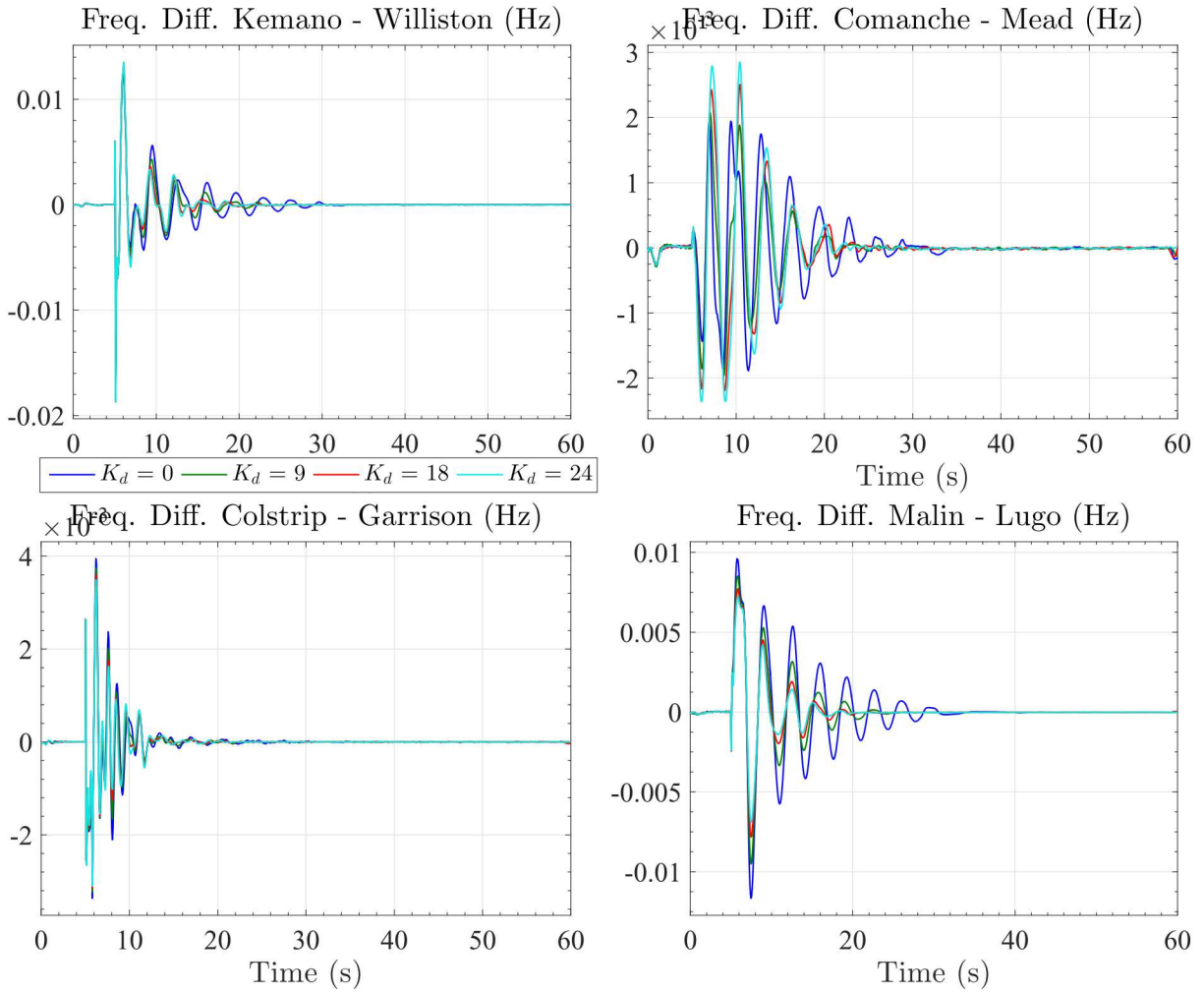


**Figure 121. Angle differences. Event: BC-AB Separation**

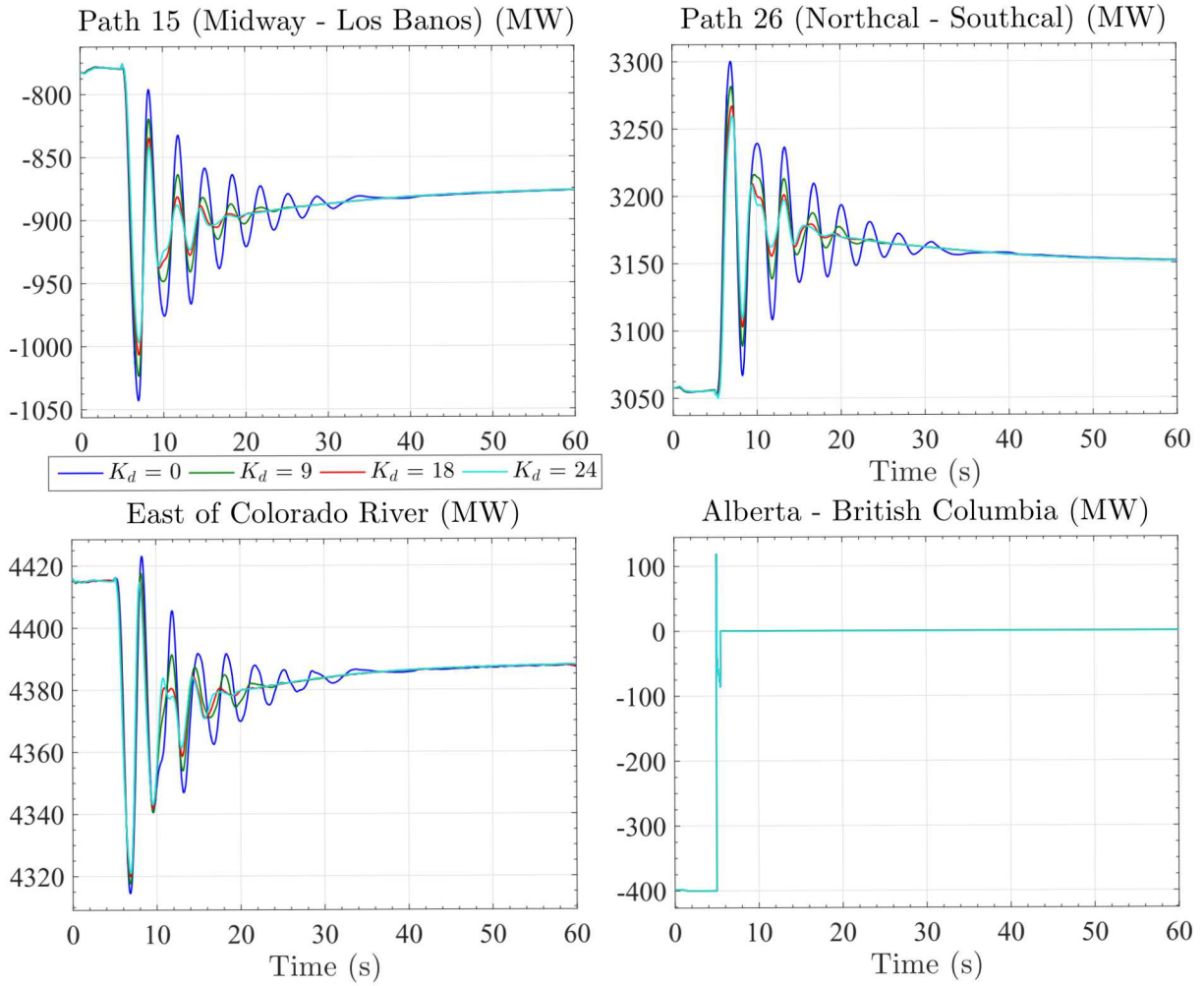




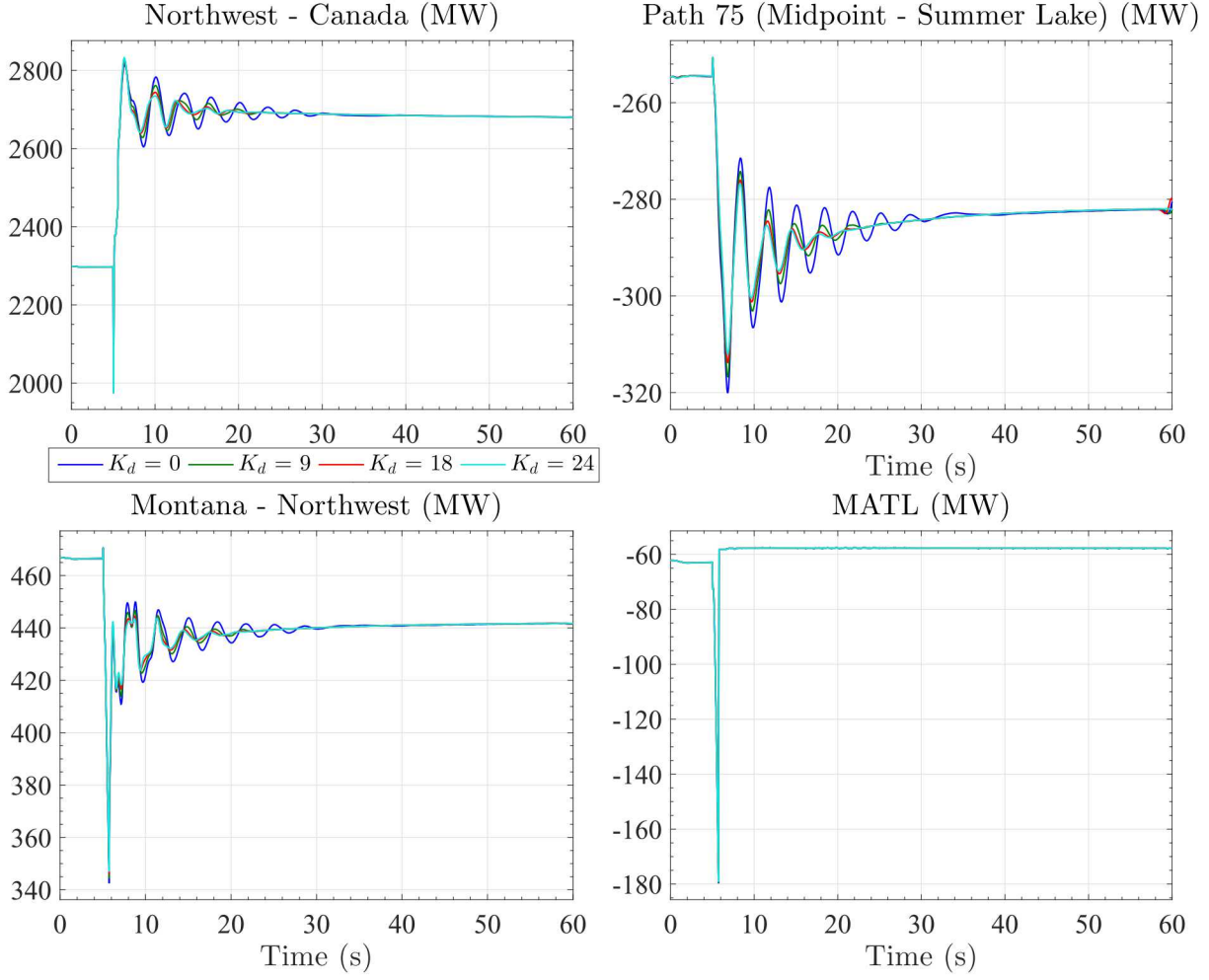
**Figure 122. Frequency differences. Event: BC-AB Separation**



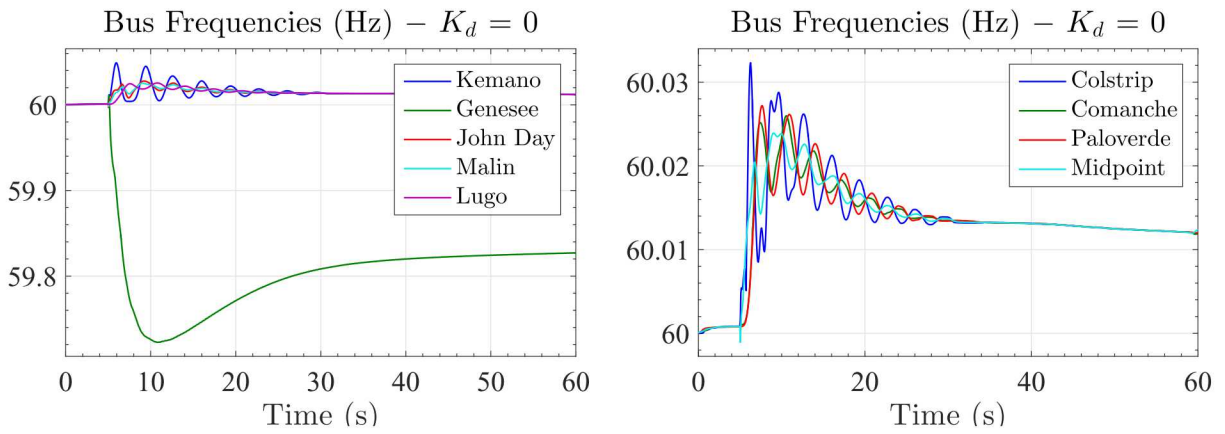
**Figure 123. Frequency differences. Event: BC-AB Separation**



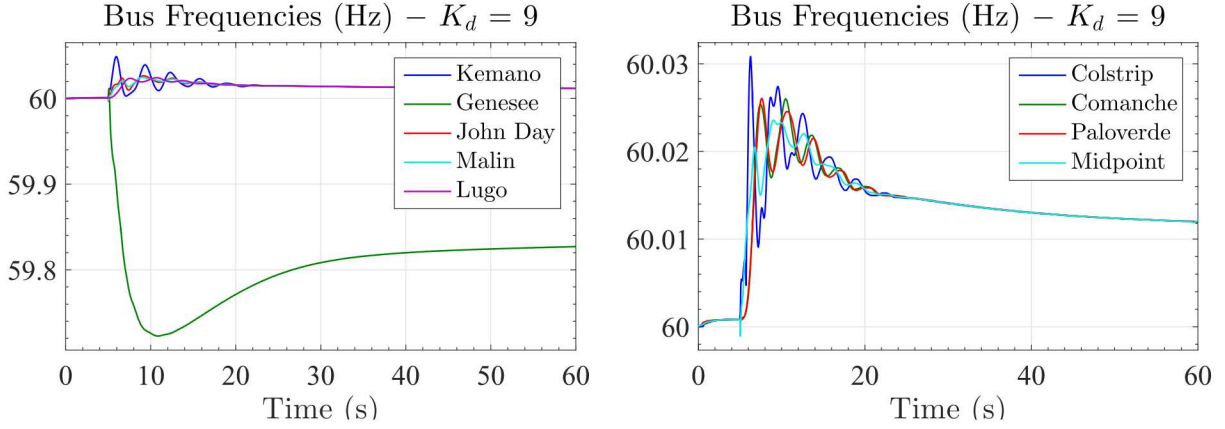
**Figure 124. Active power flows. Event: BC-AB Separation**



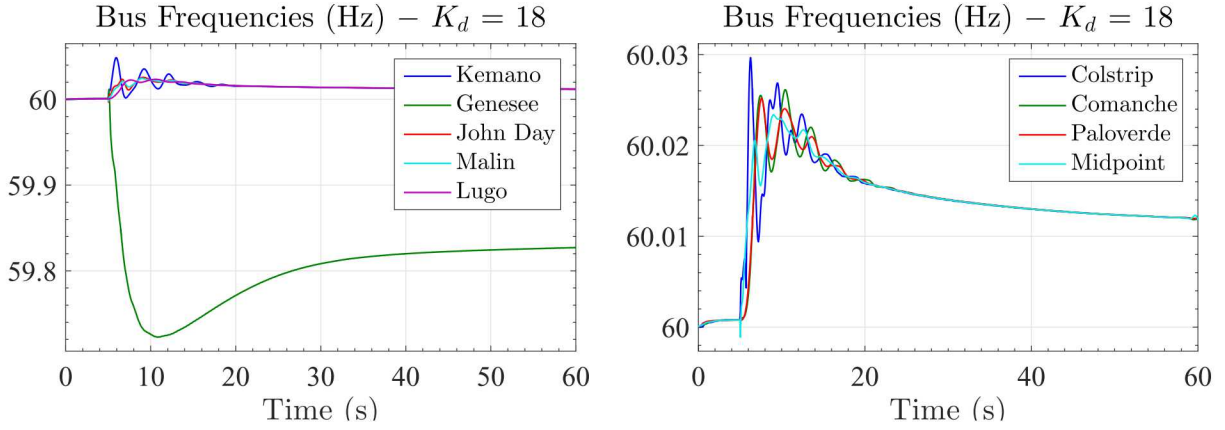
**Figure 125. Active power flows. Event: BC-AB Separation**



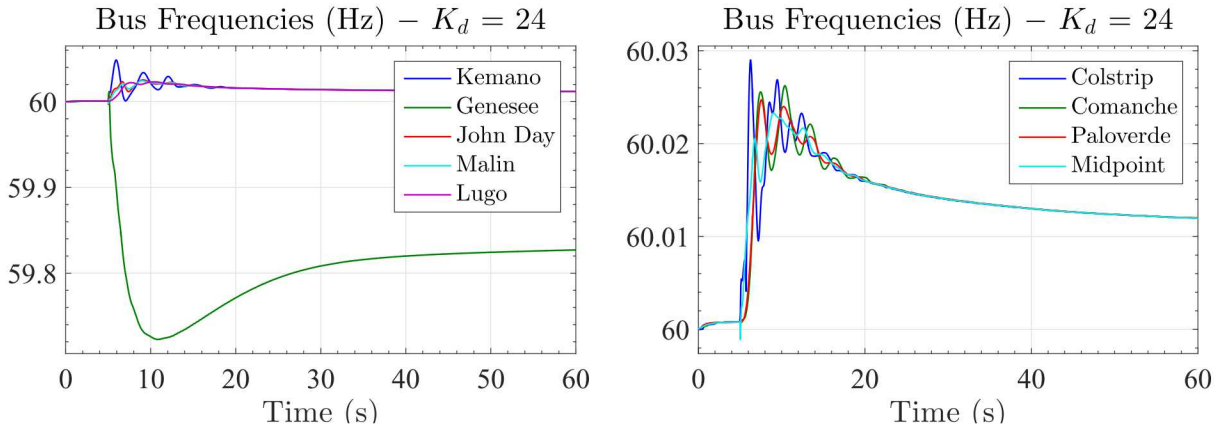
**Figure 126. Bus frequencies. Event: BC-AB Separation**



**Figure 127. Bus frequencies. Event: BC-AB Separation**

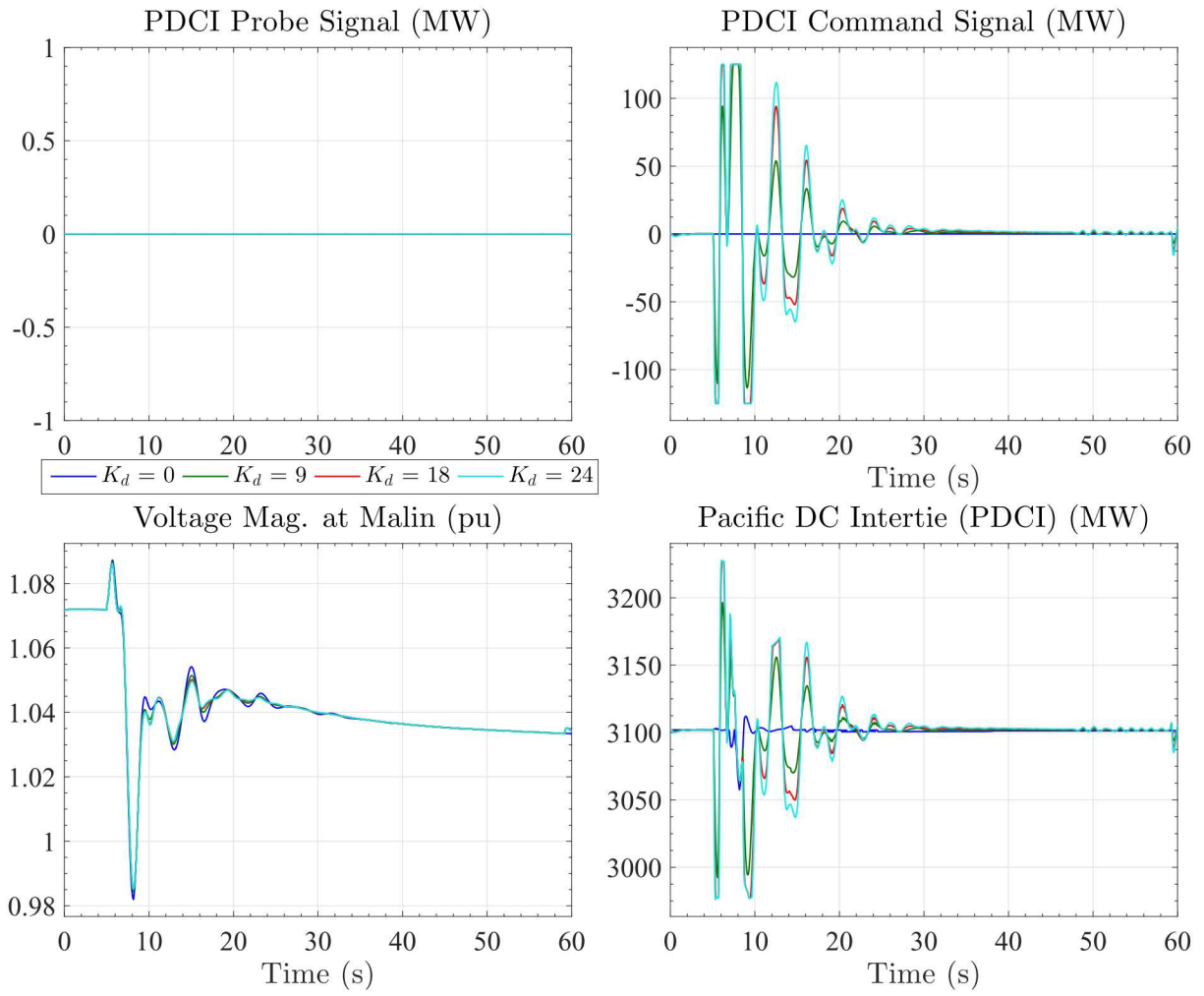


**Figure 128. Bus frequencies. Event: BC-AB Separation**



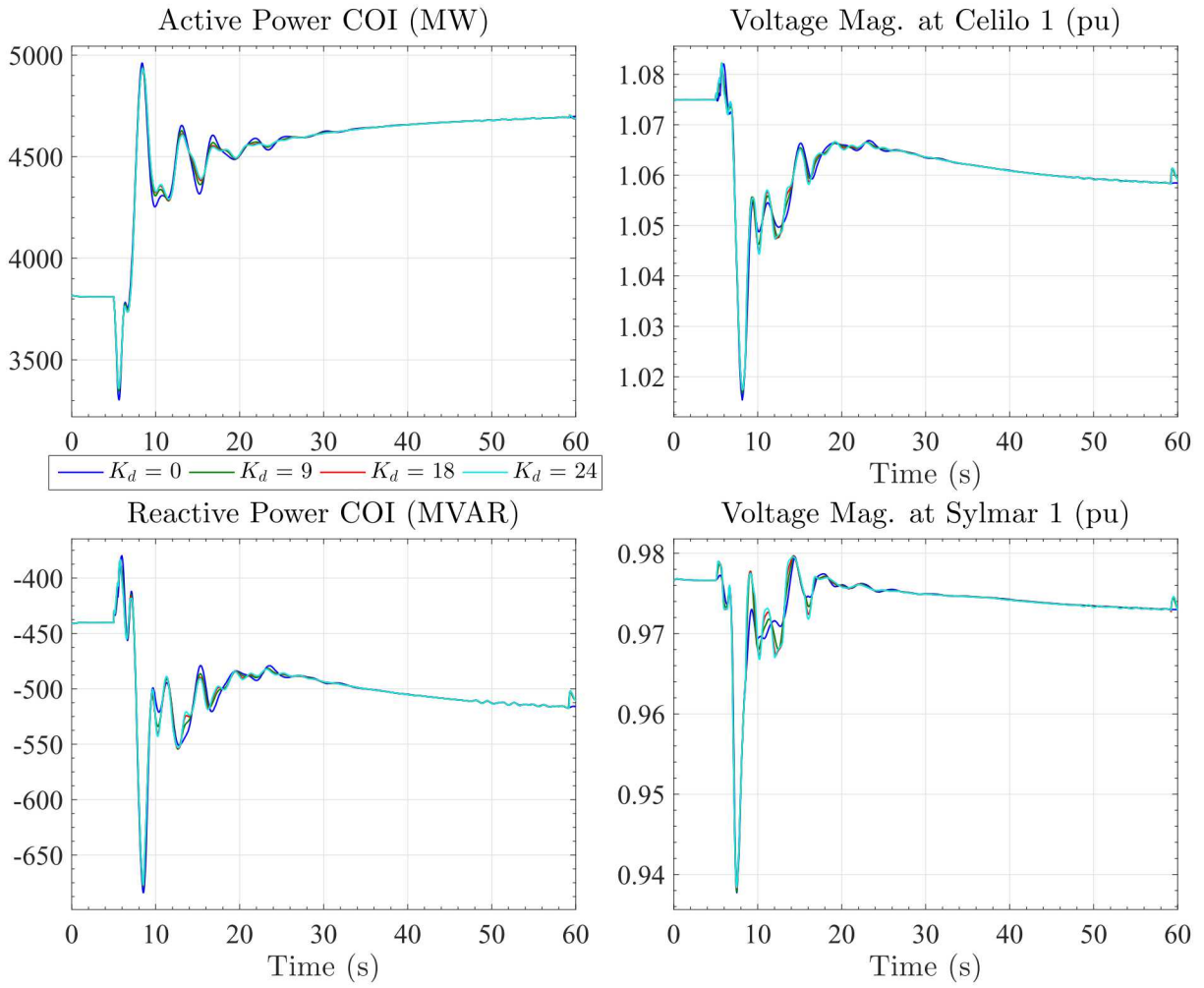
**Figure 129. Bus frequencies. Event: BC-AB Separation**

### 3.5. Test System: Heavy Summer 2016. Event: CJB + 2PV

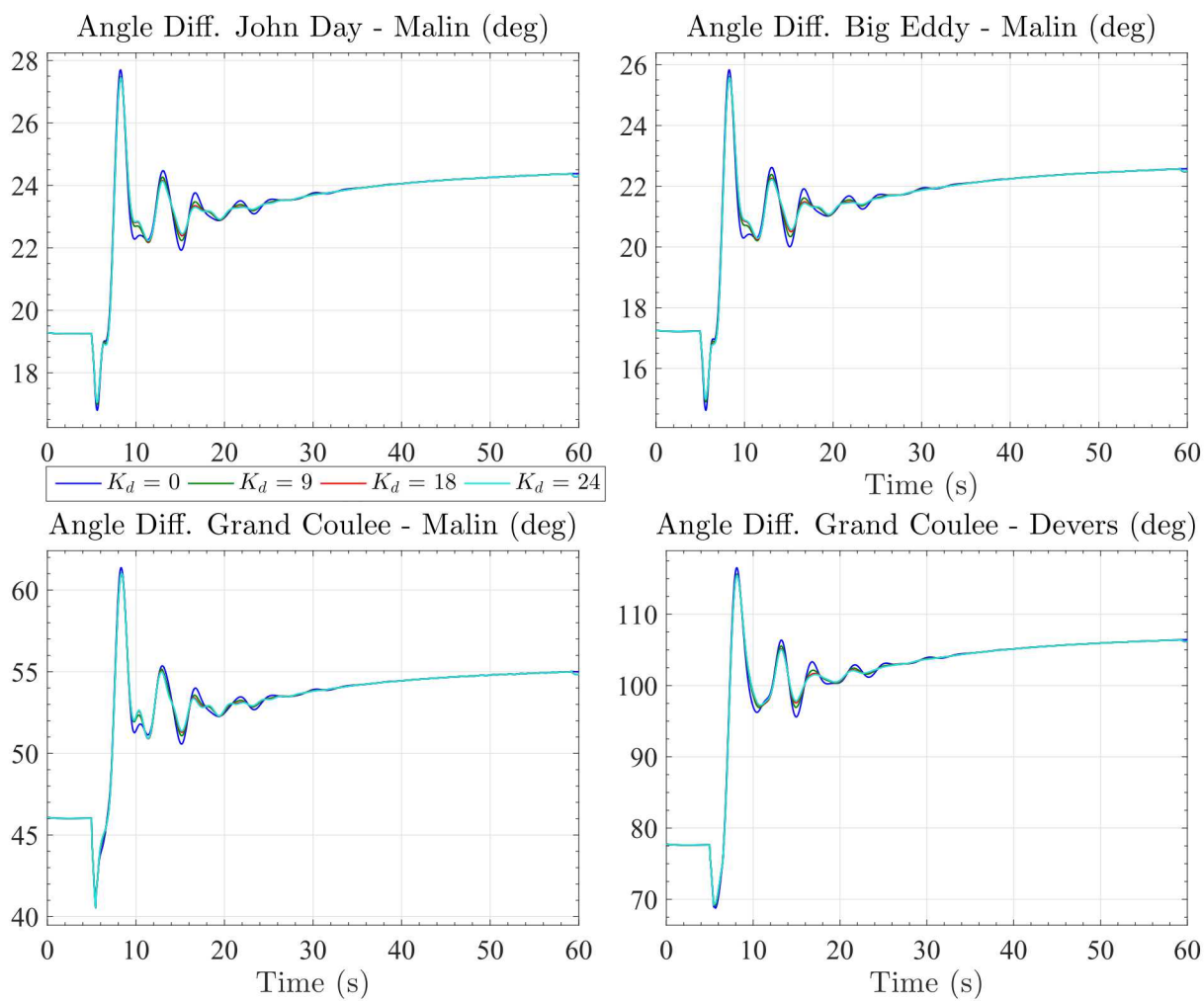


**Figure 130. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + 2PV**

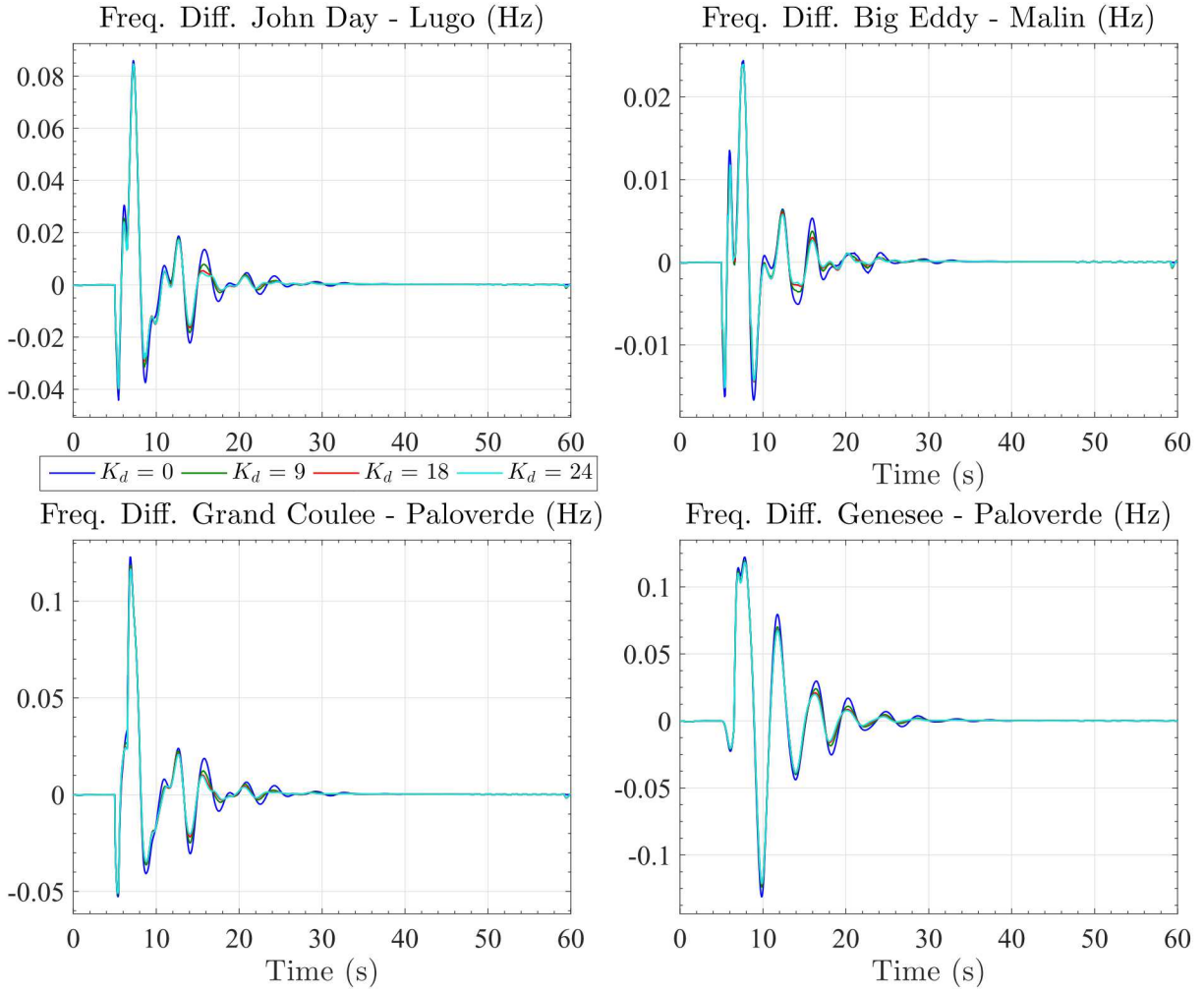




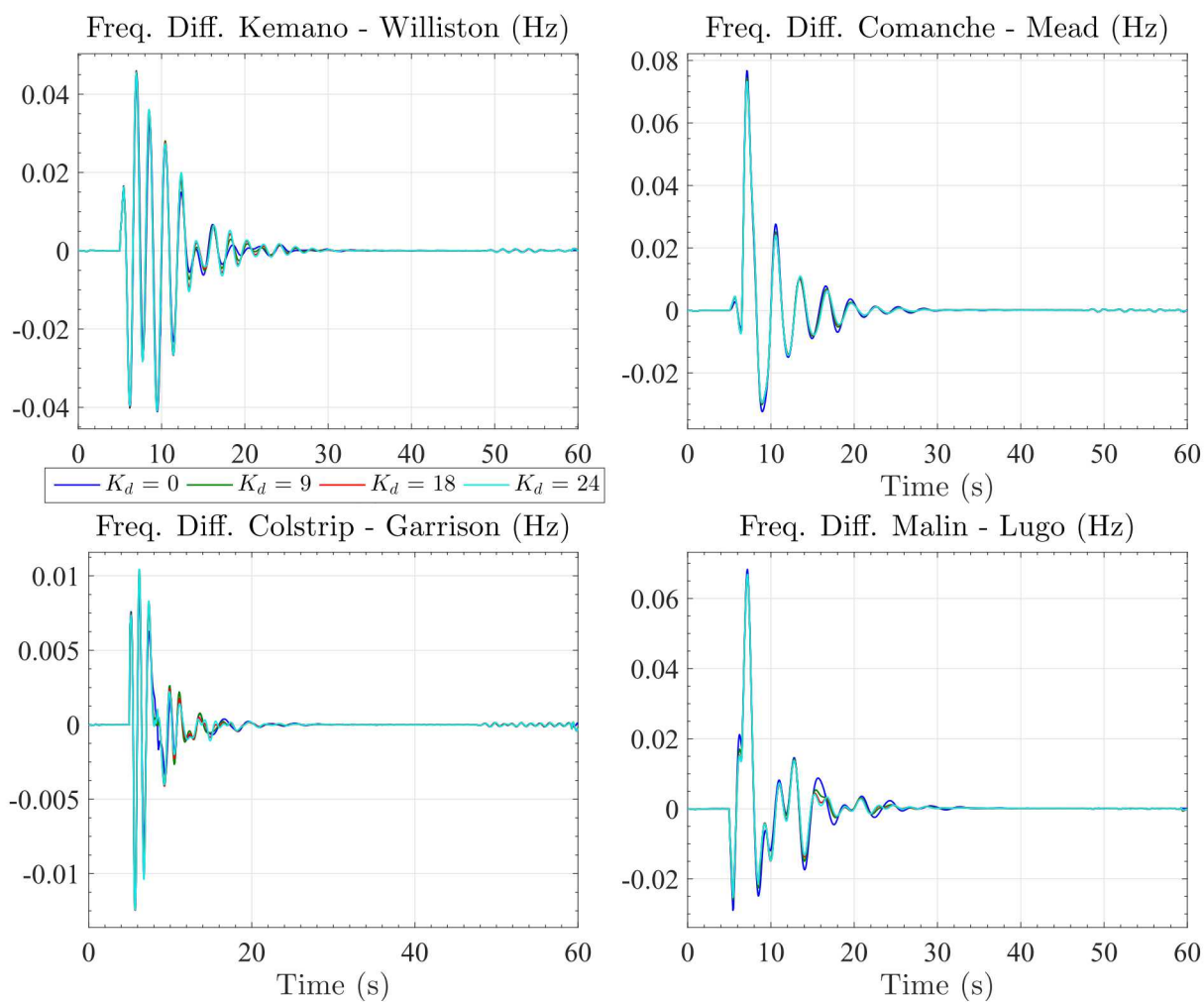
**Figure 131. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + 2PV**



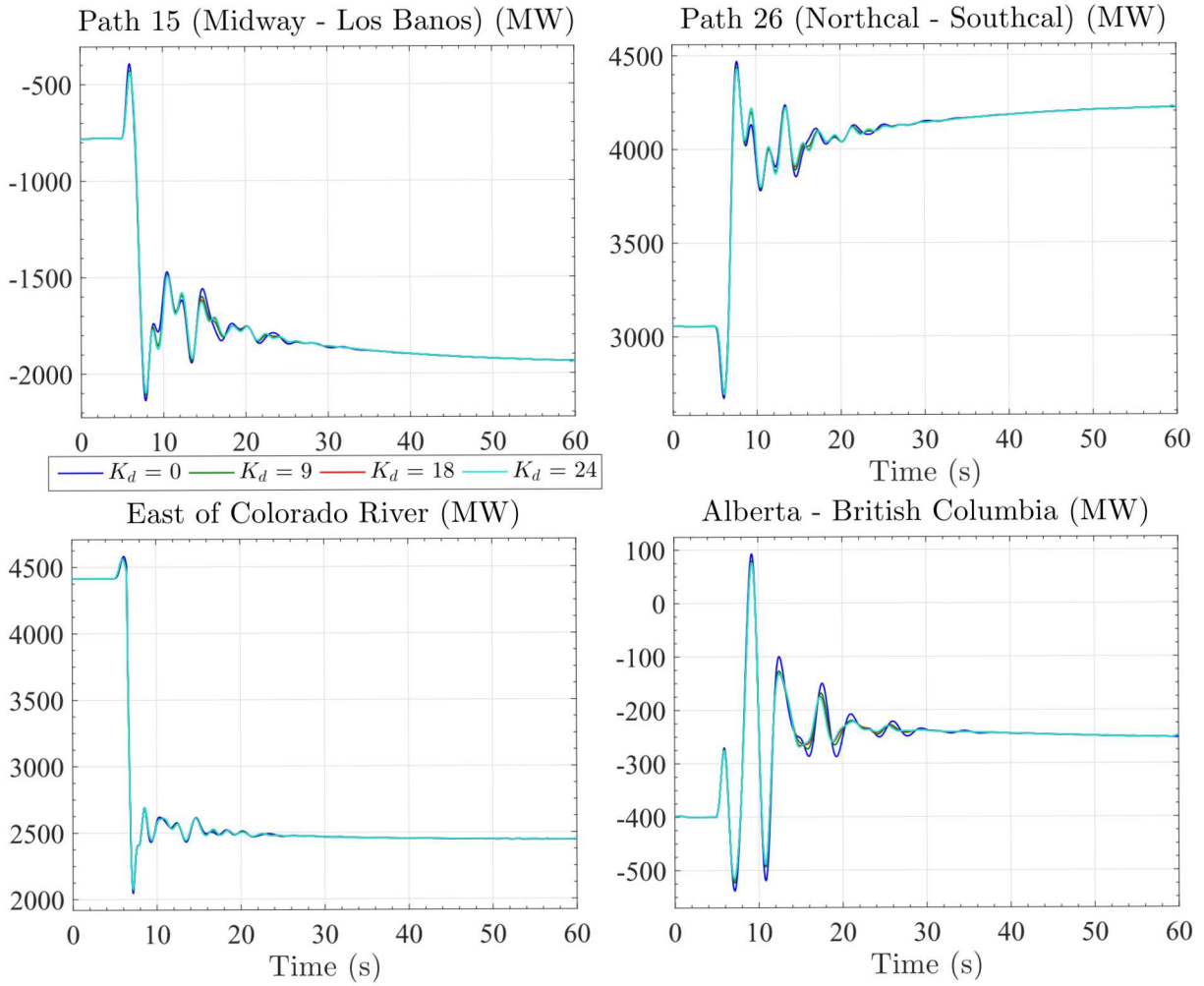
**Figure 132. Angle differences. Event: CJB + 2PV**



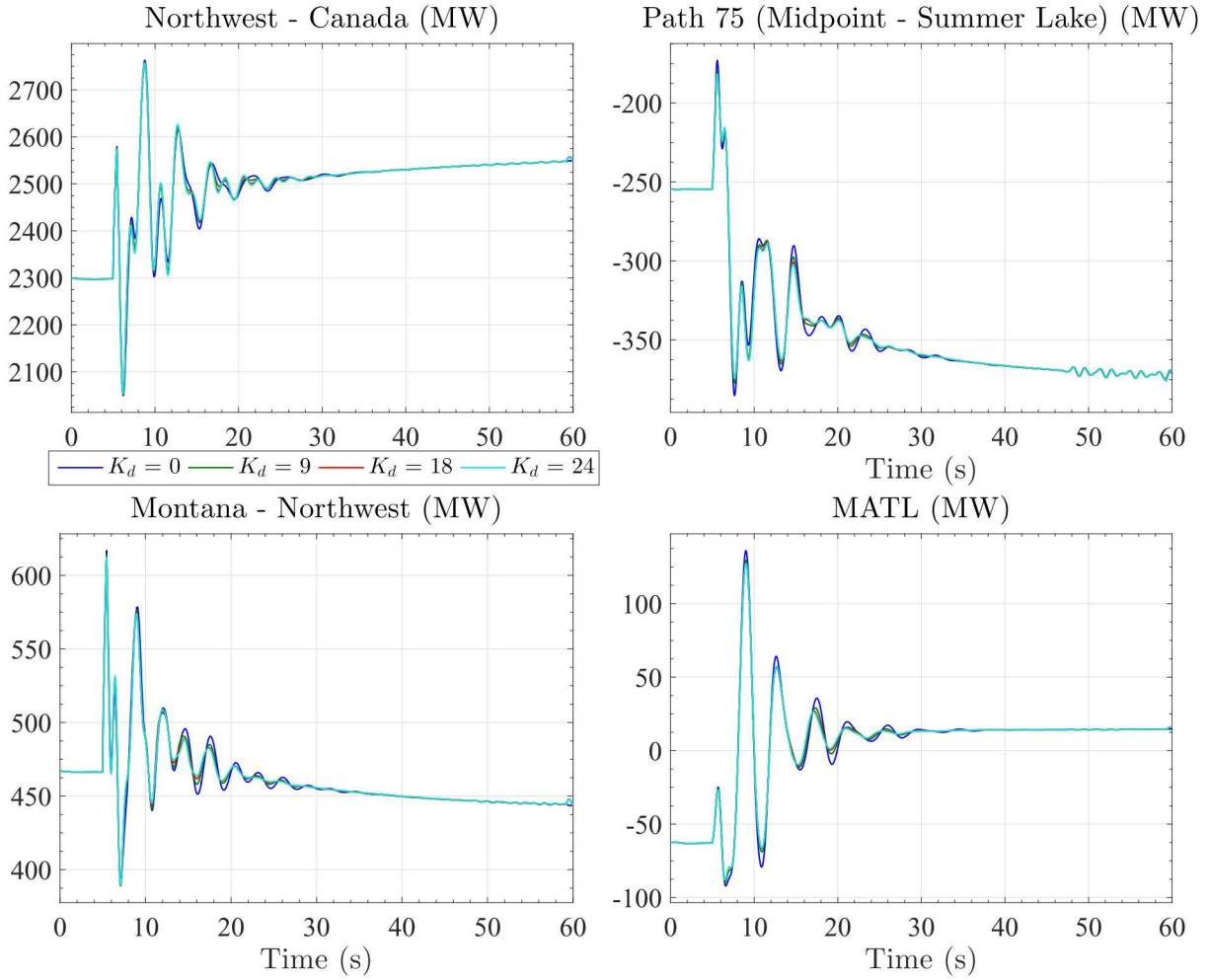
**Figure 133. Frequency differences. Event: CJB + 2PV**



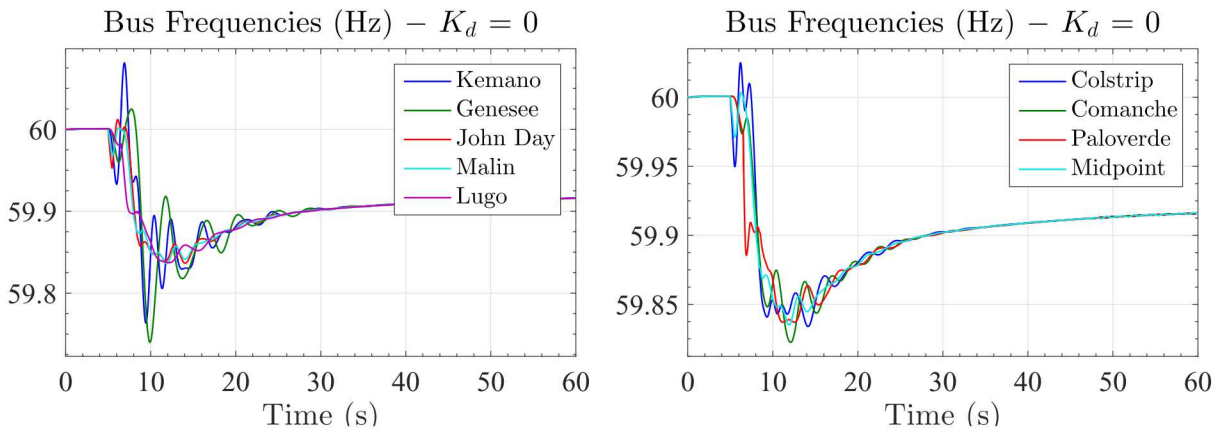
**Figure 134. Frequency differences. Event: CJB + 2PV**



**Figure 135. Active power flows. Event: CJB + 2PV**

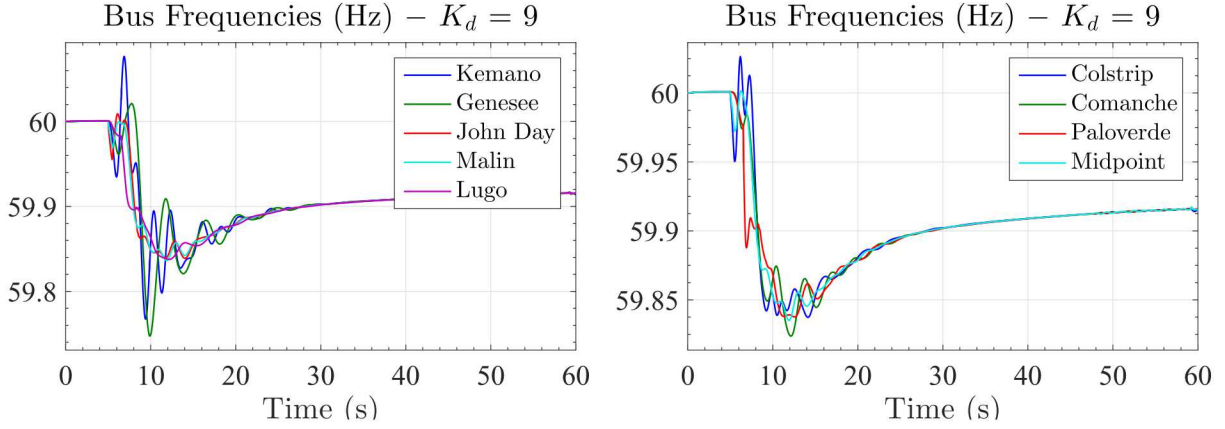


**Figure 136. Active power flows. Event: CJB + 2PV**

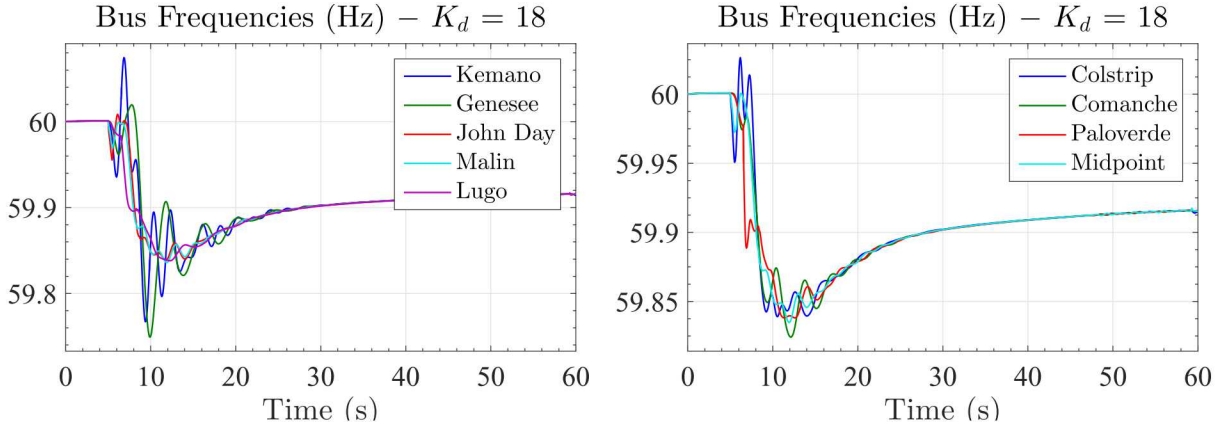


**Figure 137. Bus frequencies. Event: CJB + 2PV**

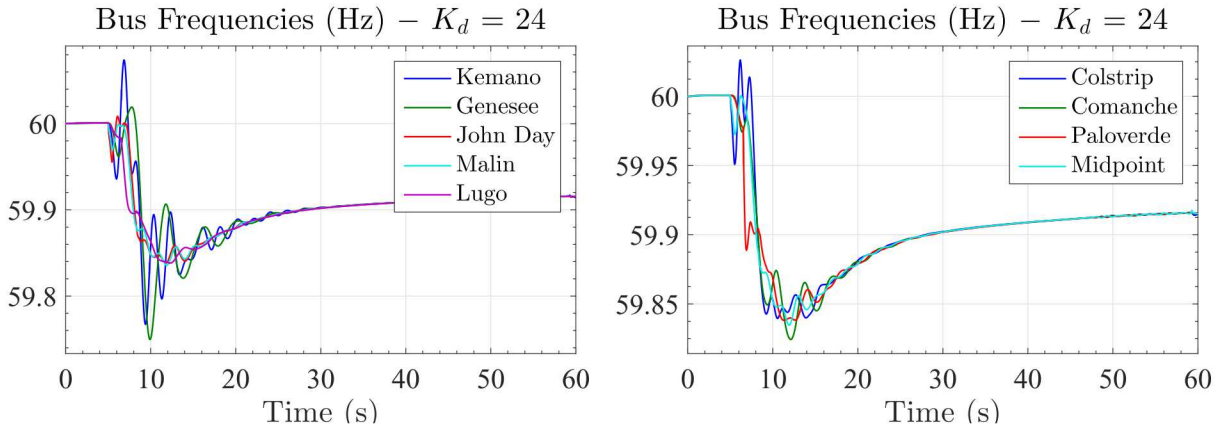




**Figure 138. Bus frequencies. Event: CJB + 2PV**

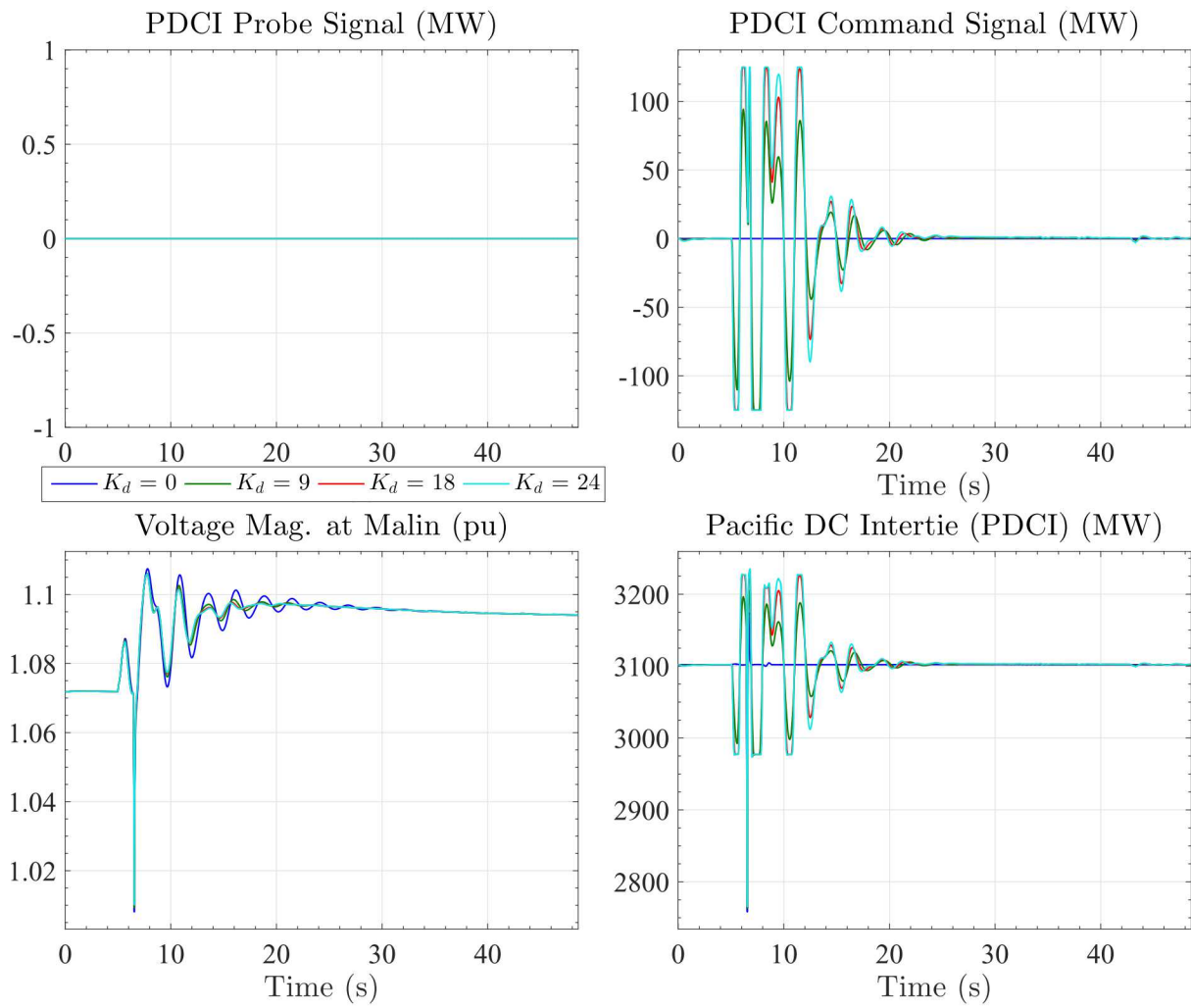


**Figure 139. Bus frequencies. Event: CJB + 2PV**

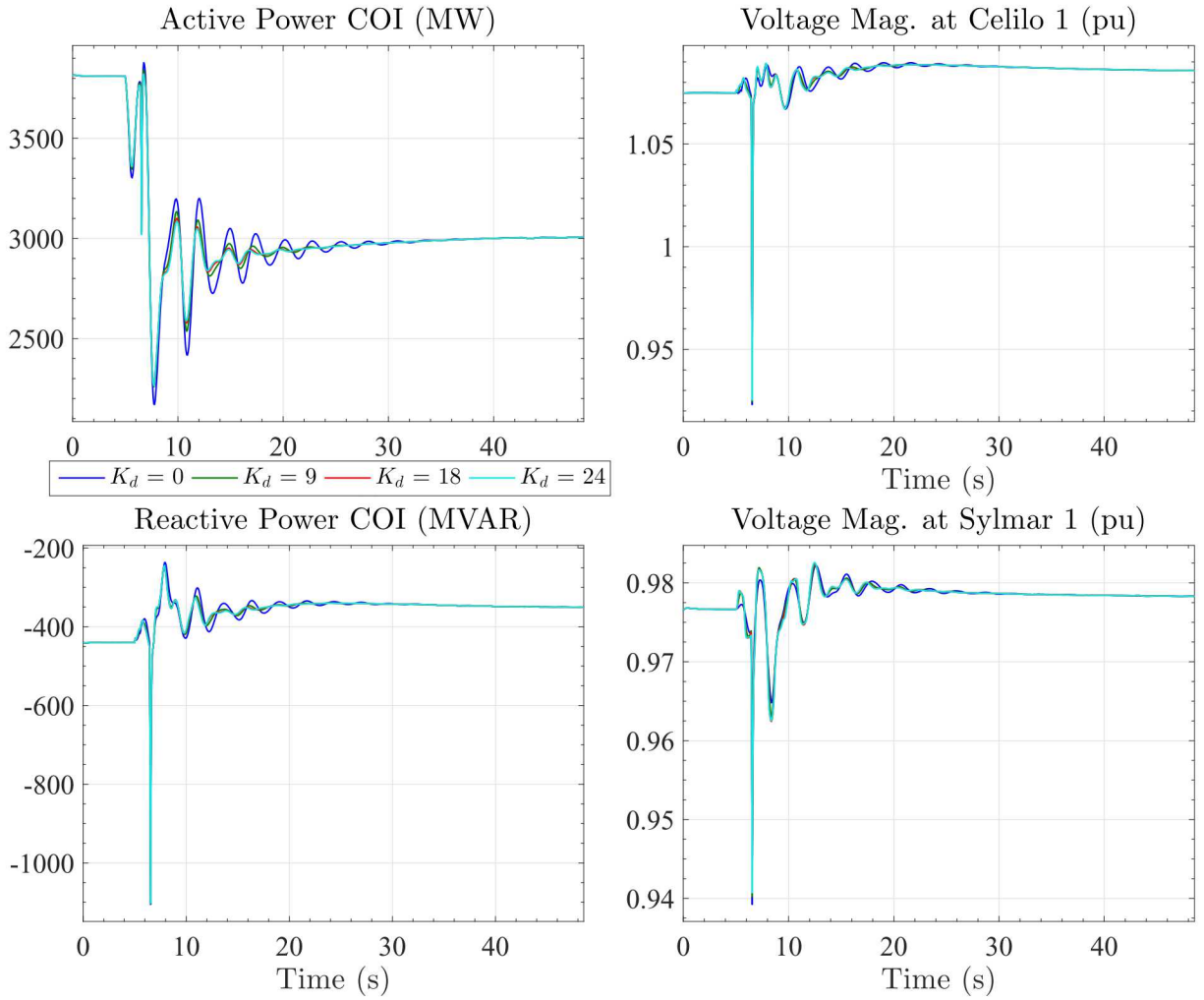


**Figure 140. Bus frequencies. Event: CJB + 2PV**

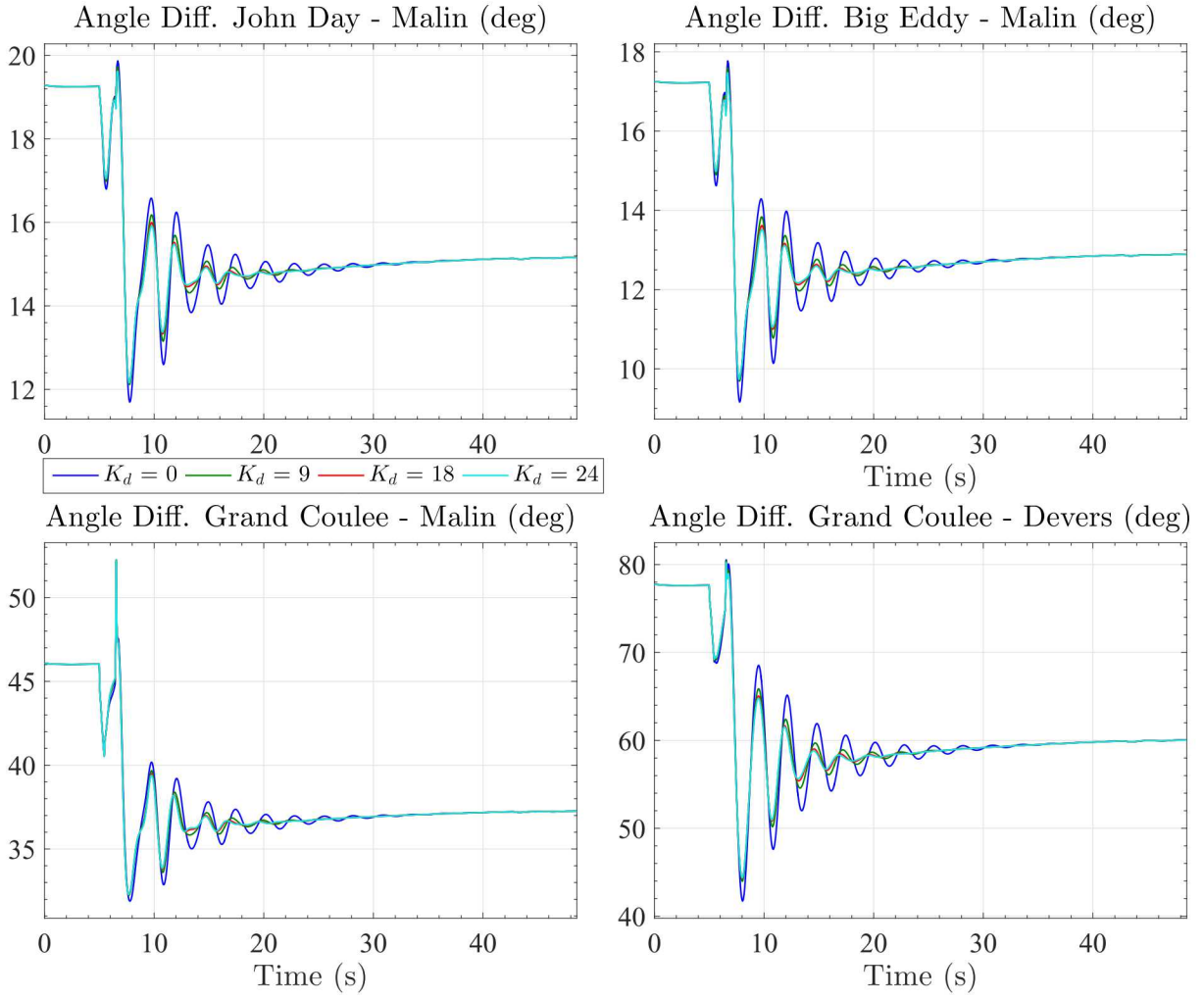
### 3.6. Test System: Heavy Summer 2016. Event: CJB + BCUS Separation



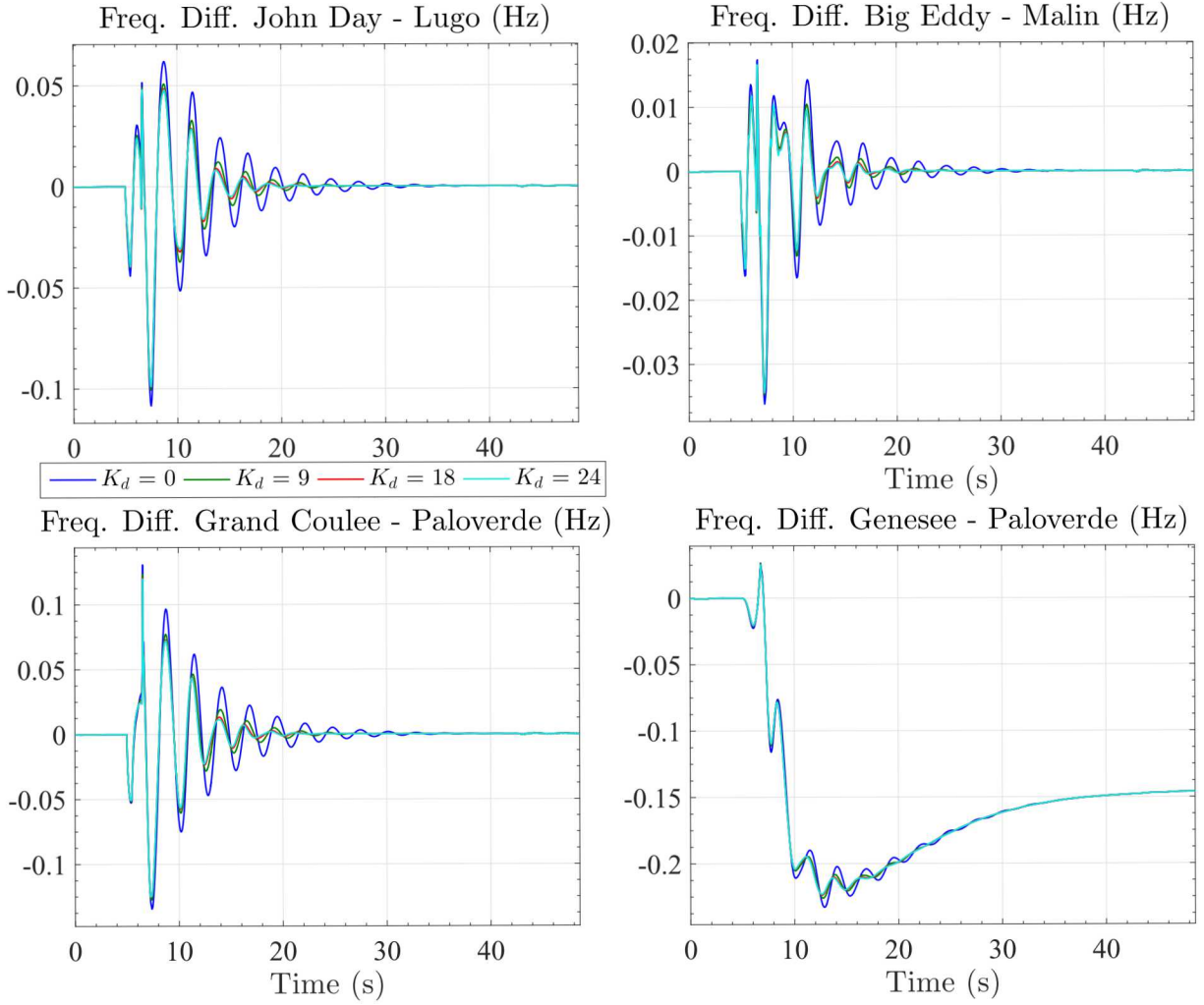
**Figure 141. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCUS Separation**



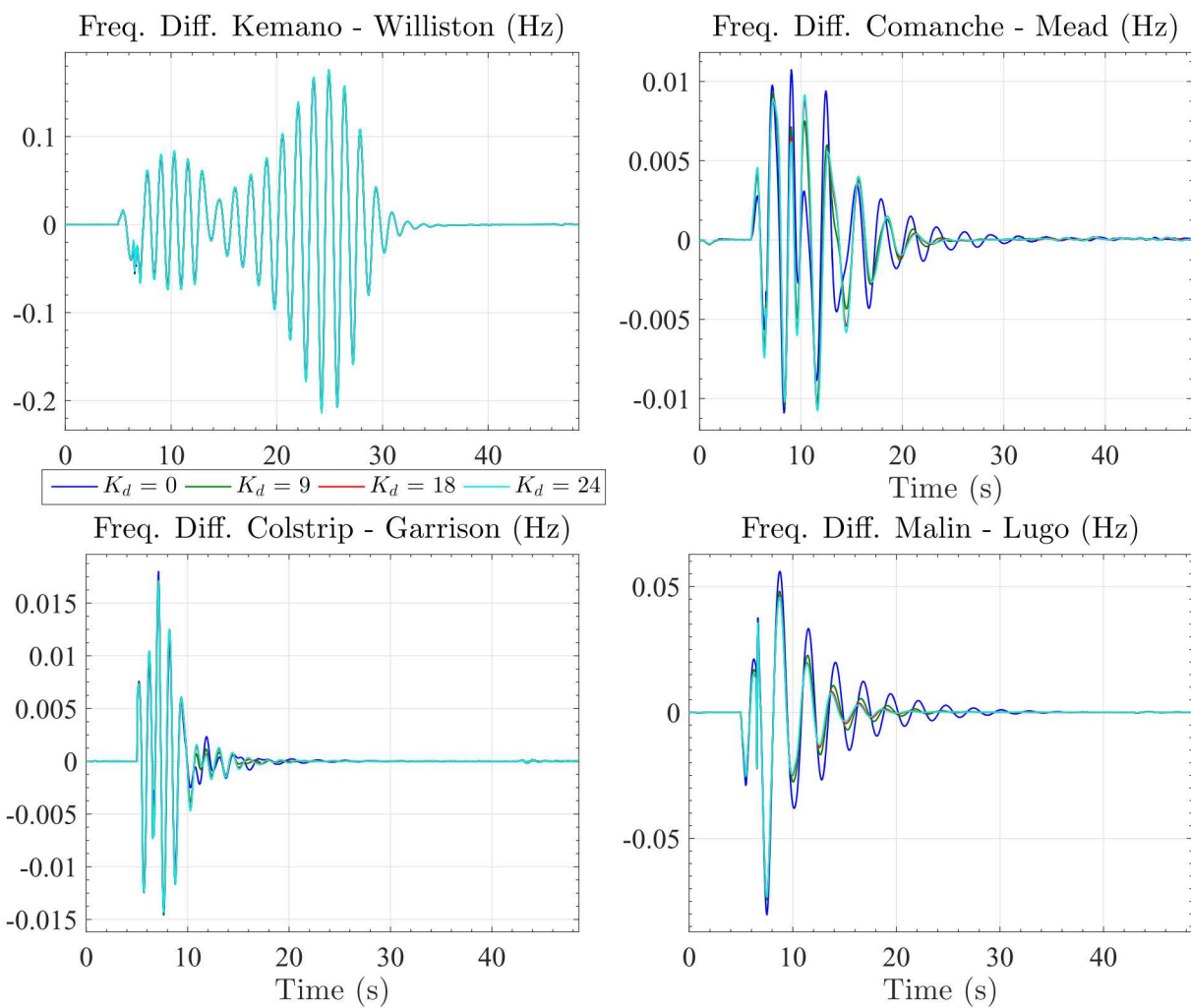
**Figure 142. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCUS Separation**



**Figure 143. Angle differences. Event: CJB + BCUS Separation**

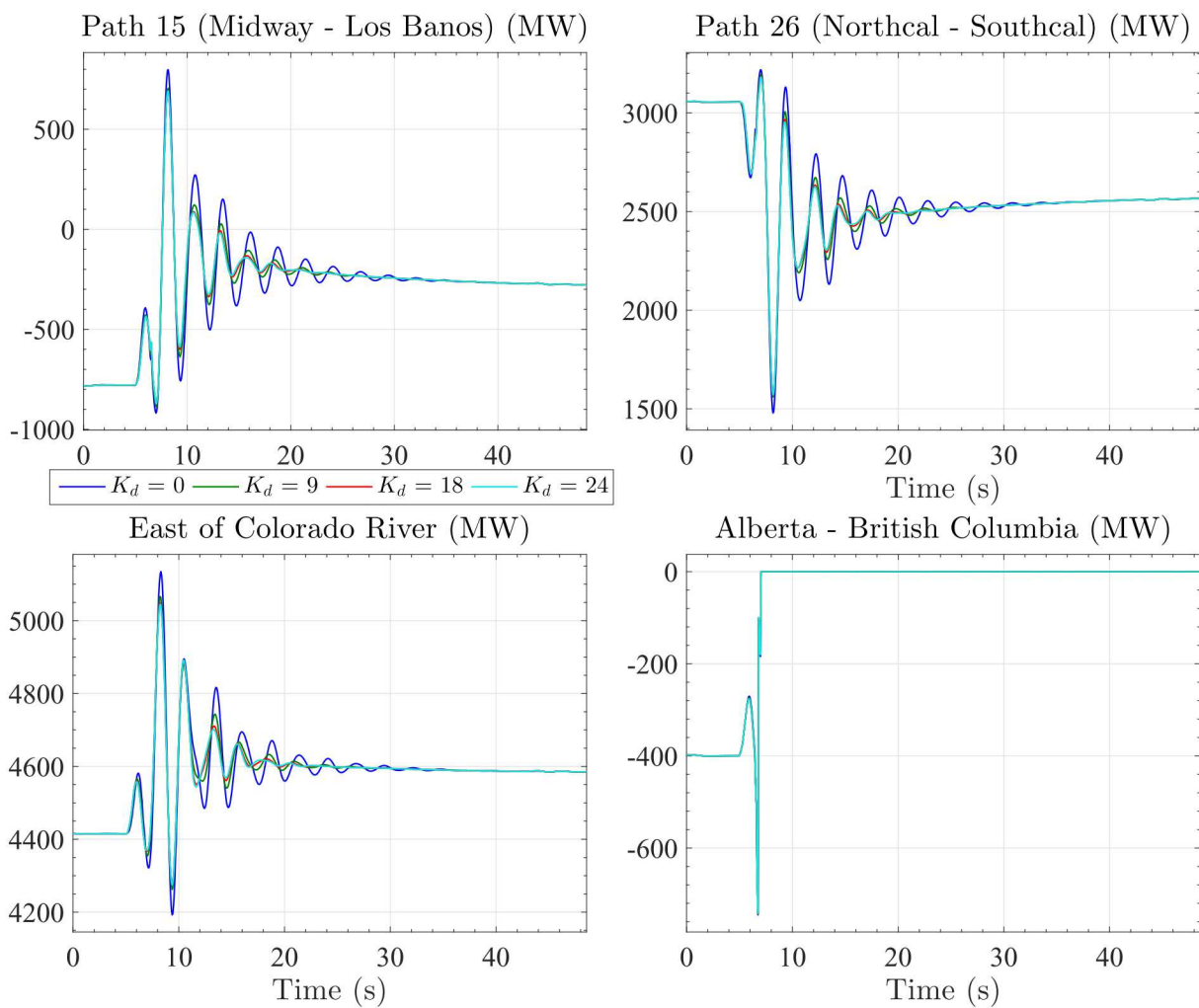


**Figure 144. Frequency differences. Event: CJB + BCUS Separation**

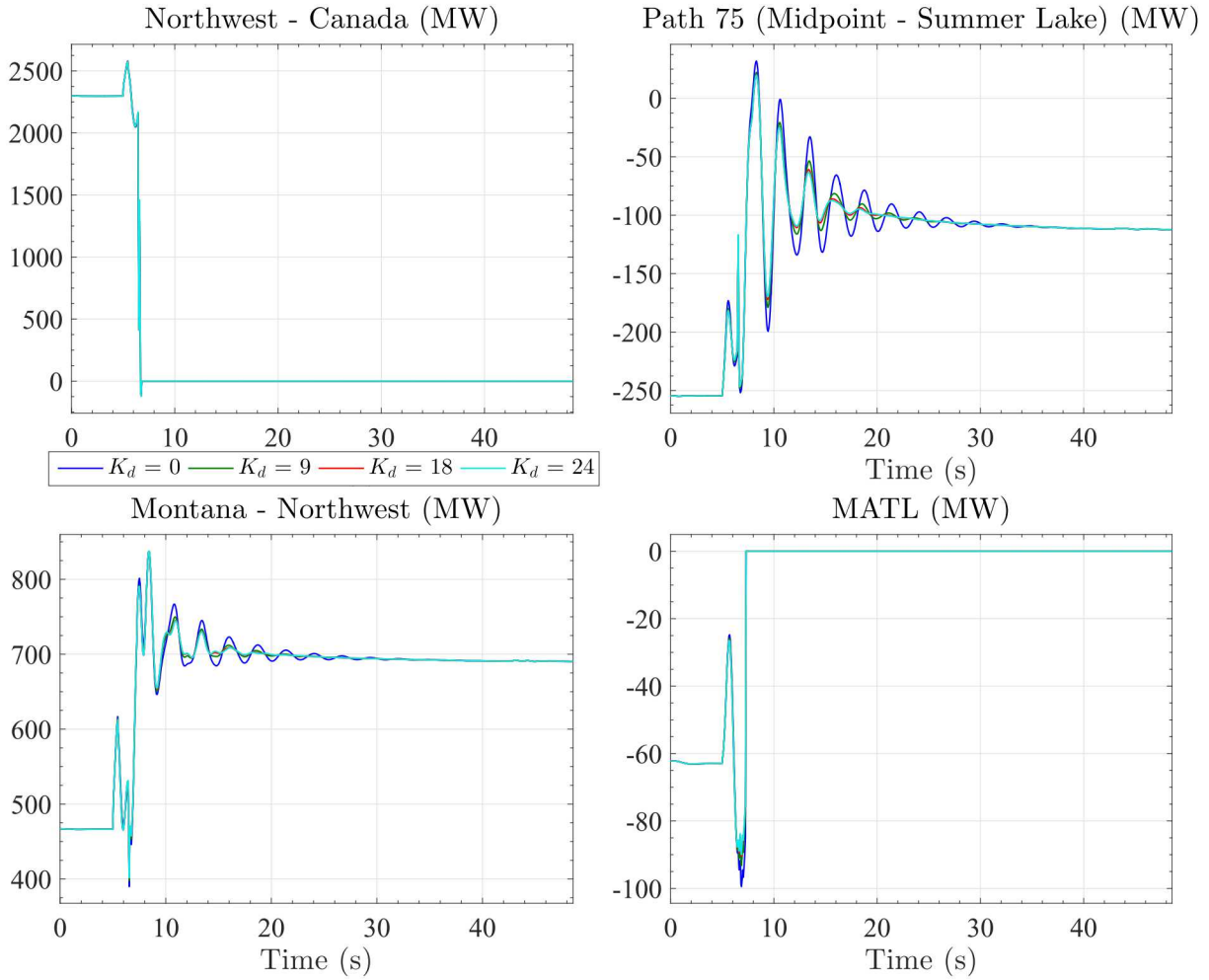


**Figure 145. Frequency differences. Event: CJB + BCUS Separation**

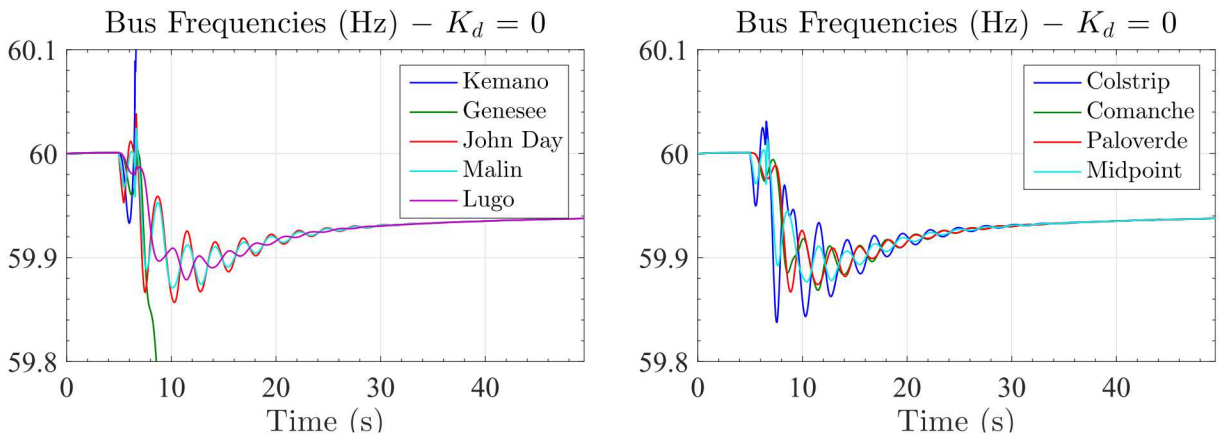




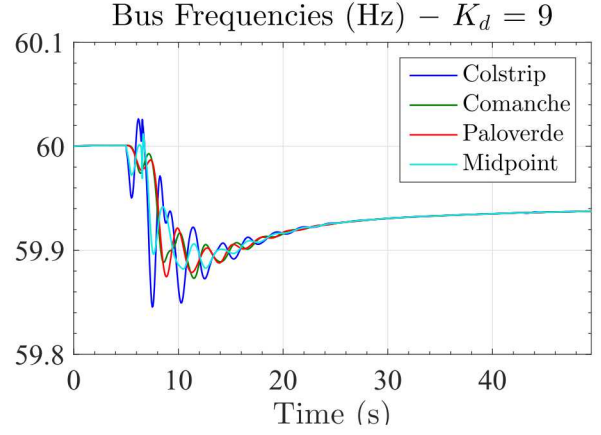
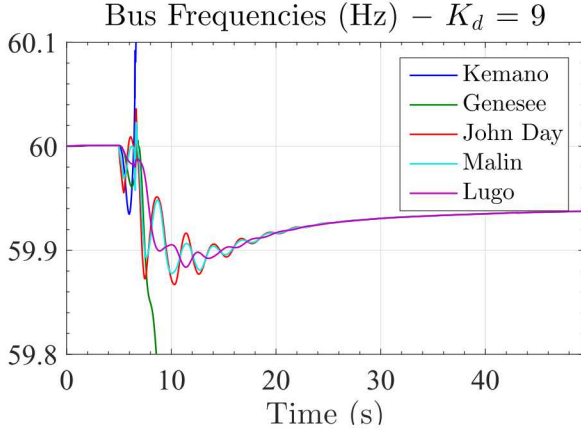
**Figure 146. Active power flows. Event: CJB + BCUS Separation**



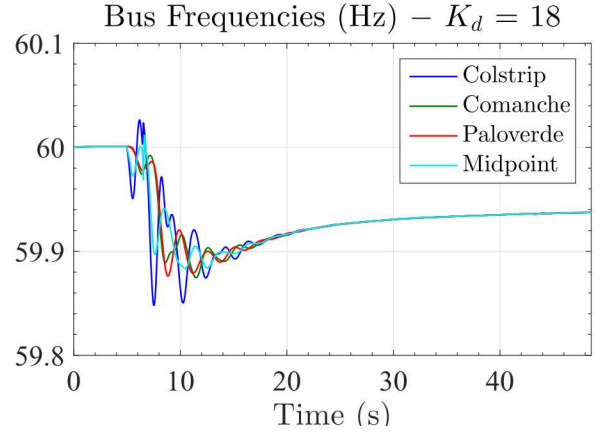
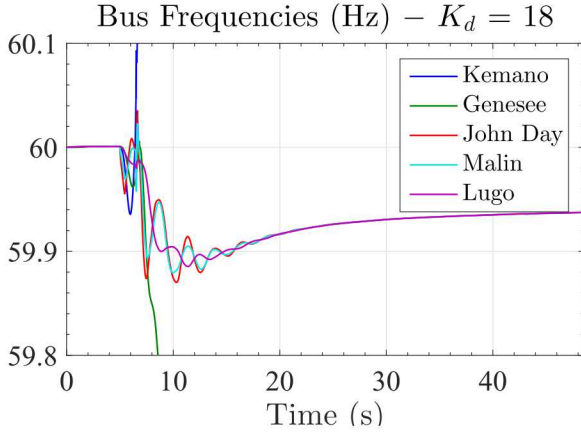
**Figure 147. Active power flows. Event: CJB + BCUS Separation**



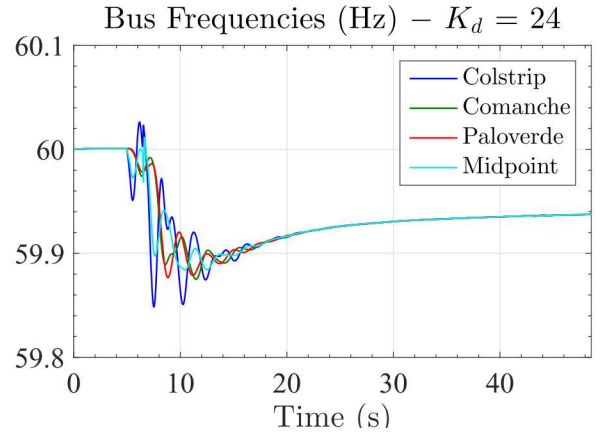
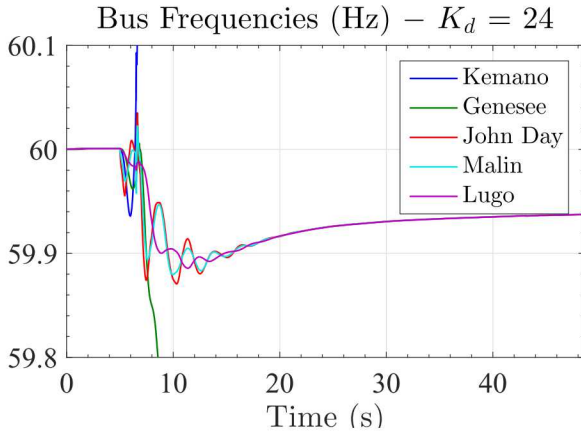
**Figure 148. Bus frequencies. Event: CJB + BCUS Separation**



**Figure 149. Bus frequencies. Event: CJB + BCUS Separation**

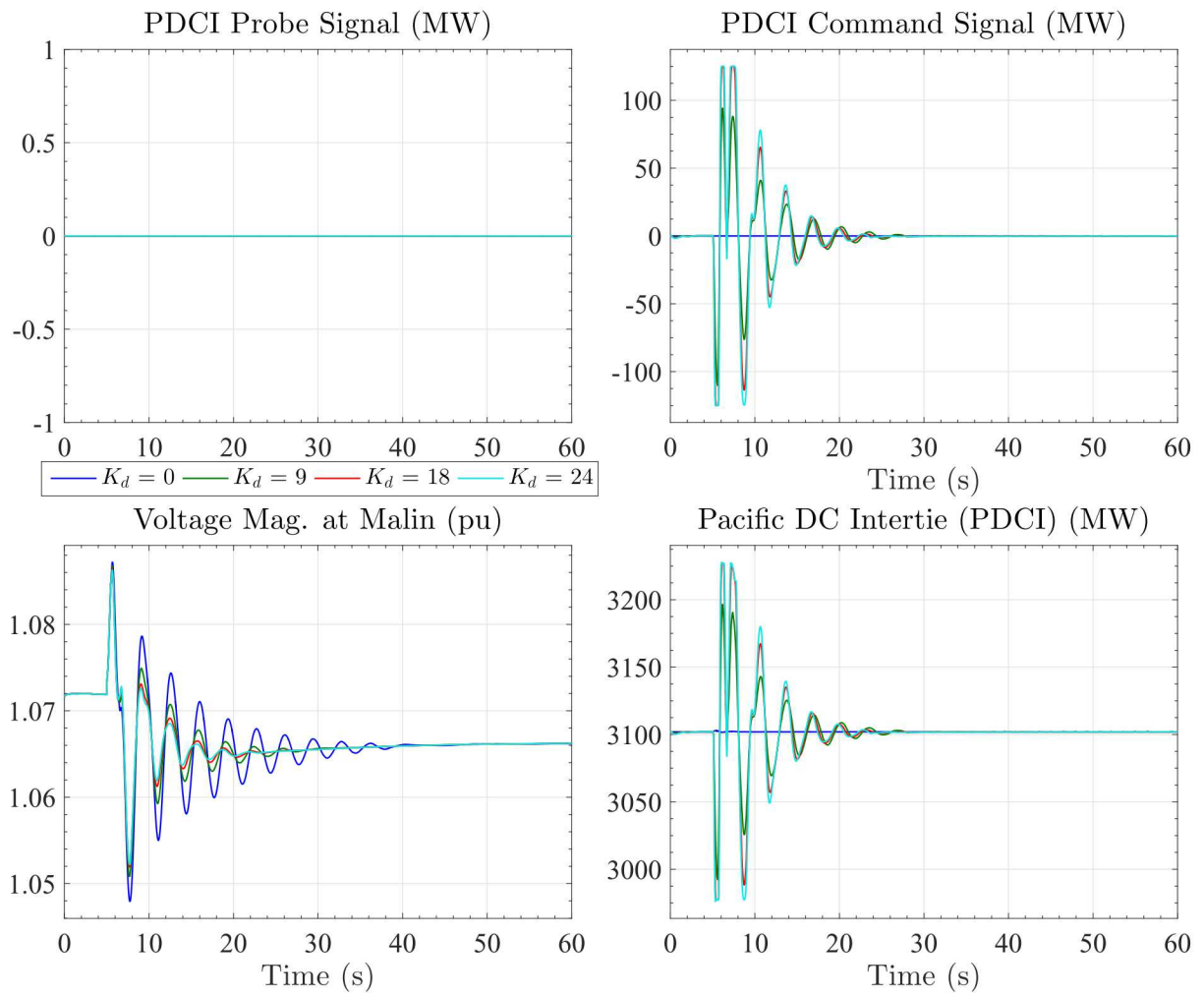


**Figure 150. Bus frequencies. Event: CJB + BCUS Separation**

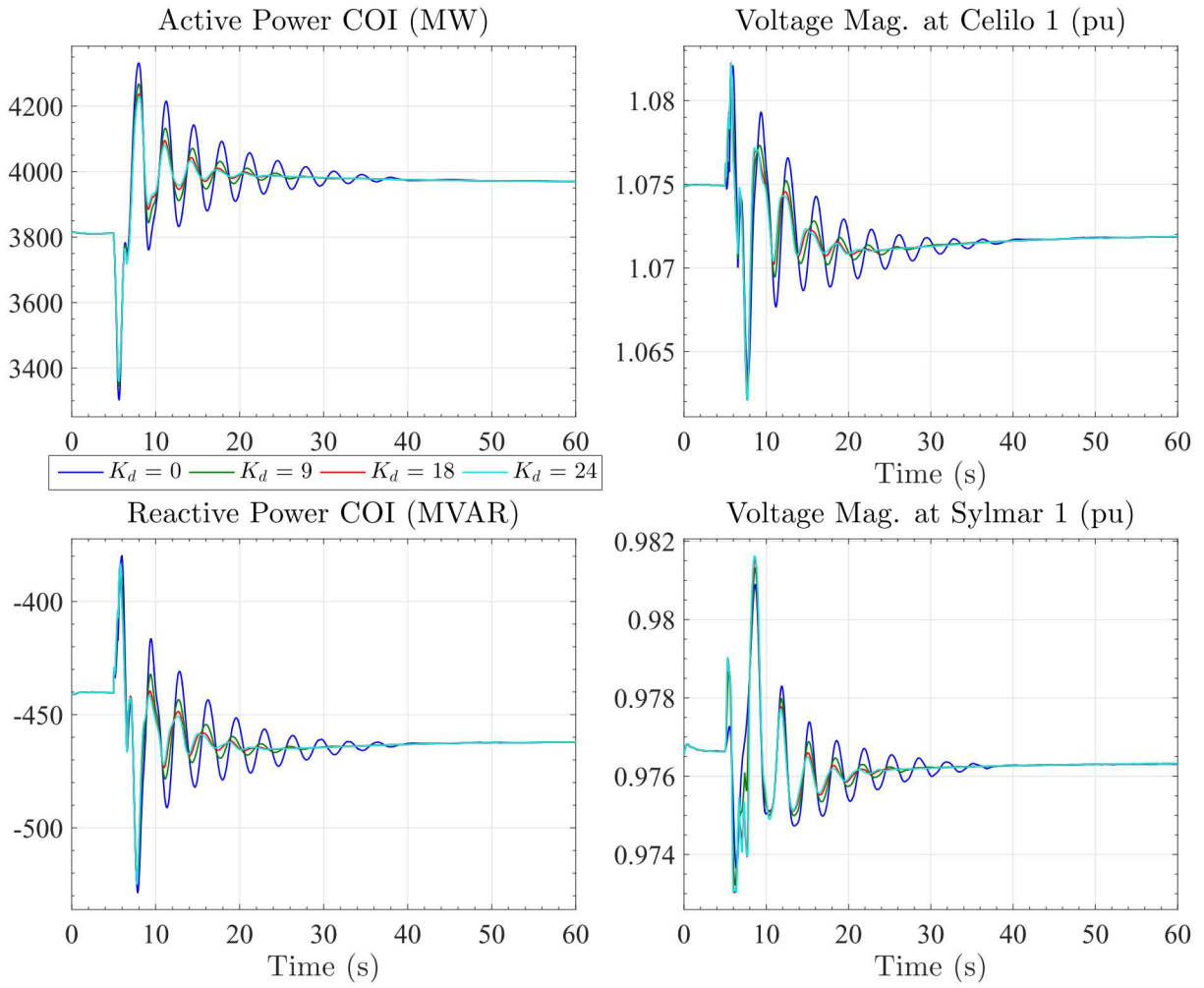


**Figure 151. Bus frequencies. Event: CJB + BCUS Separation**

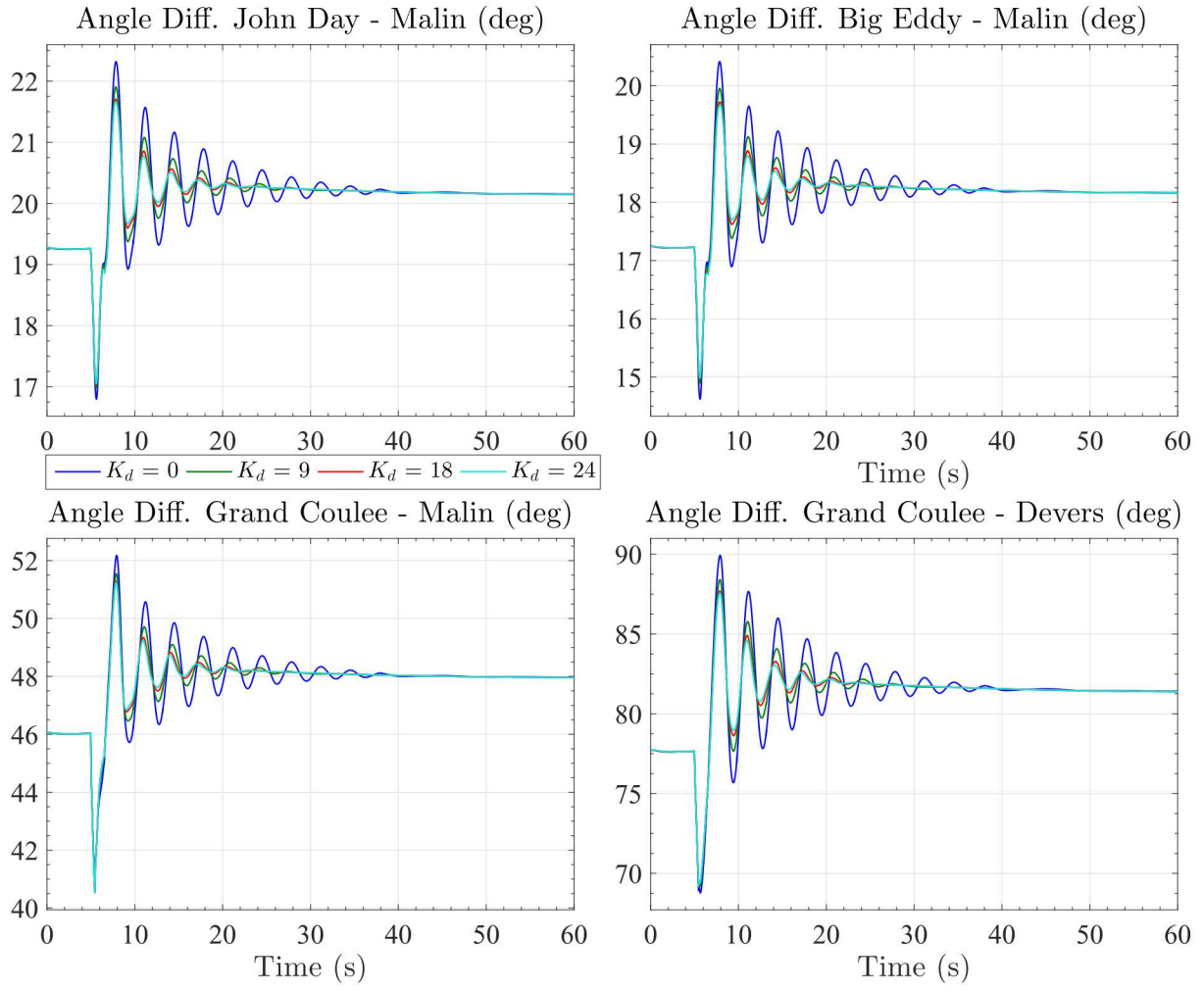
### 3.7. Test System: Heavy Summer 2016. Event: CJB + BCAB Separation



**Figure 152. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCAB Separation**

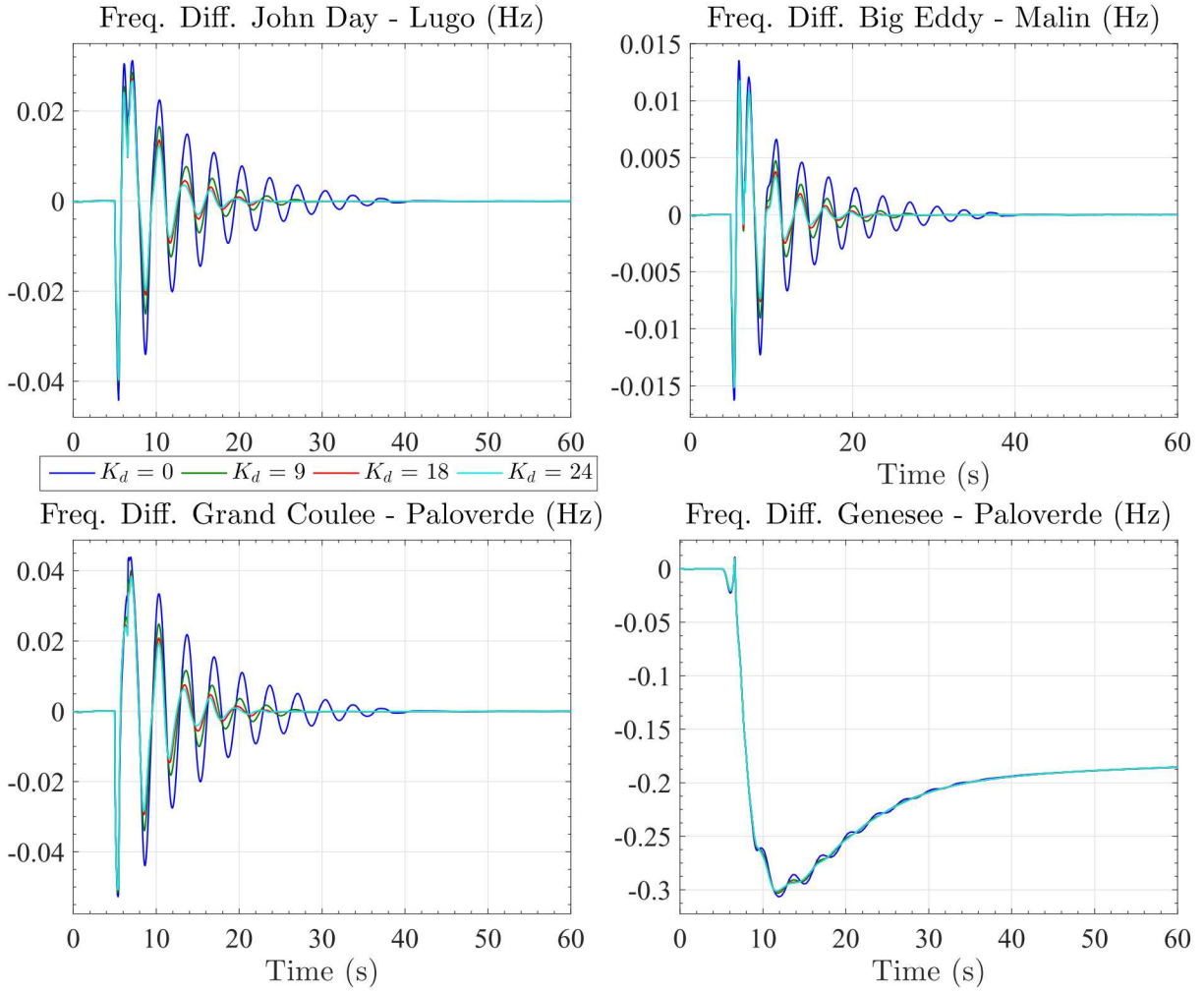


**Figure 153. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCAB Separation**

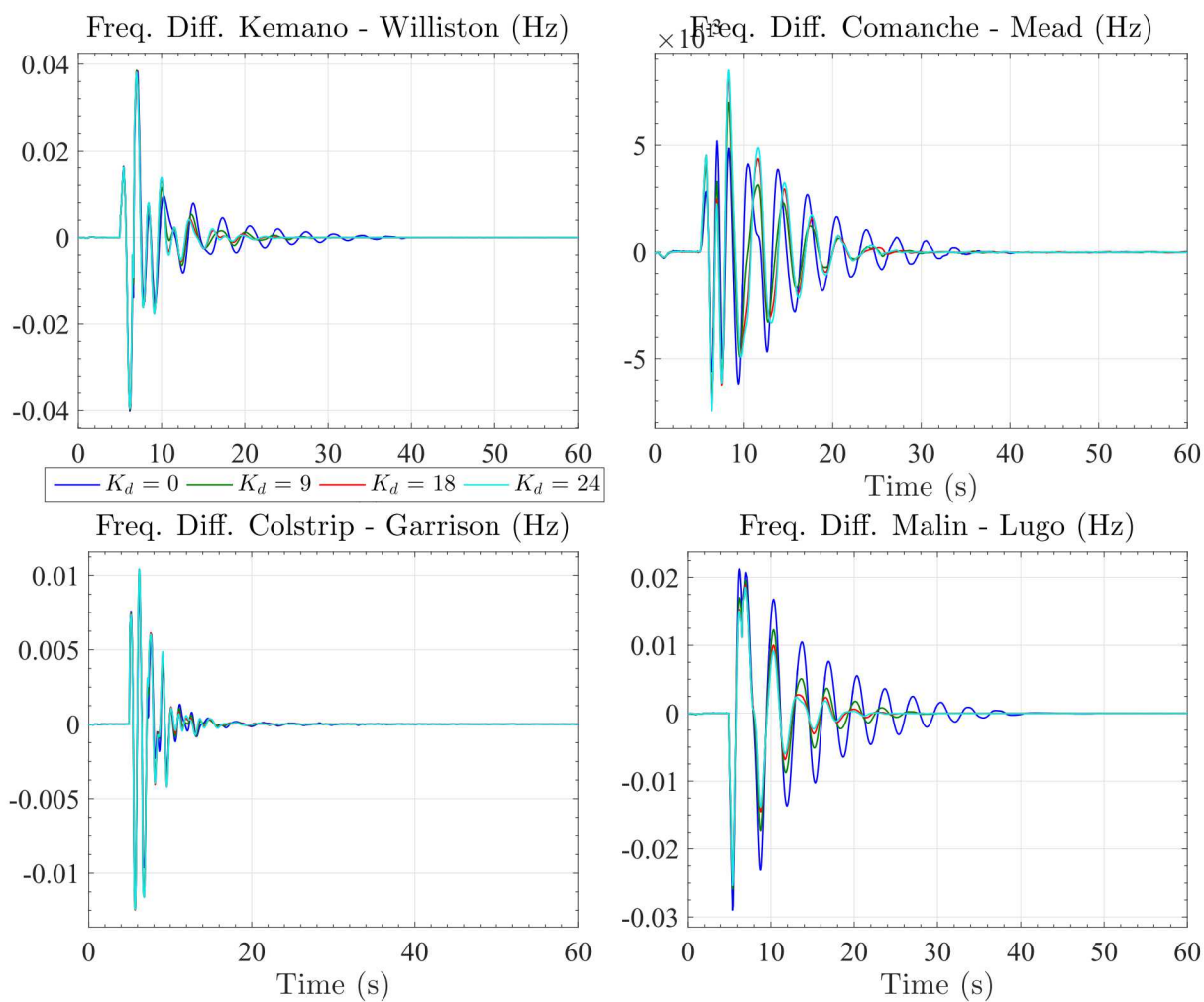


**Figure 154. Angle differences. Event: CJB + BCAB Separation**

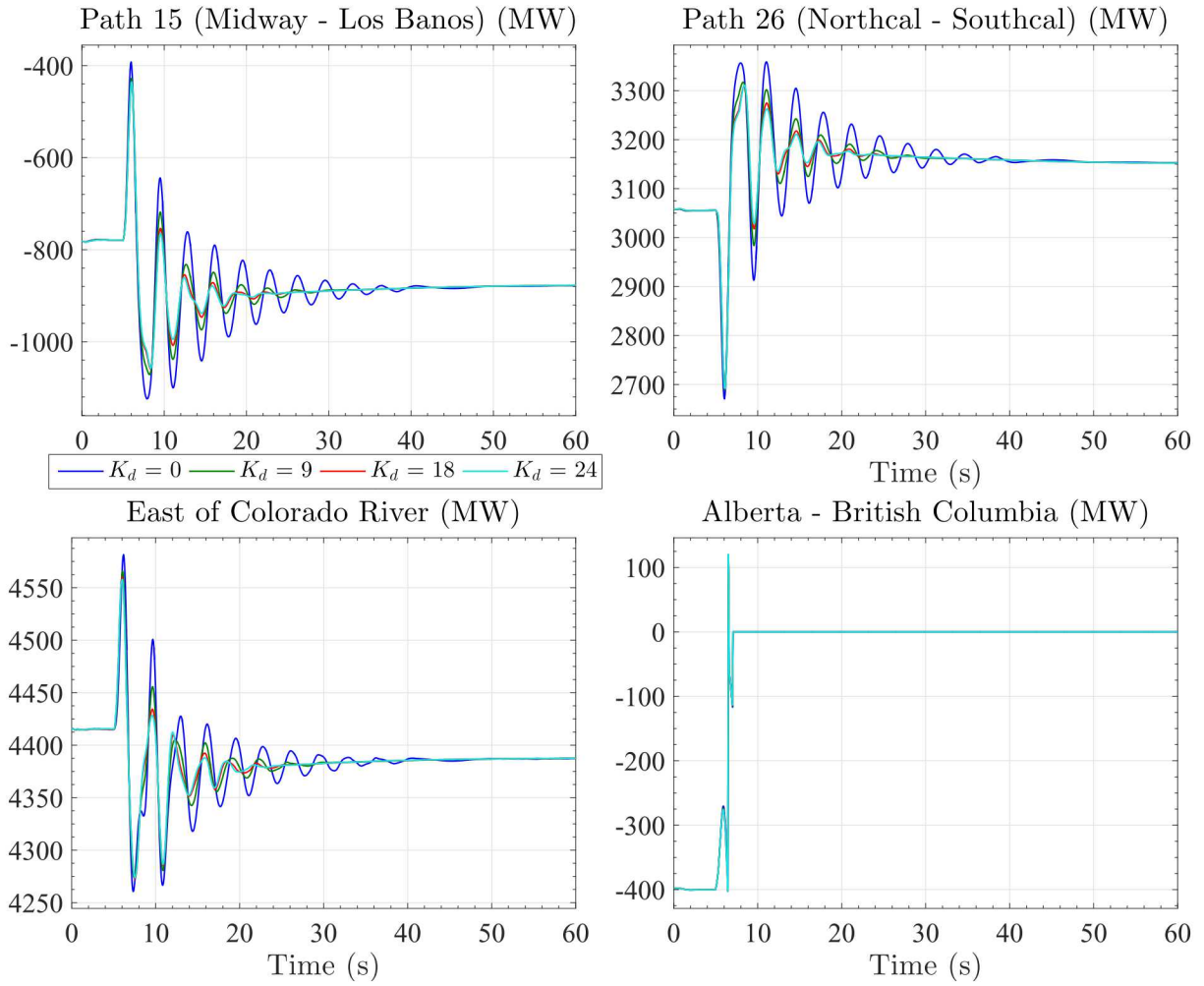




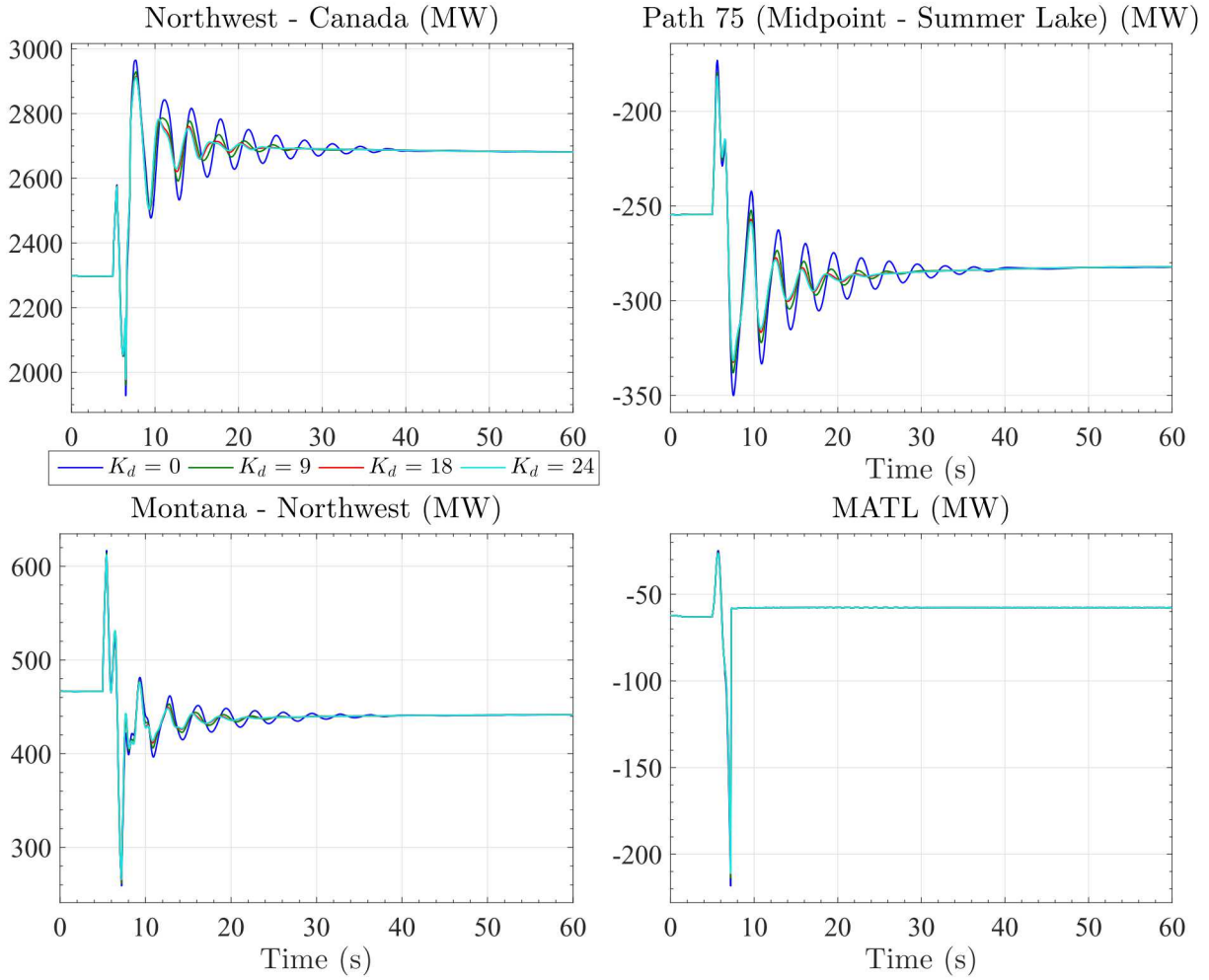
**Figure 155. Frequency differences. Event: CJB + BCAB Separation**



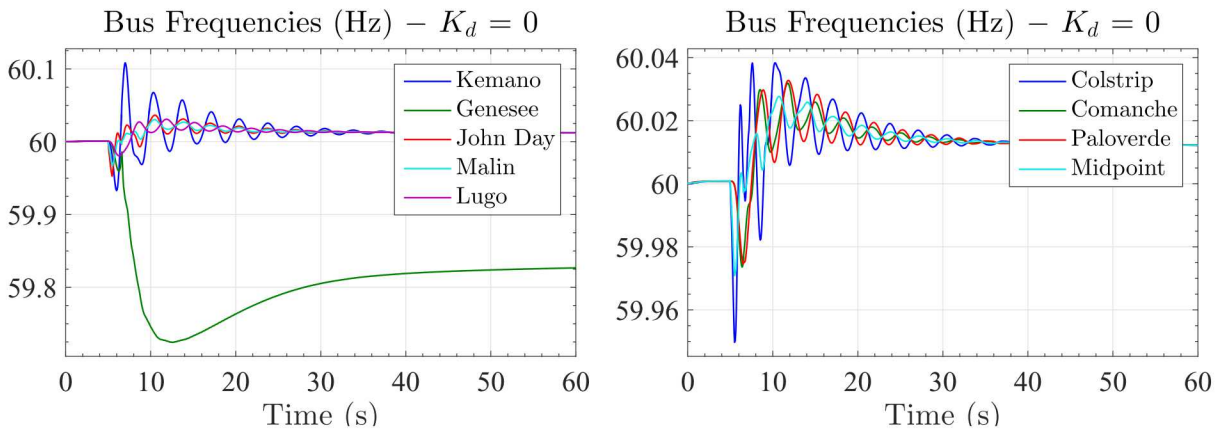
**Figure 156. Frequency differences. Event: CJB + BCAB Separation**



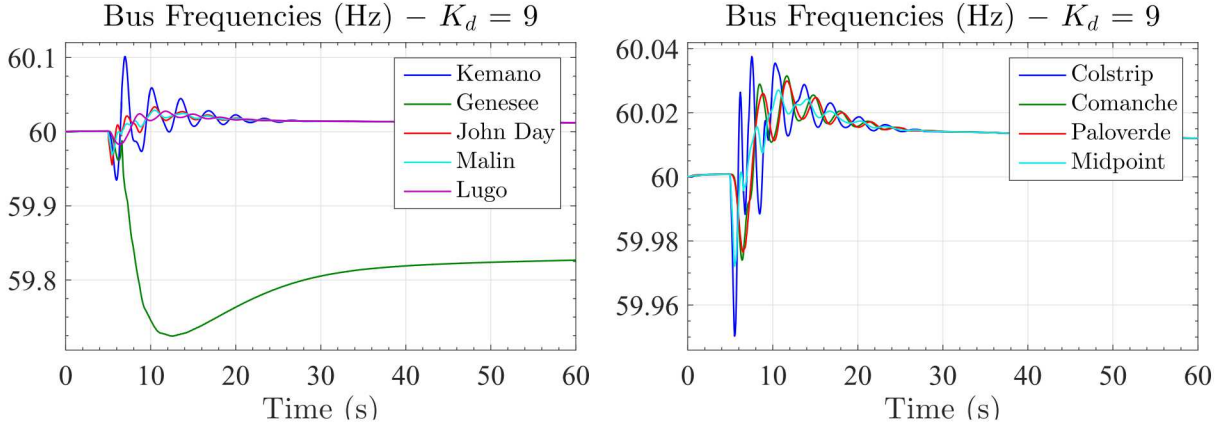
**Figure 157. Active power flows. Event: CJB + BCAB Separation**



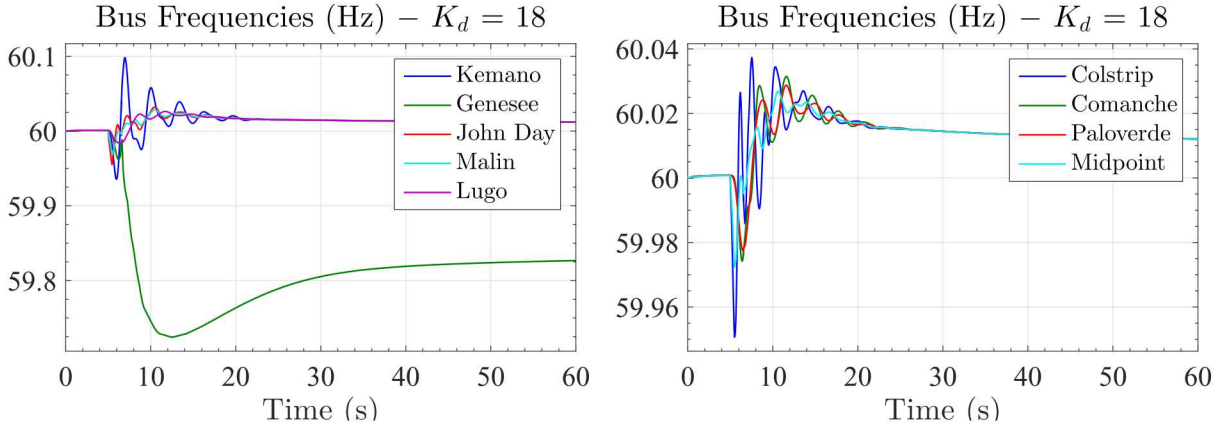
**Figure 158. Active power flows. Event: CJB + BCAB Separation**



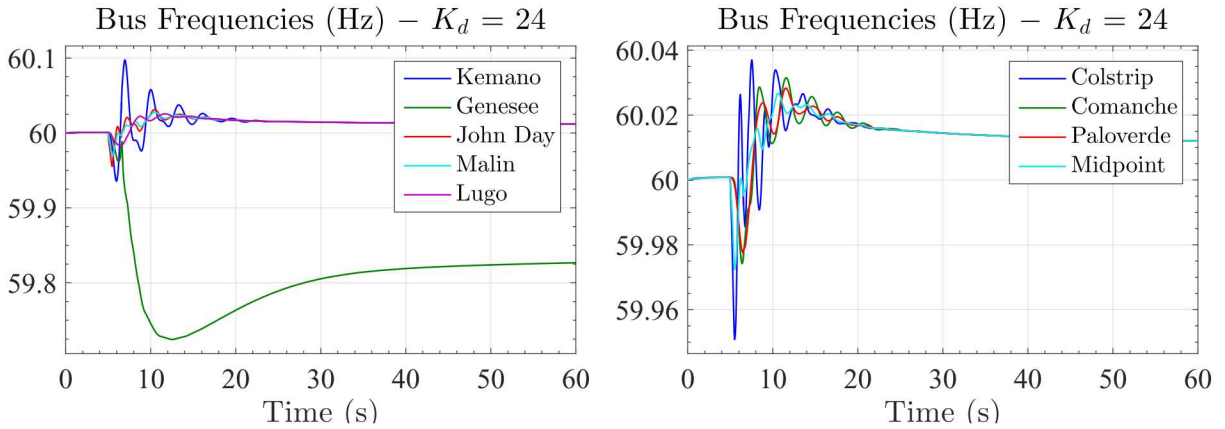
**Figure 159. Bus frequencies. Event: CJB + BCAB Separation**



**Figure 160. Bus frequencies. Event: CJB + BCAB Separation**



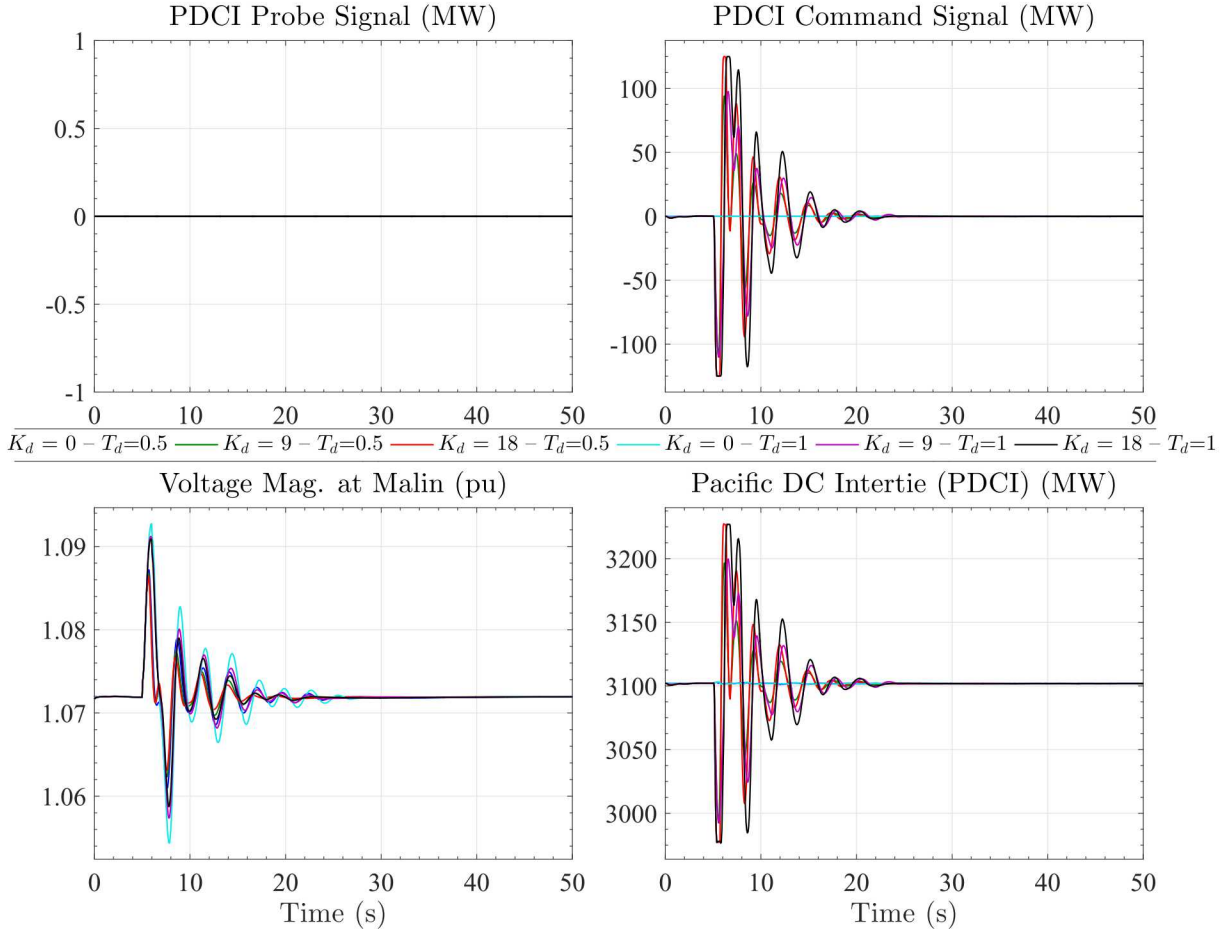
**Figure 161. Bus frequencies. Event: CJB + BCAB Separation**



**Figure 162. Bus frequencies. Event: CJB + BCAB Separation**

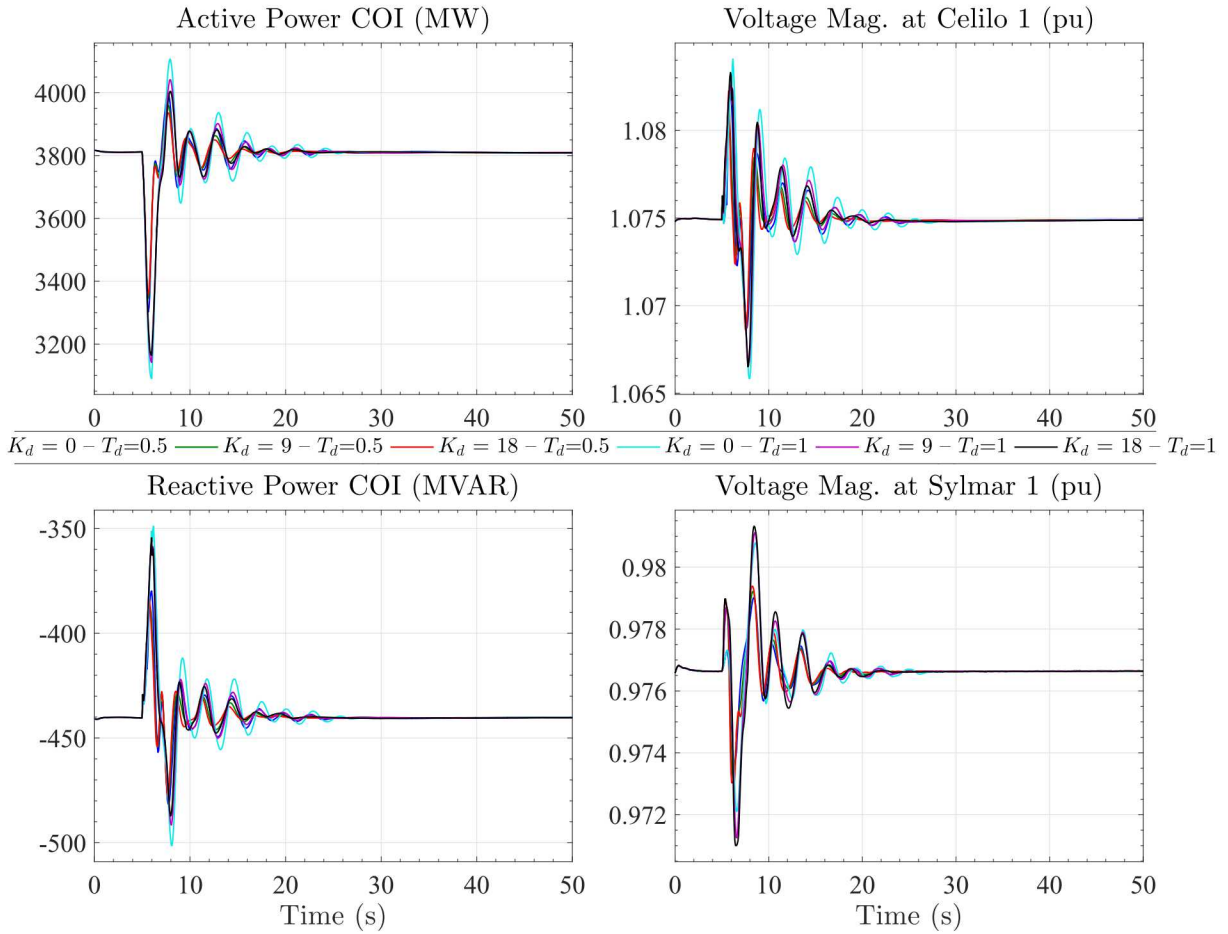
## 4. CHIEF JOSEPH BRAKE DURATION COMPARISON

### 4.1. Test System: Heavy Summer 2016. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

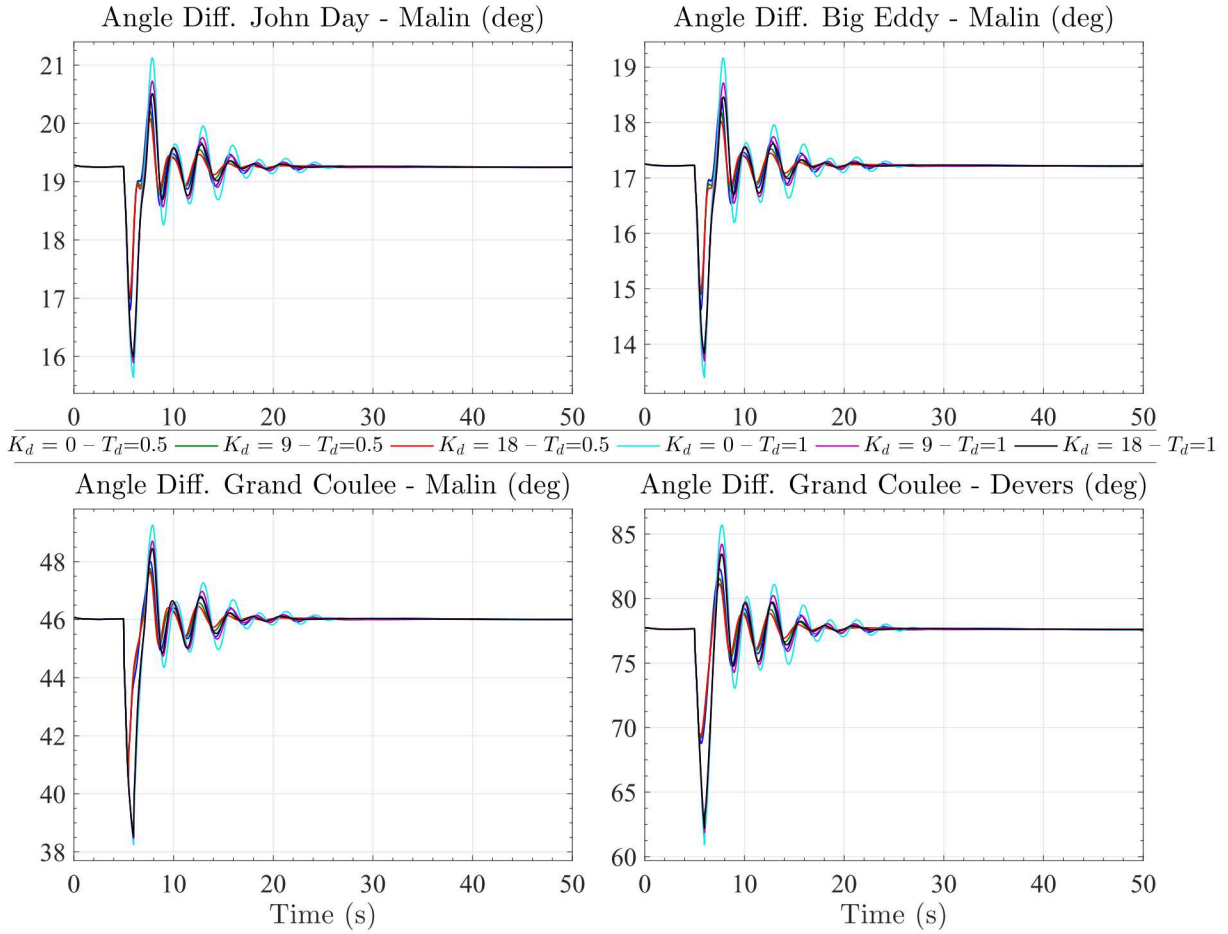


**Figure 163. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**

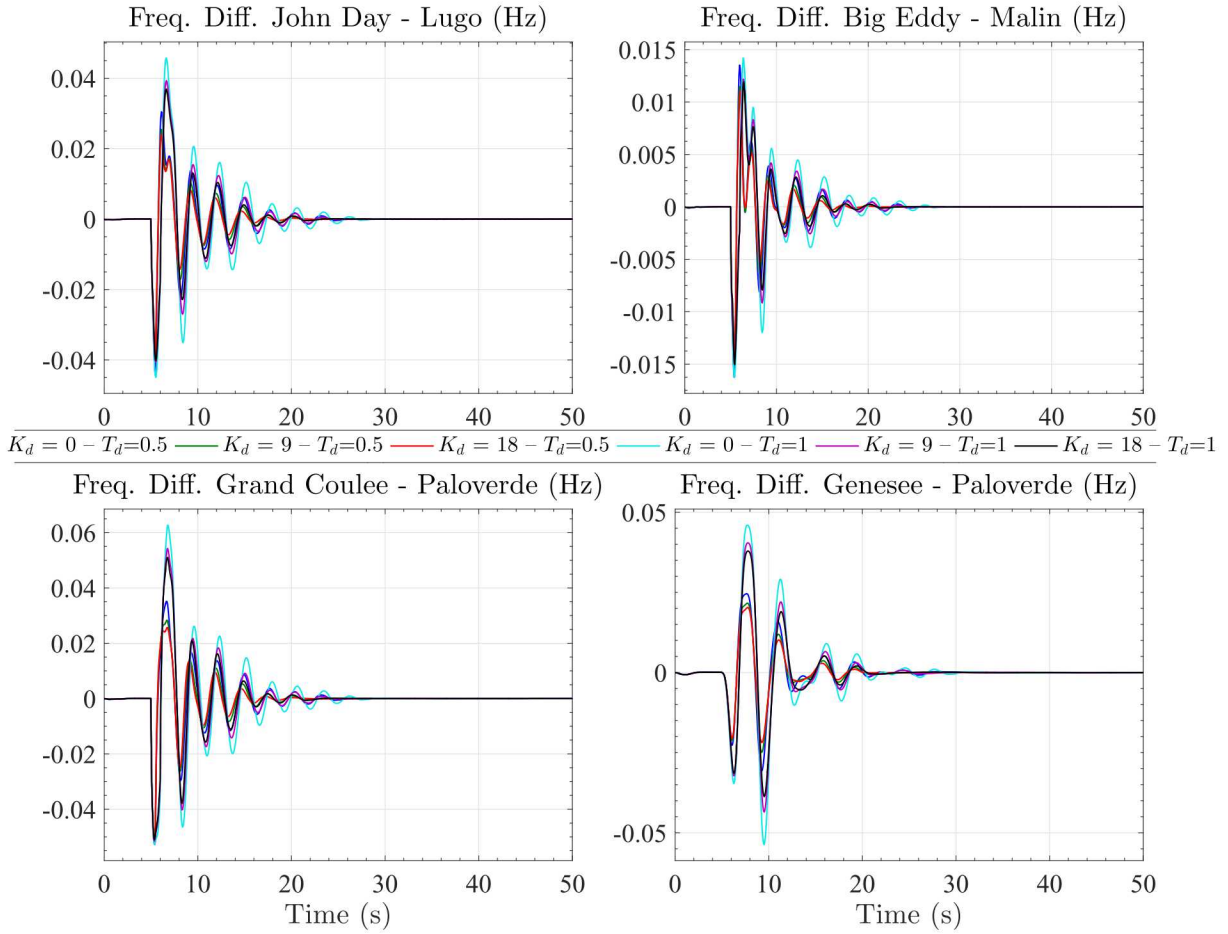




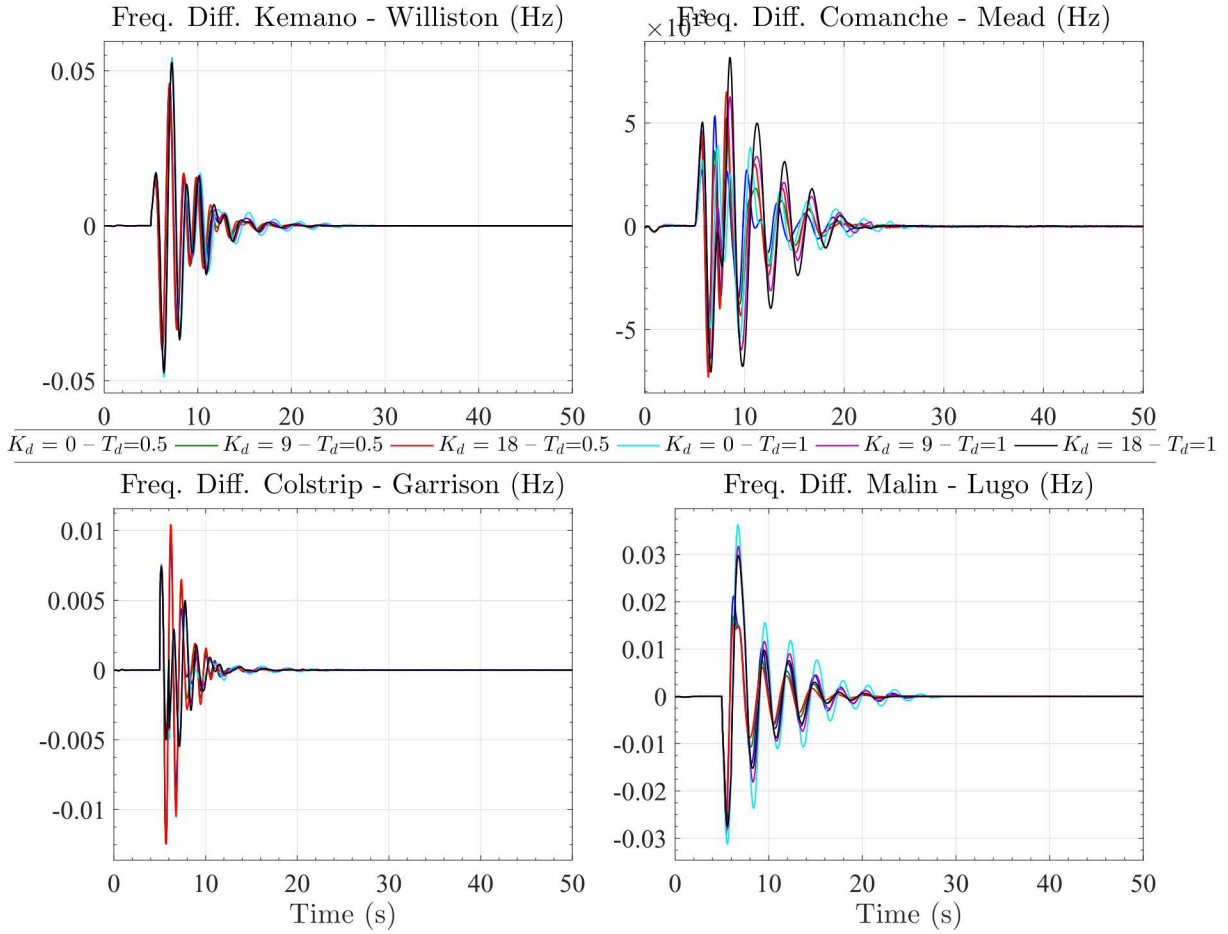
**Figure 164. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joseph Brake 0.5 sec,  $Kd = 0$**



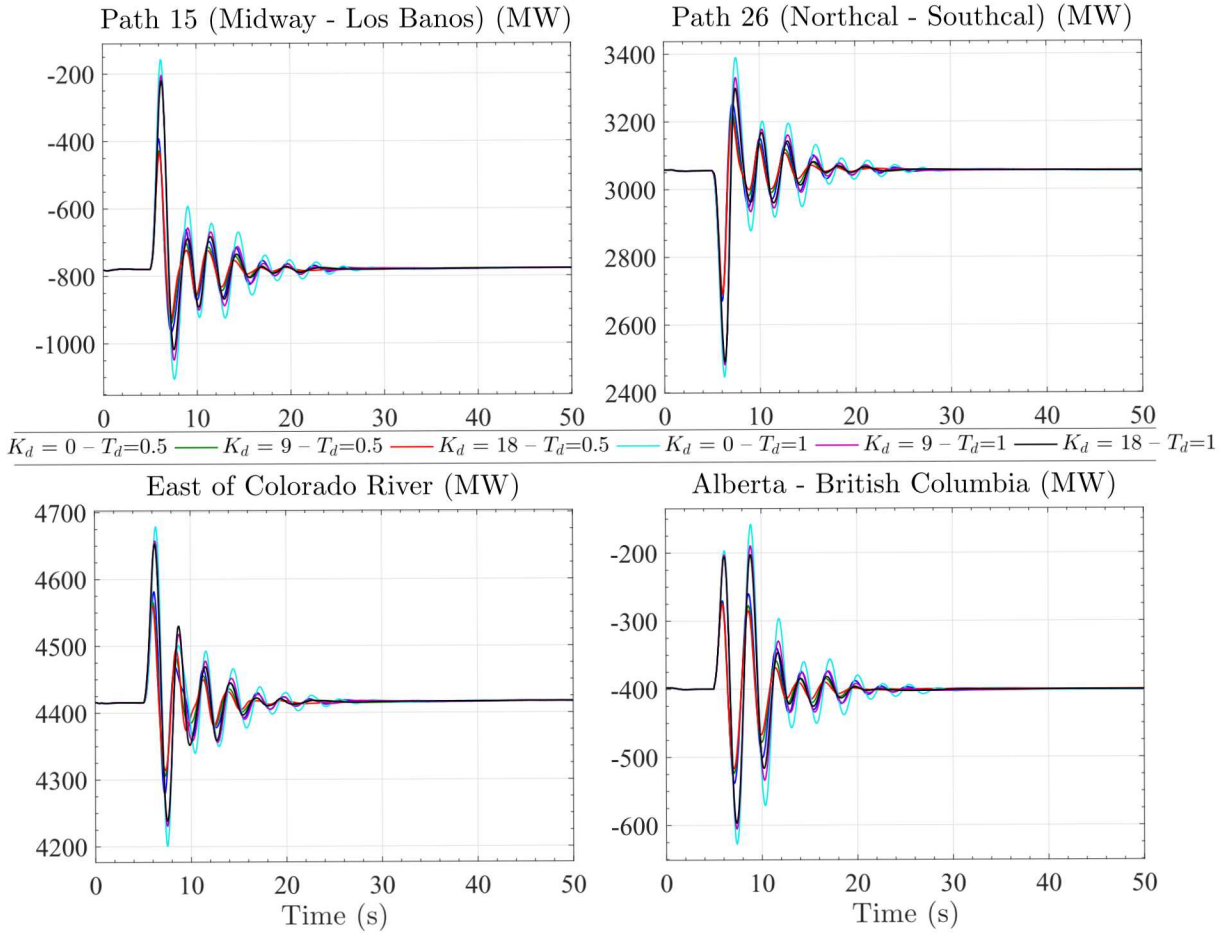
**Figure 165. Angle differences. Event: Chief Joseph Brake 0.5 sec,  $Kd = 0$**



**Figure 166. Frequency differences. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



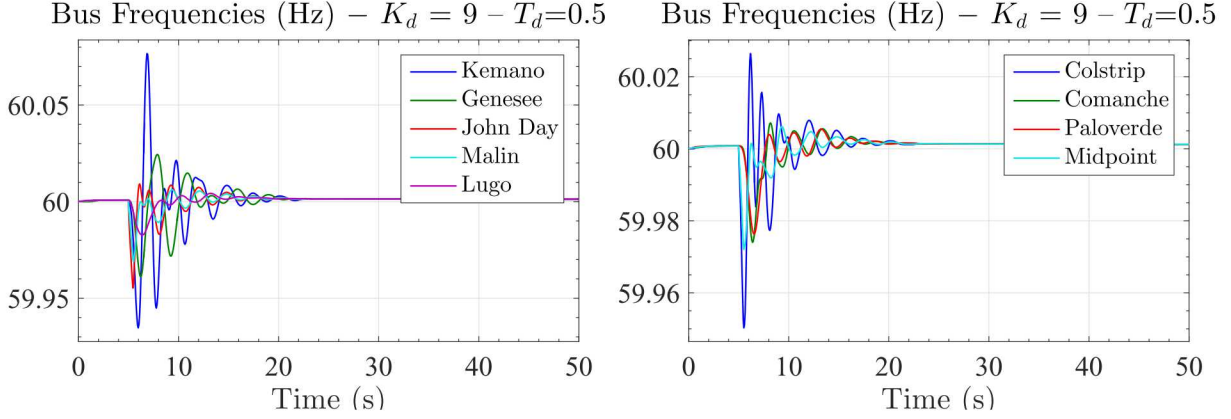
**Figure 167. Frequency differences. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



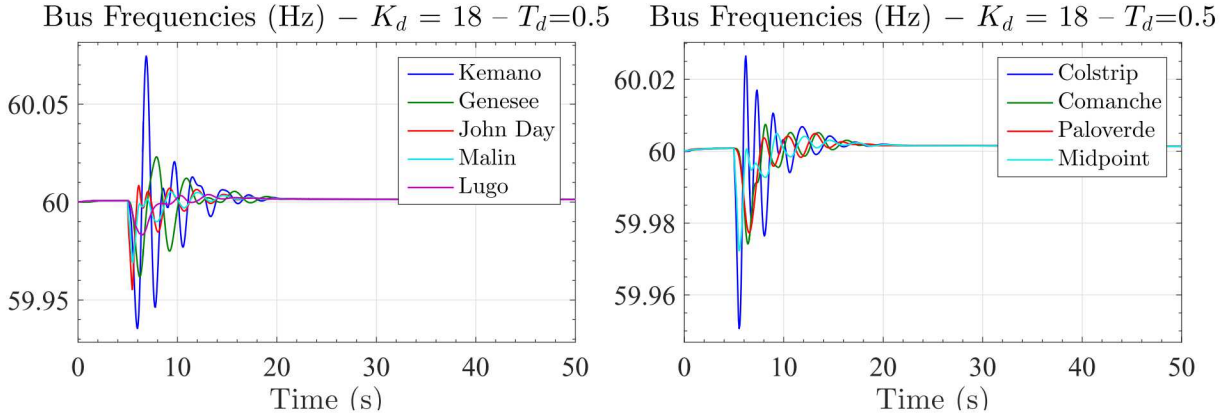
**Figure 168. Active power flows. Event: Chief Joseph Brake 0.5 sec,  $Kd = 0$**



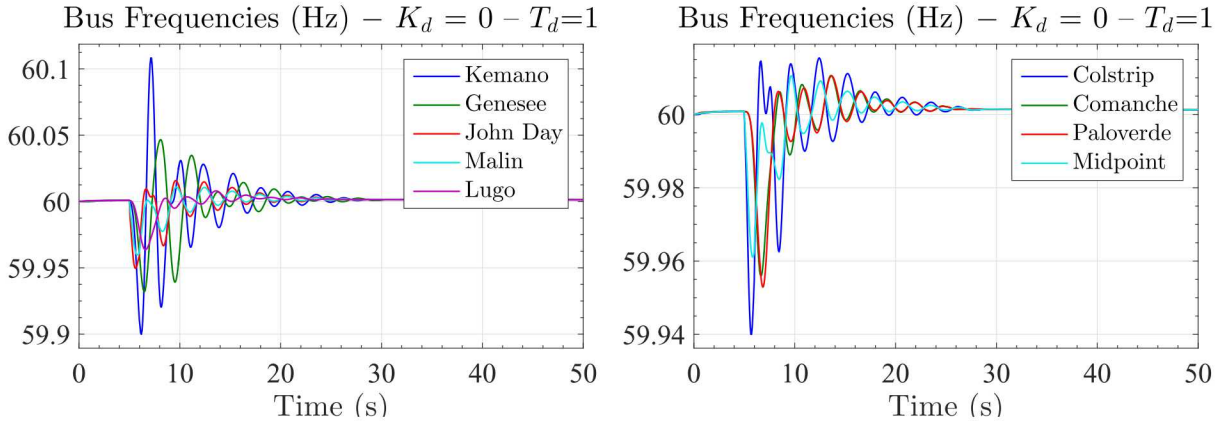




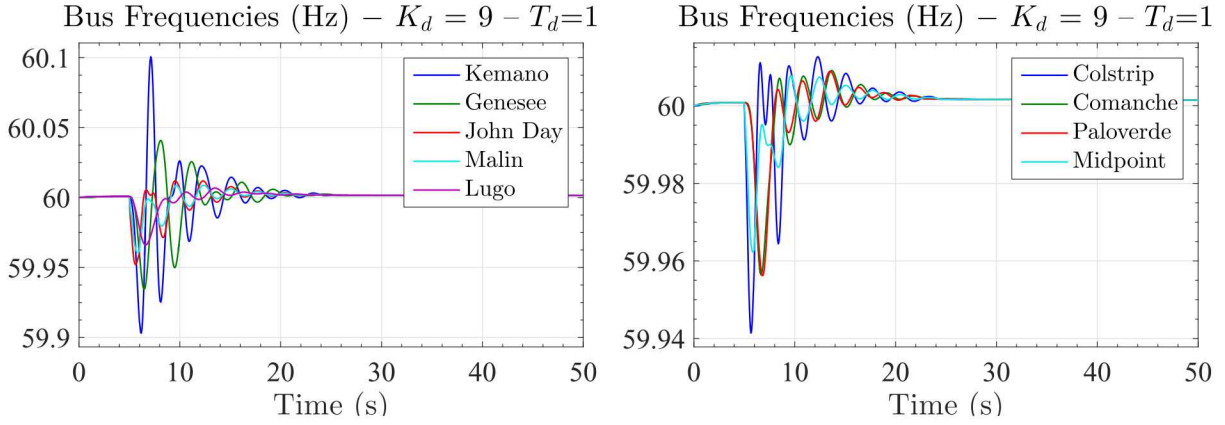
**Figure 171. Bus frequencies. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



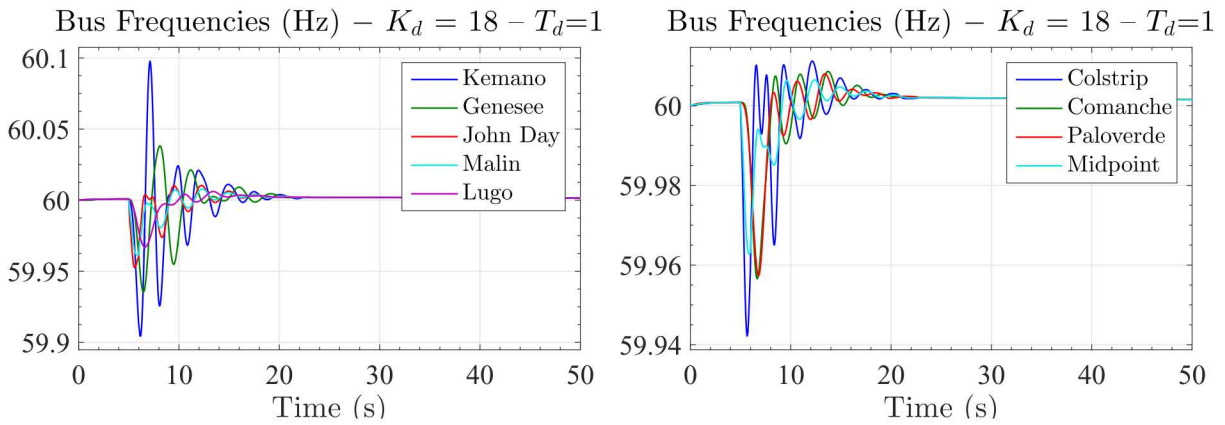
**Figure 172. Bus frequencies. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



**Figure 173. Bus frequencies. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



**Figure 174. Bus frequencies. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



**Figure 175. Bus frequencies. Event: Chief Joseph Brake 0.5 sec,  $K_d = 0$**



## 5. FORCED OSCILLATIONS (HIGHER FREQUENCIES)

### 5.1. Test System: Heavy Summer 2016. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

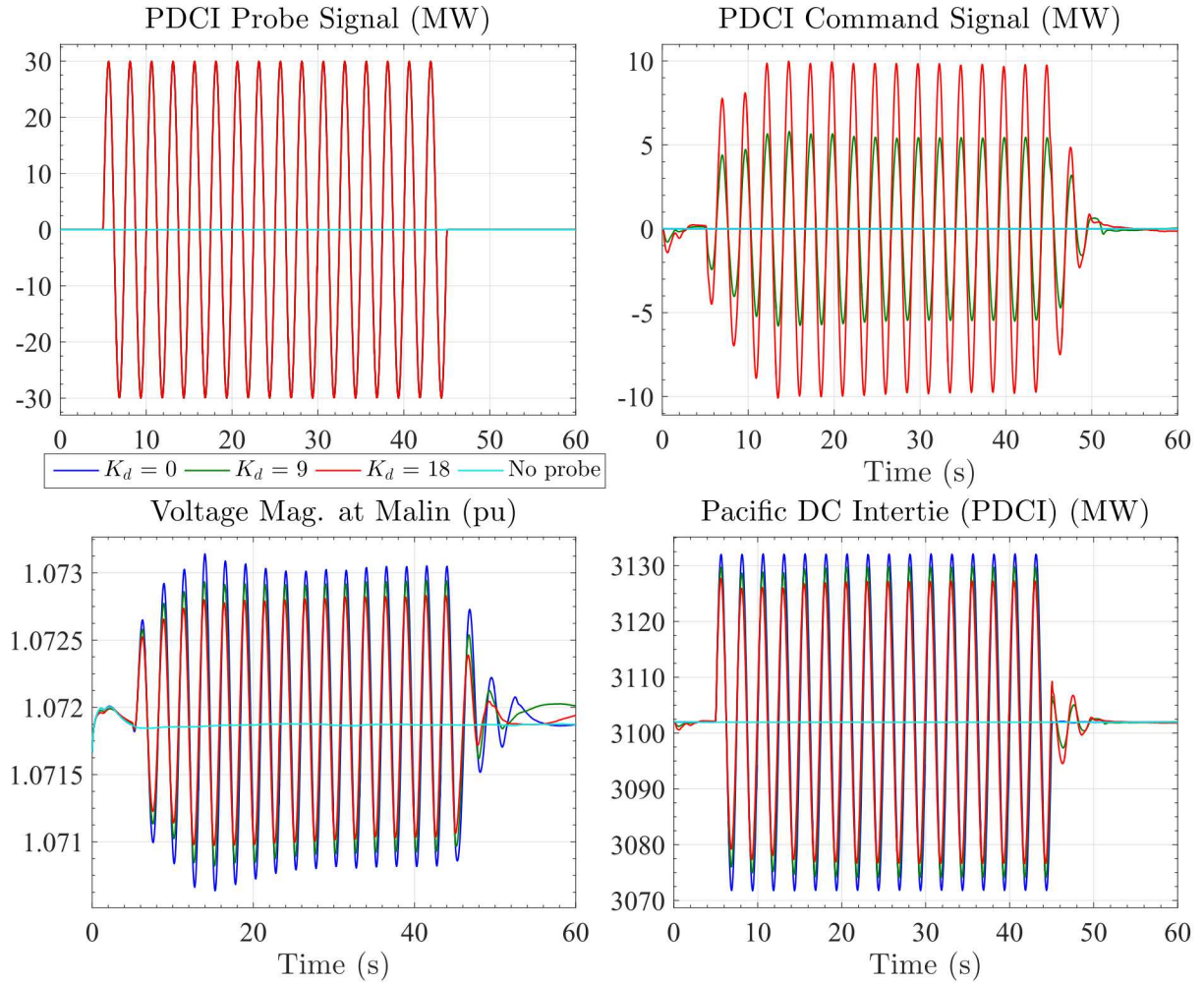
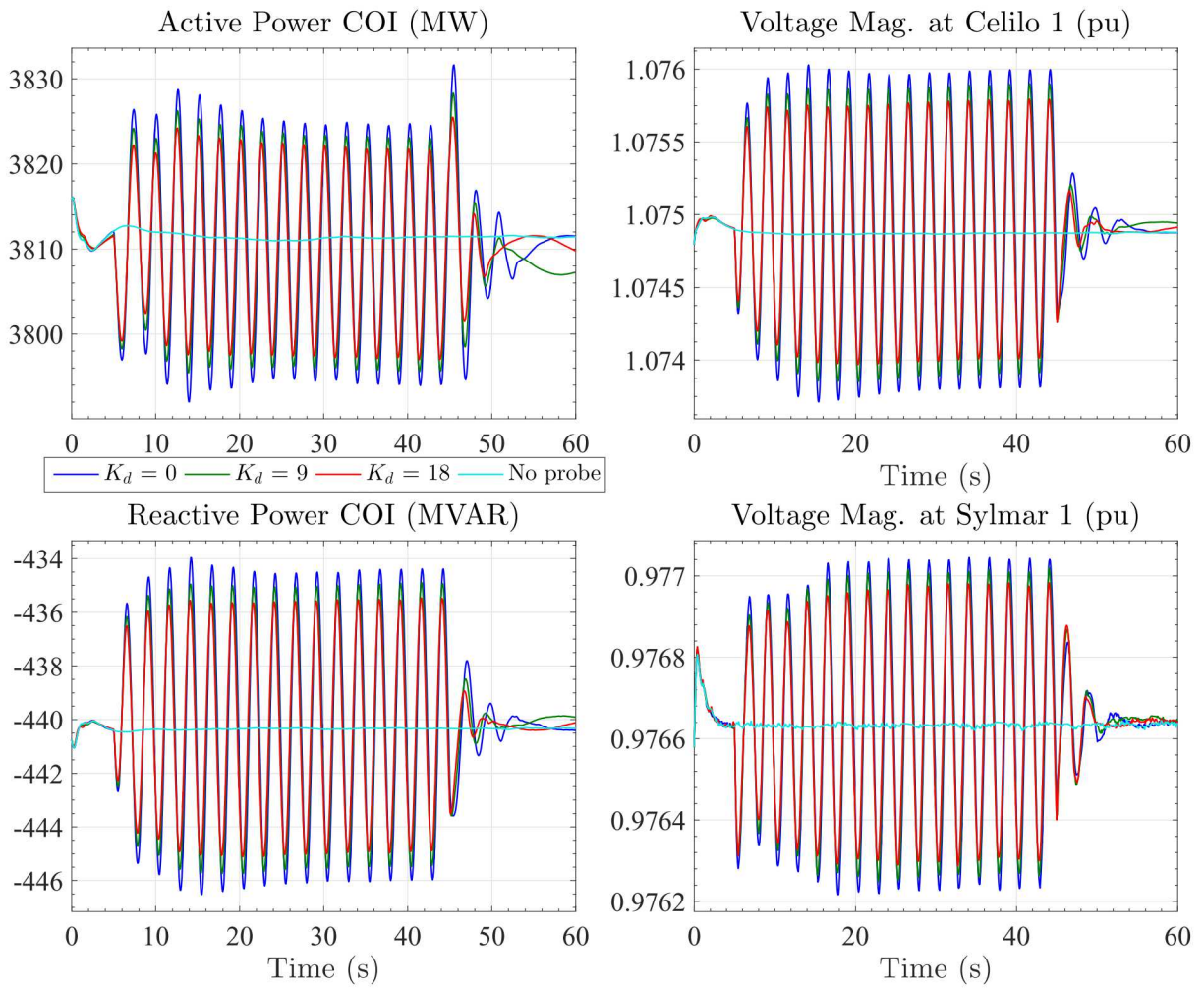
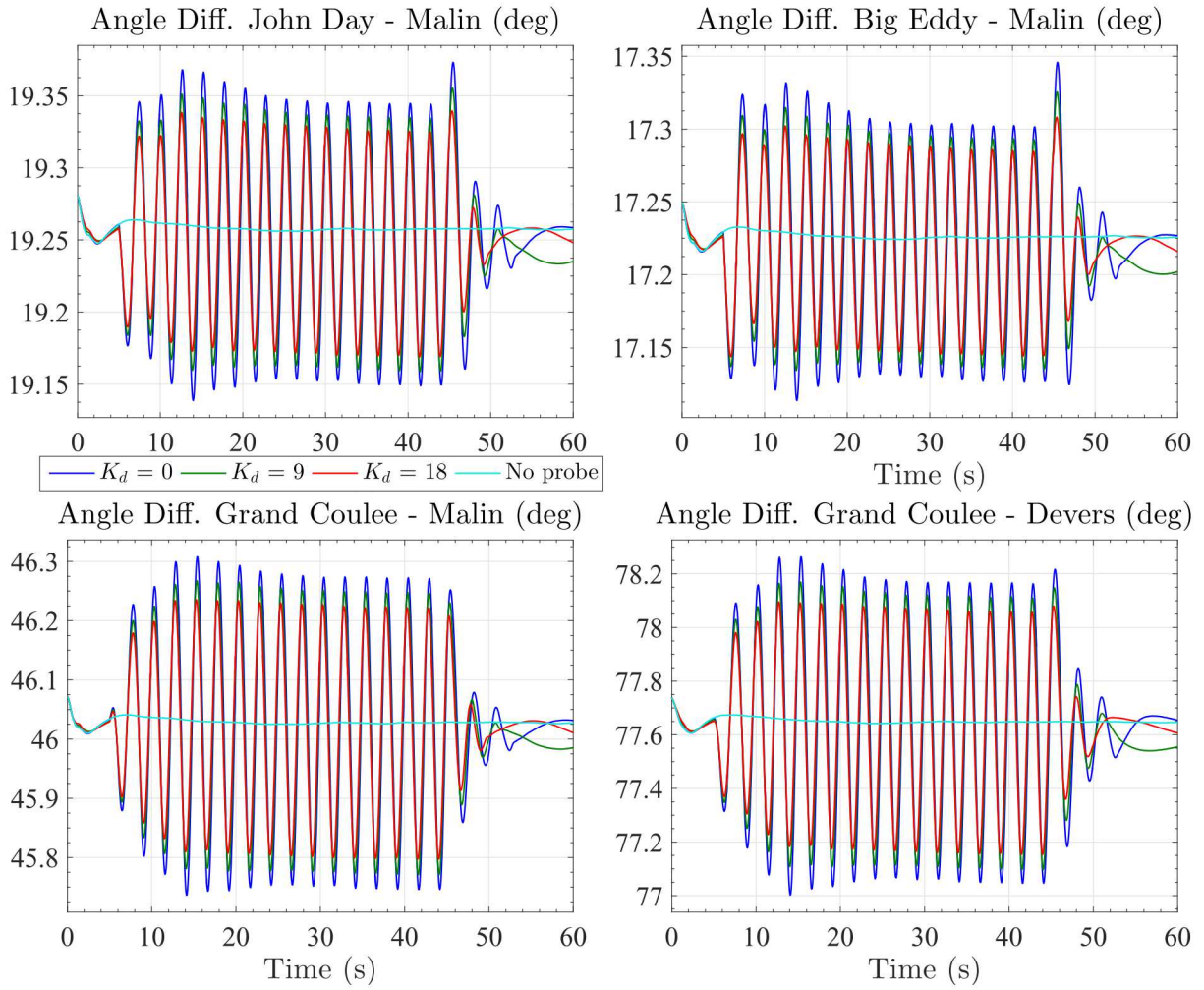


Figure 176. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)



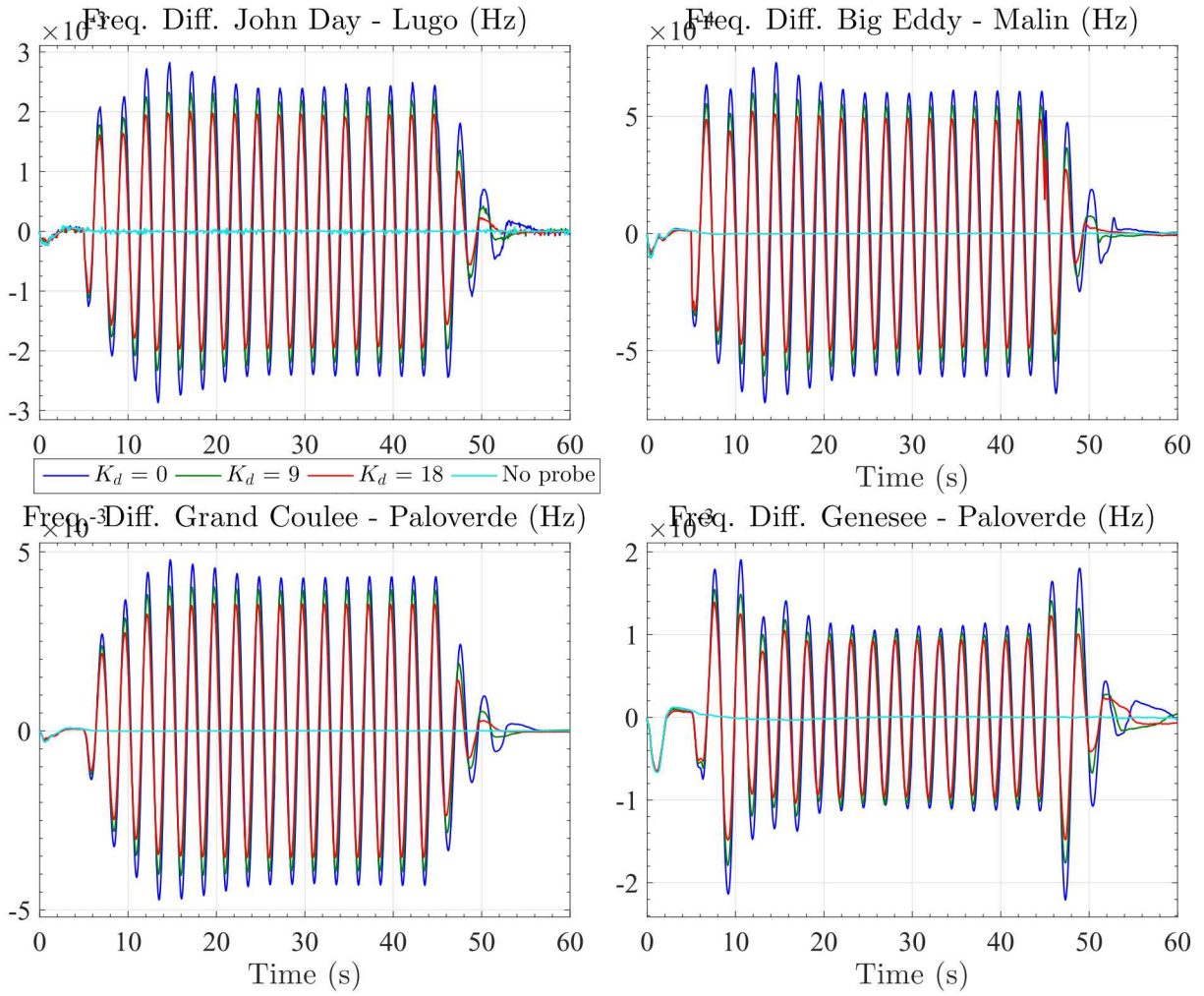
**Figure 177. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**



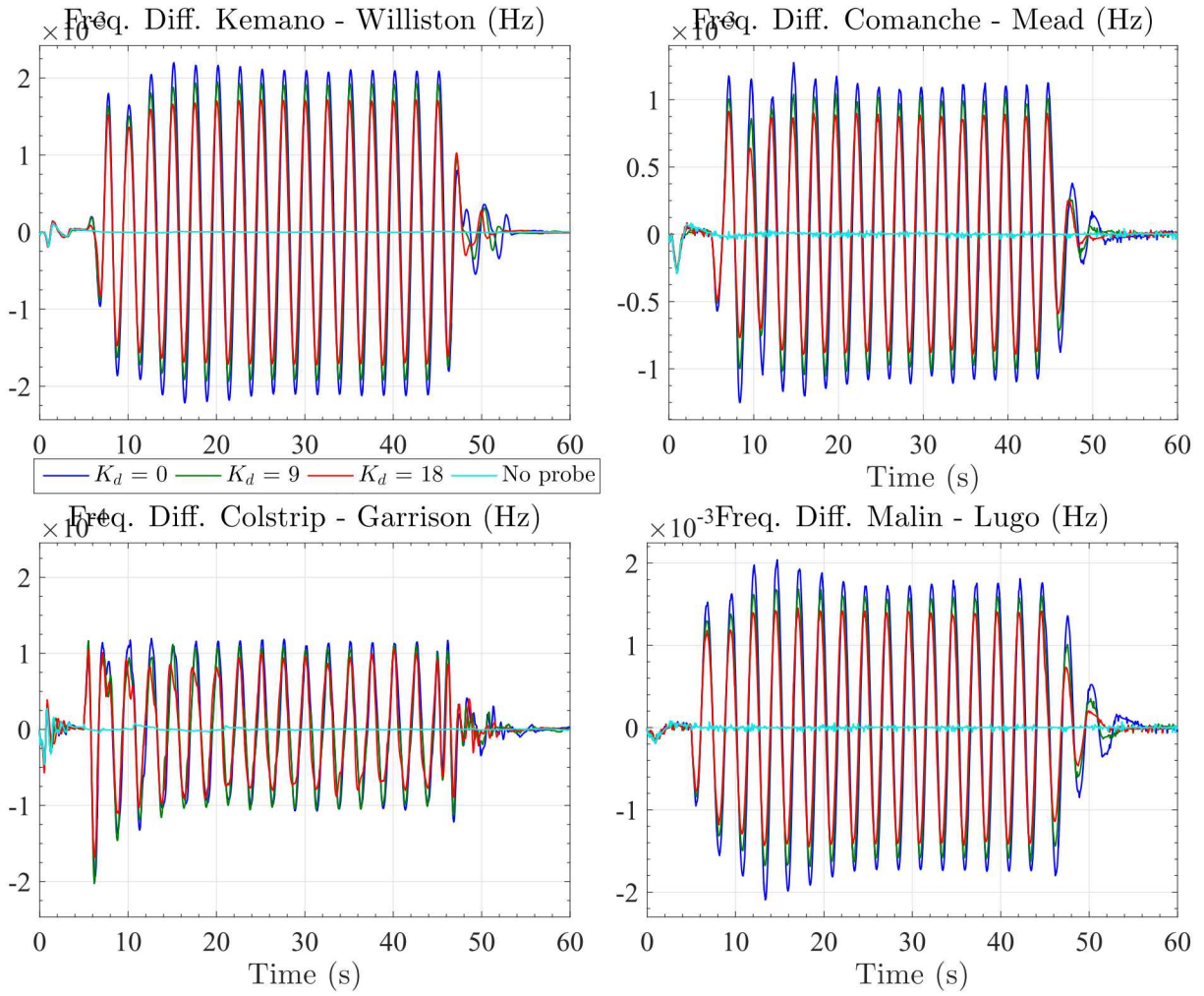


**Figure 178. Angle differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**

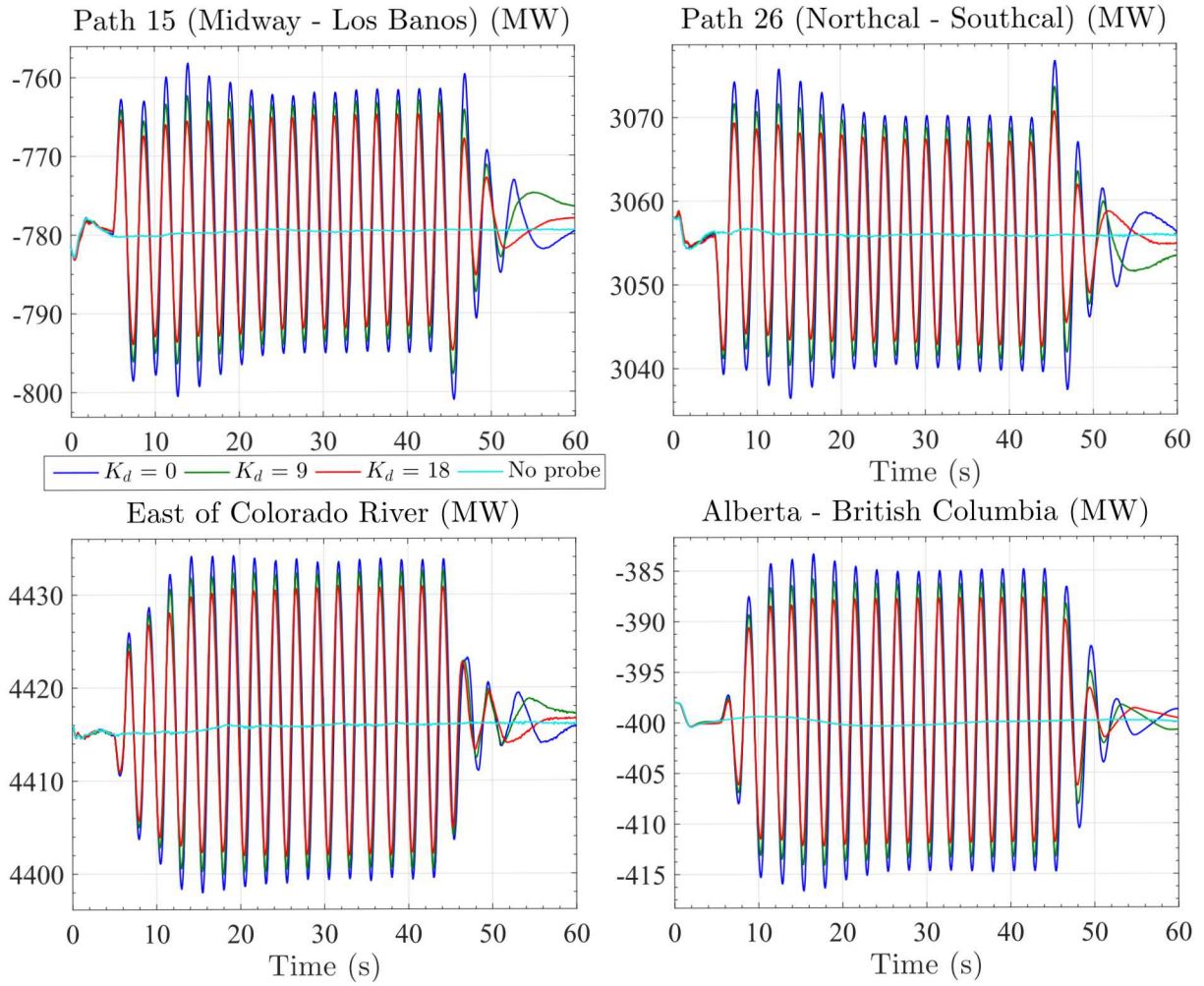




**Figure 179. Frequency differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**

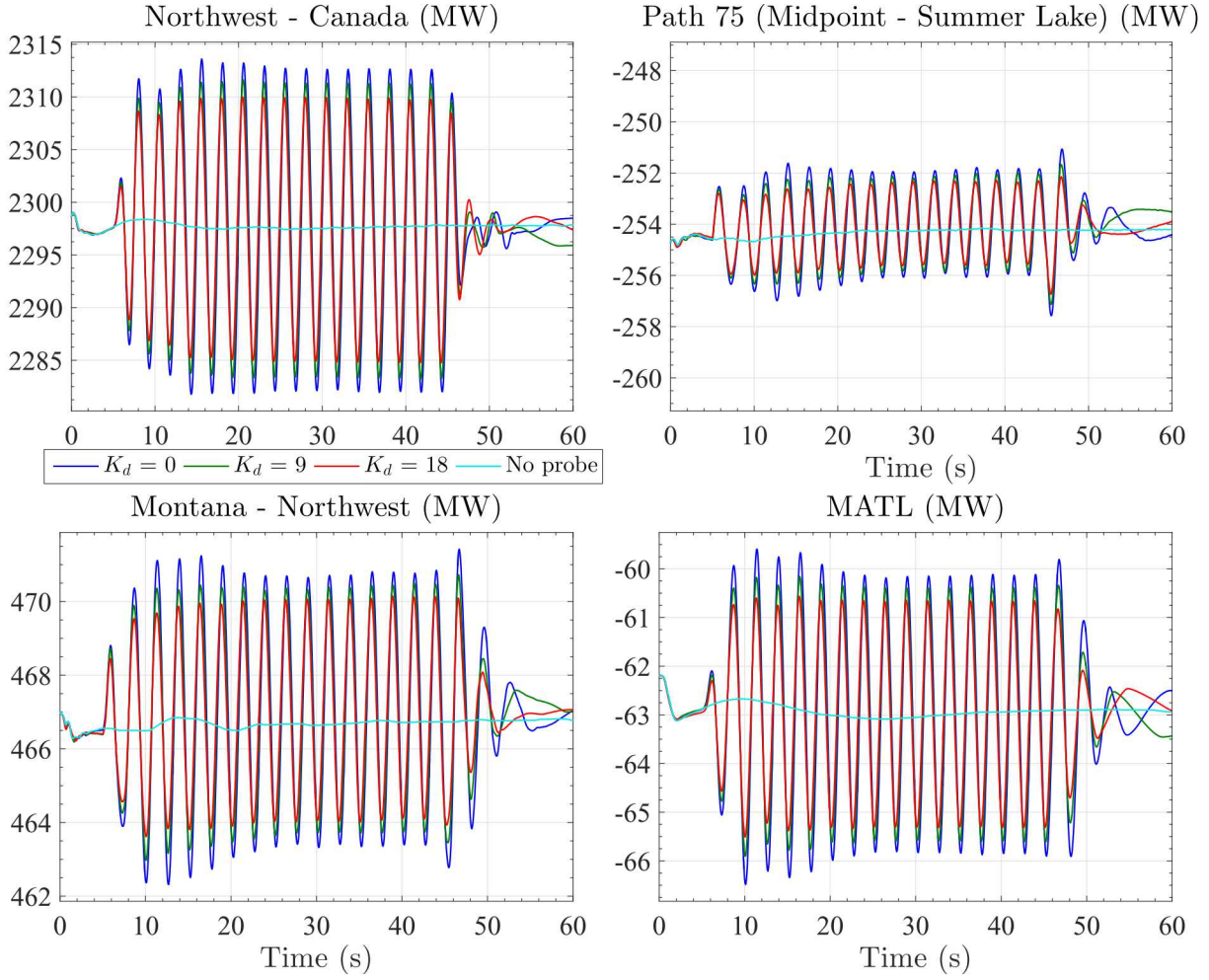


**Figure 180. Frequency differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**

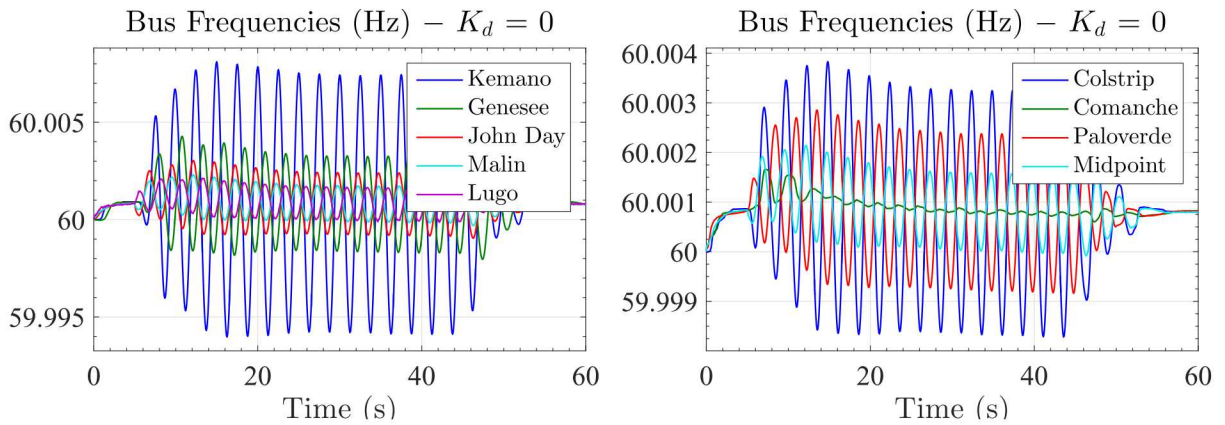


**Figure 181. Active power flows. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**





**Figure 182. Active power flows. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**



**Figure 183. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)**

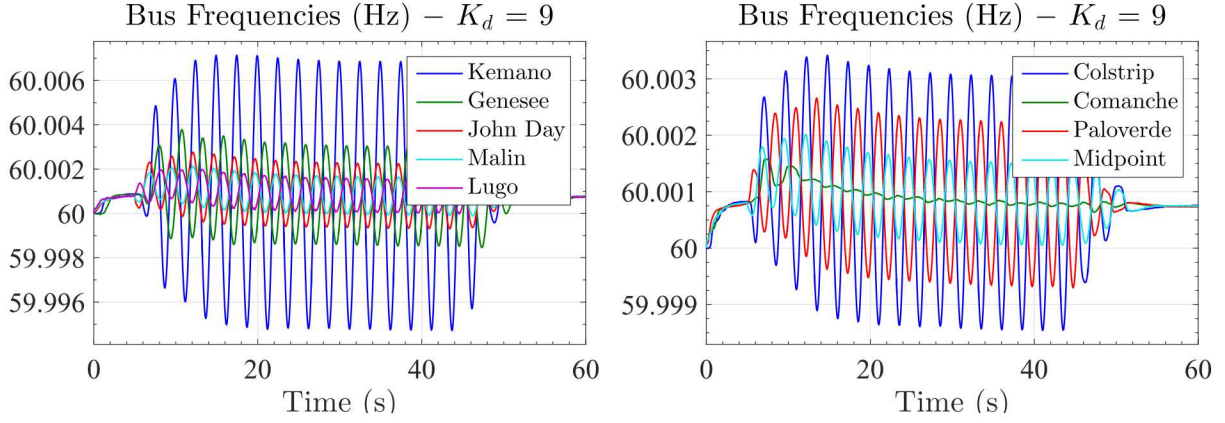


Figure 184. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

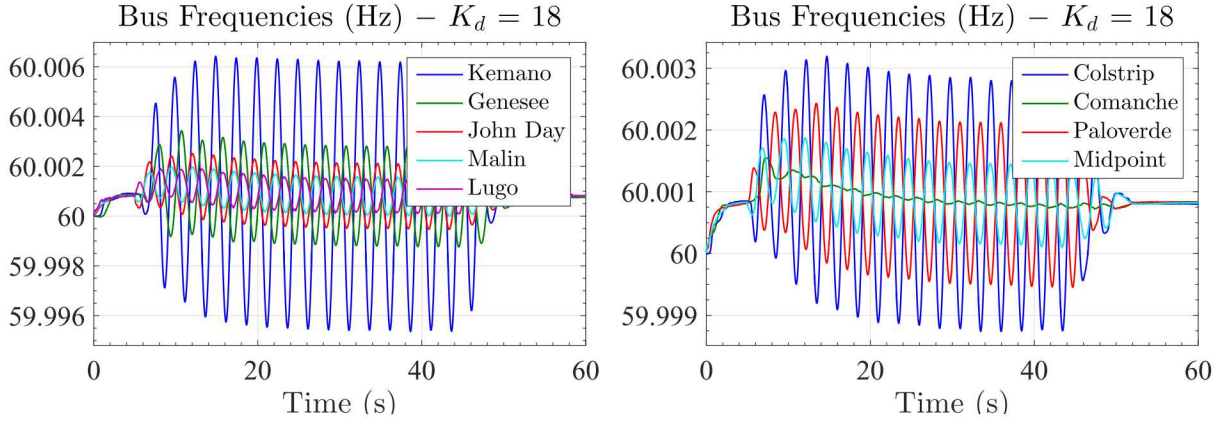


Figure 185. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

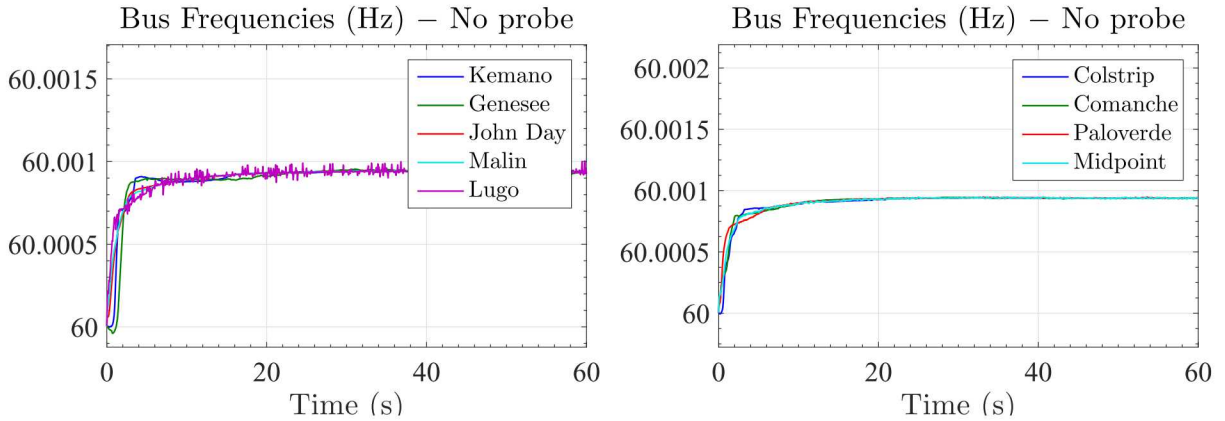


Figure 186. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

5.2. Test System: Heavy Summer 2016. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

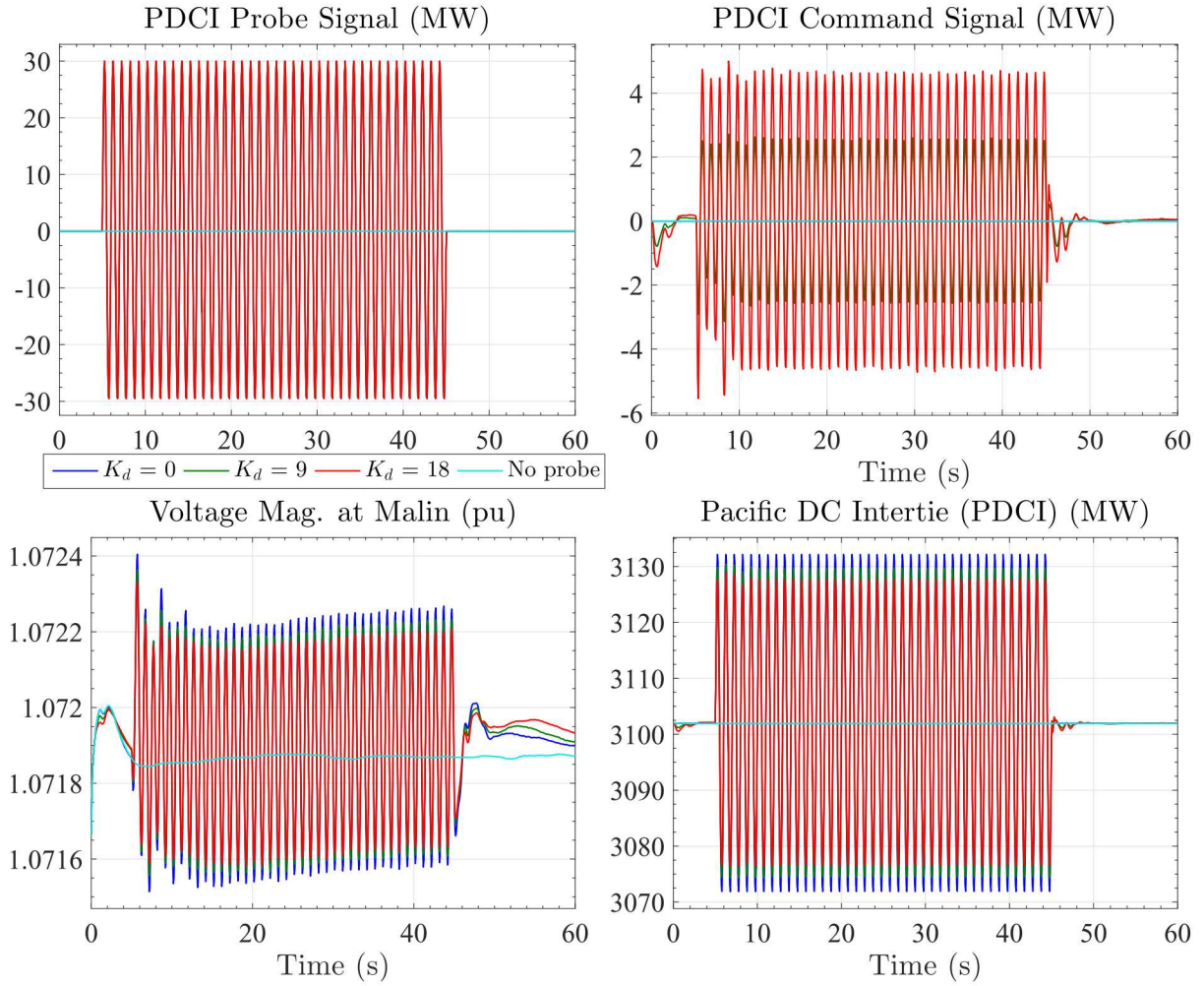
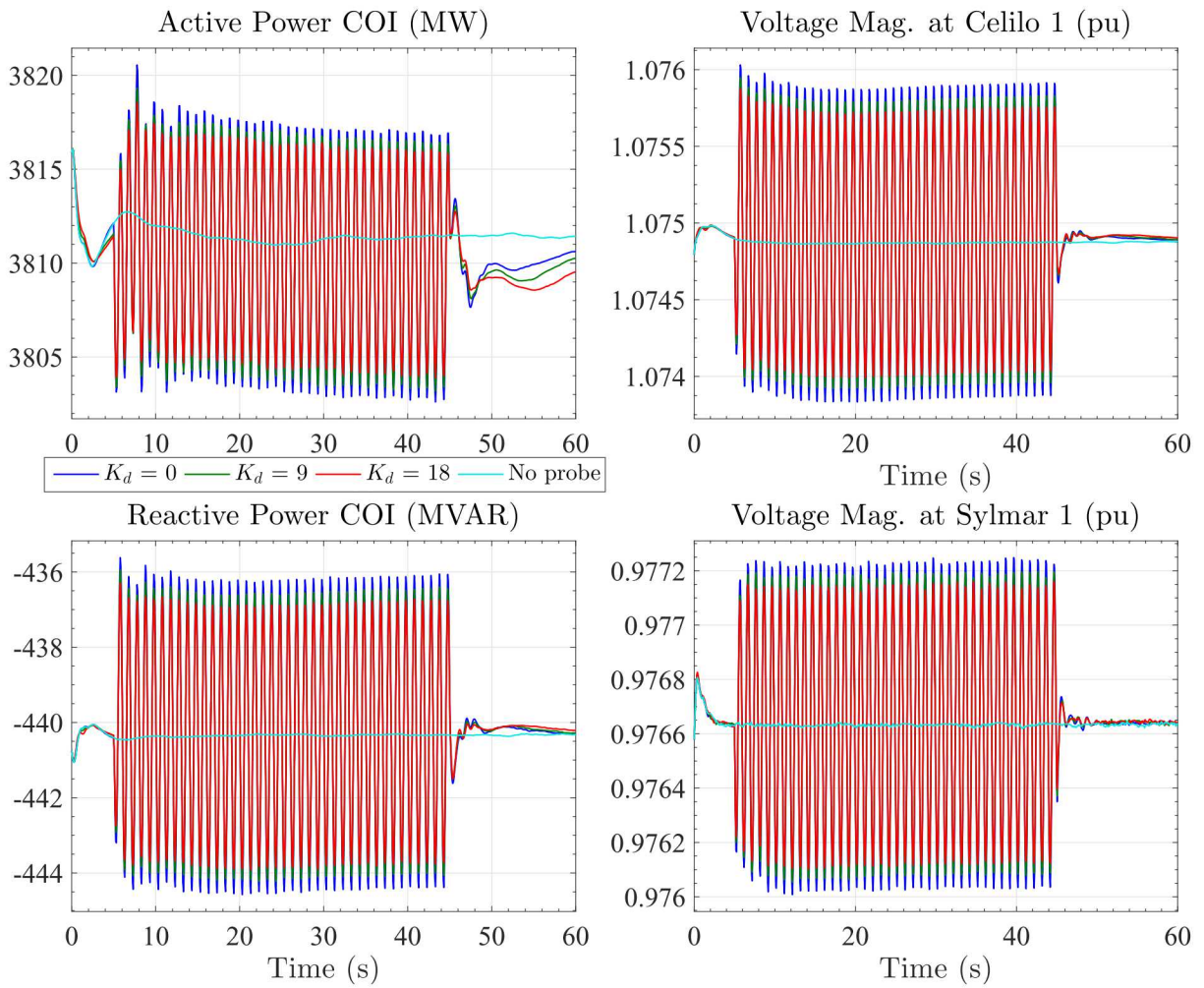
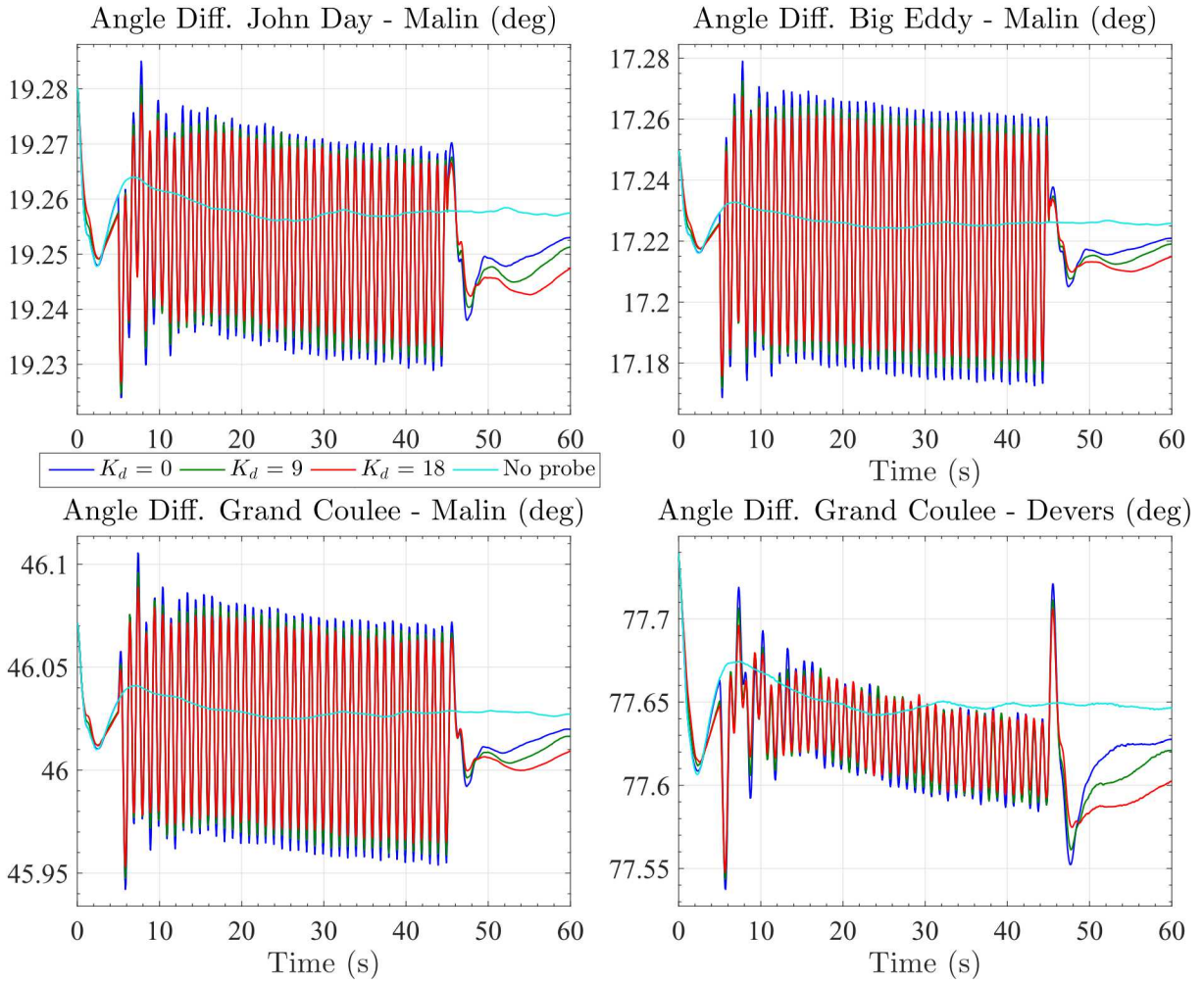


Figure 187. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

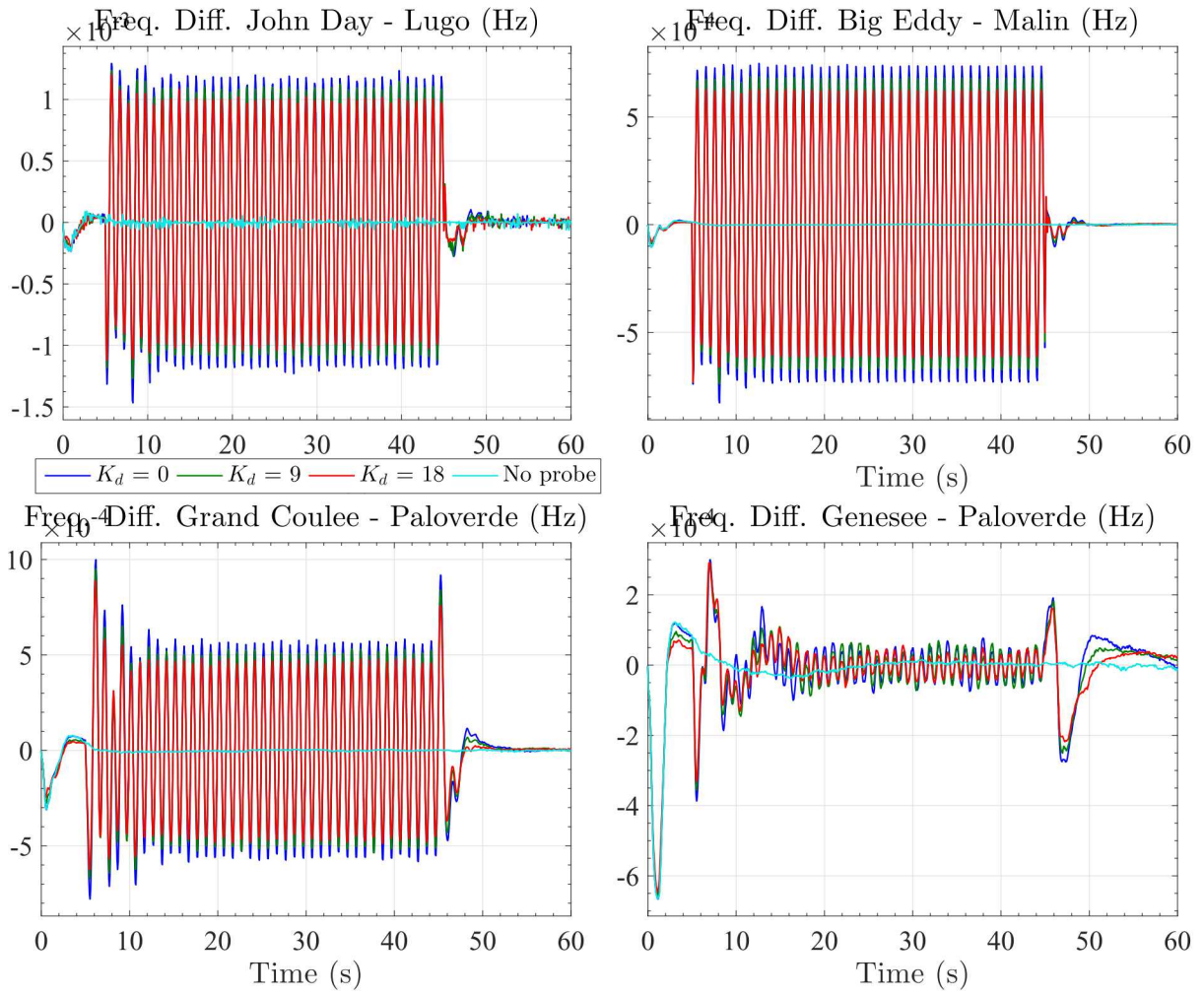




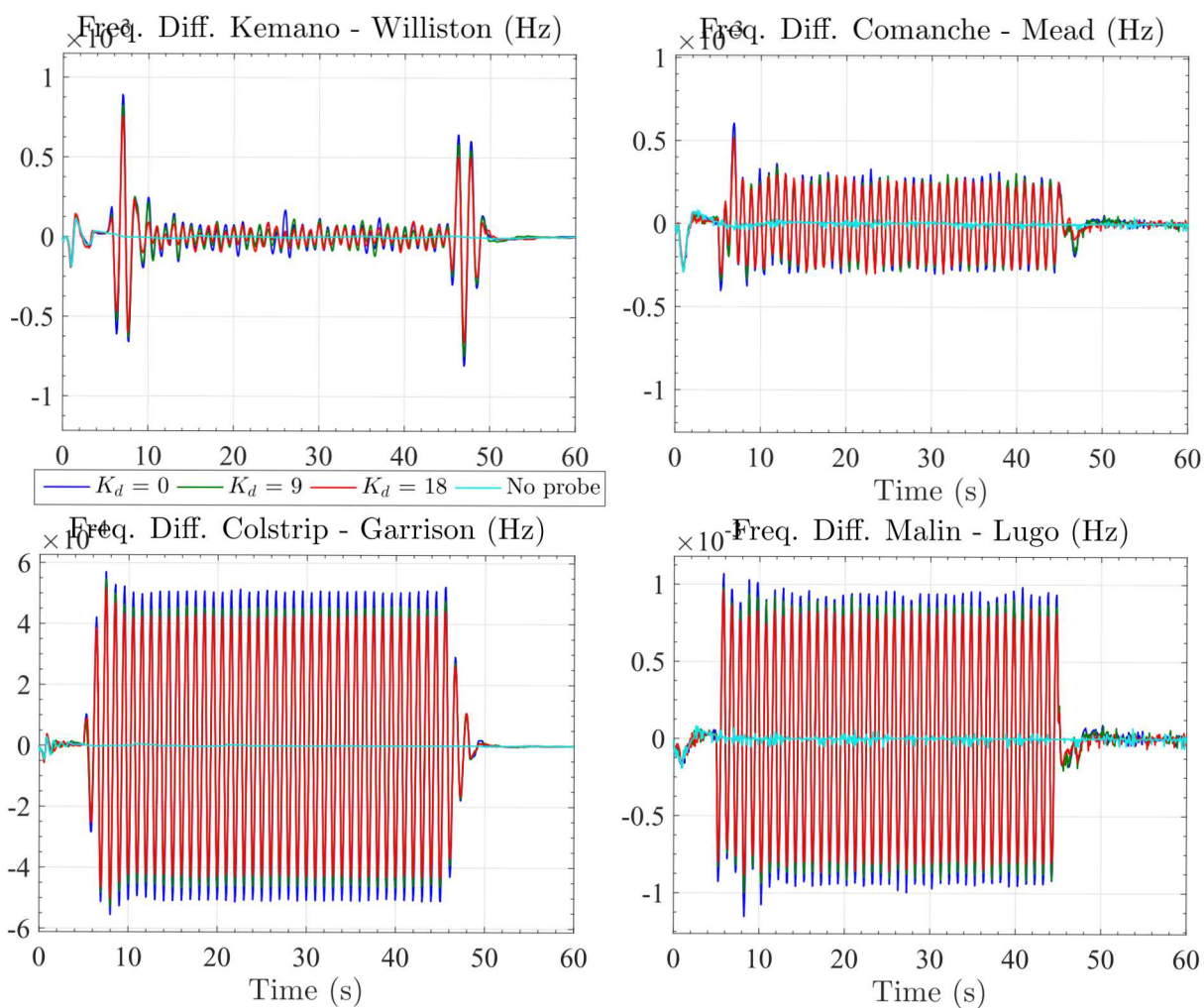
**Figure 188. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)**



**Figure 189. Angle differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)**

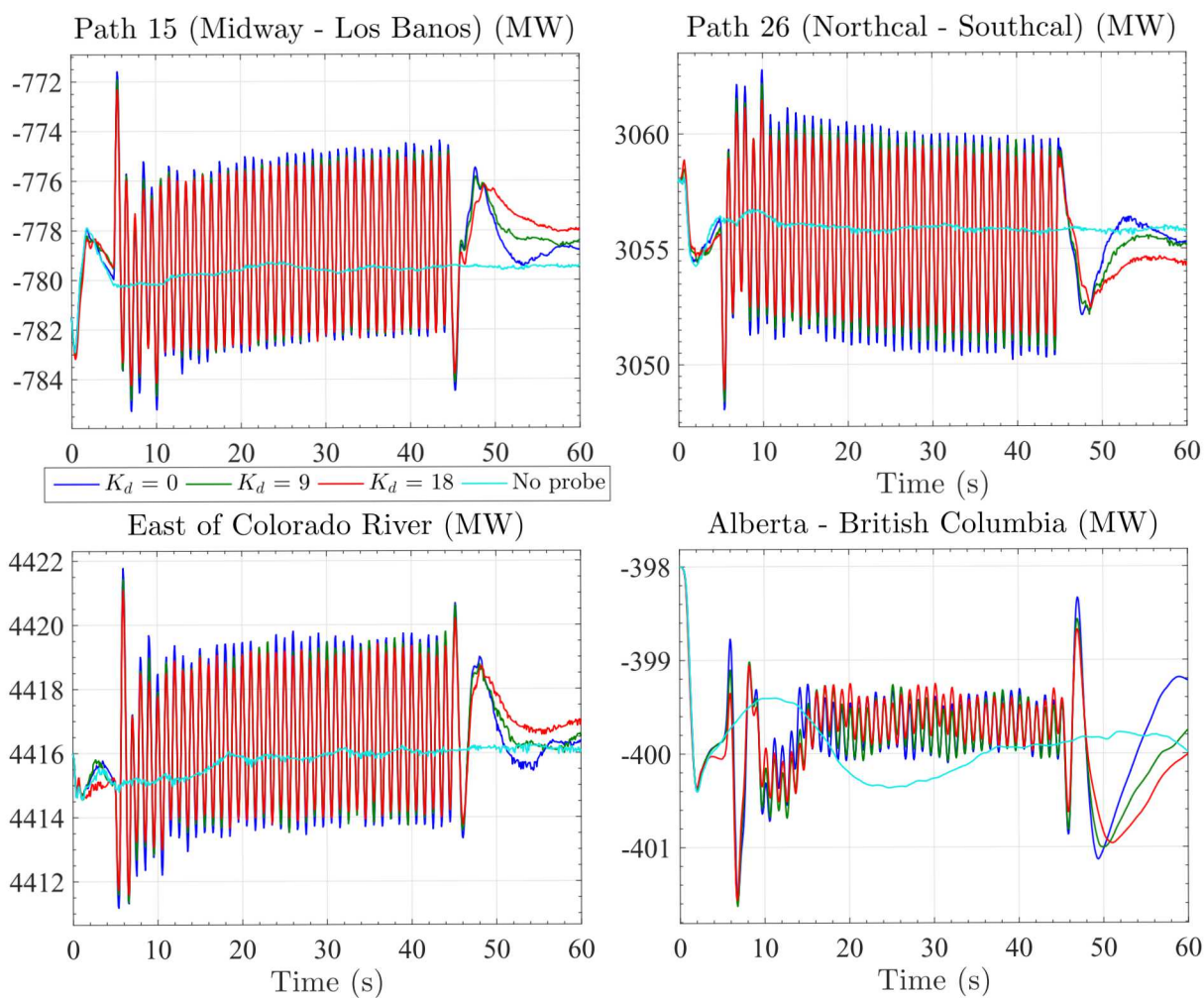


**Figure 190. Frequency differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)**



**Figure 191. Frequency differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)**





**Figure 192. Active power flows. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)**

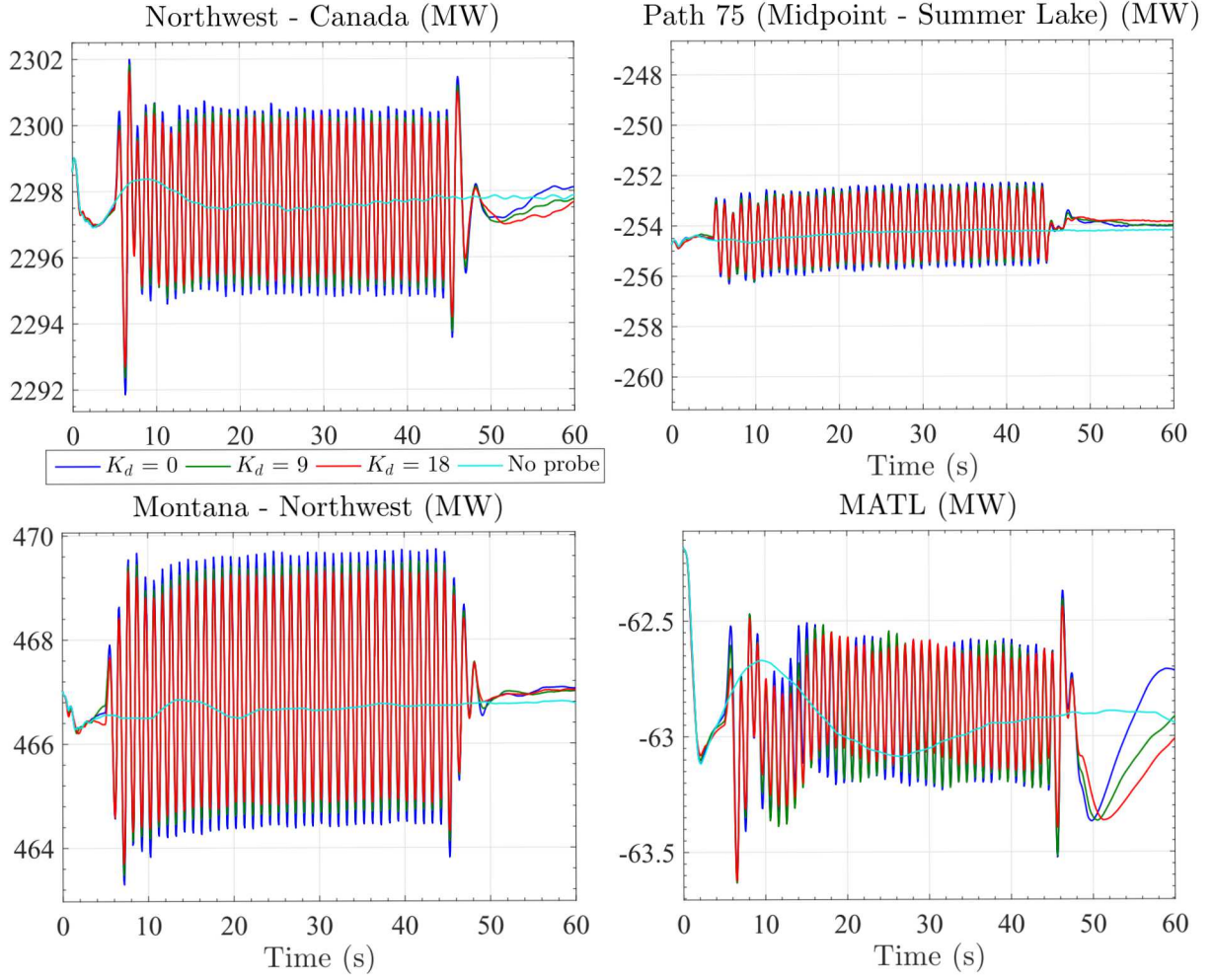


Figure 193. Active power flows. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

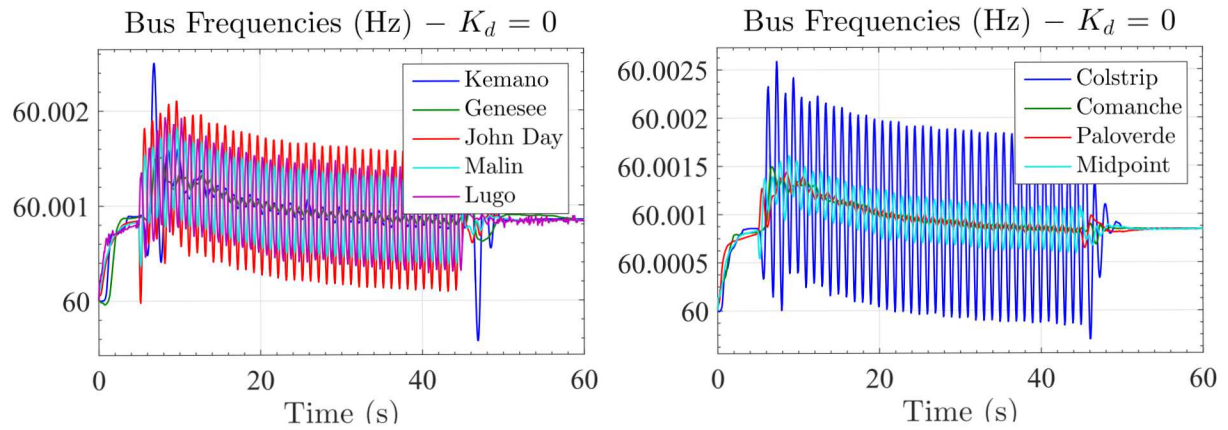


Figure 194. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)



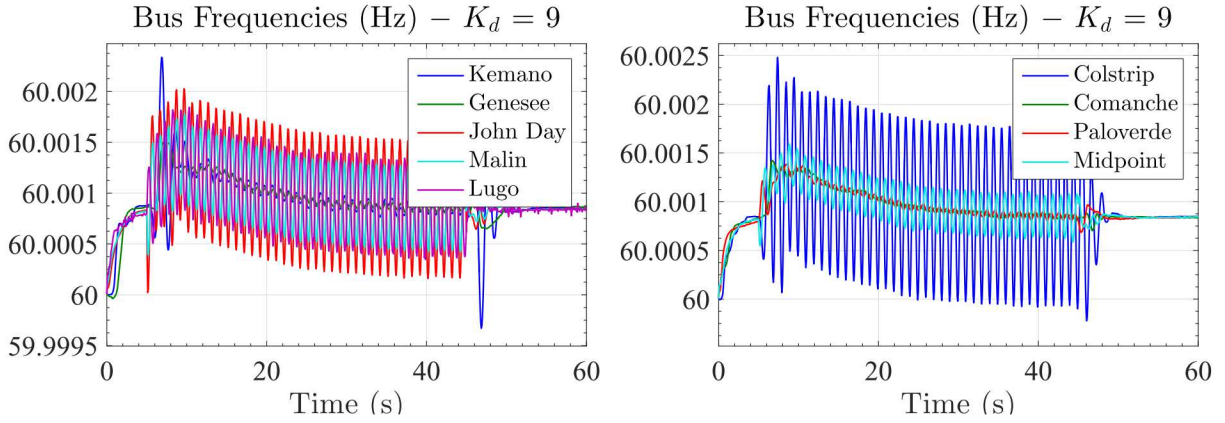


Figure 195. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

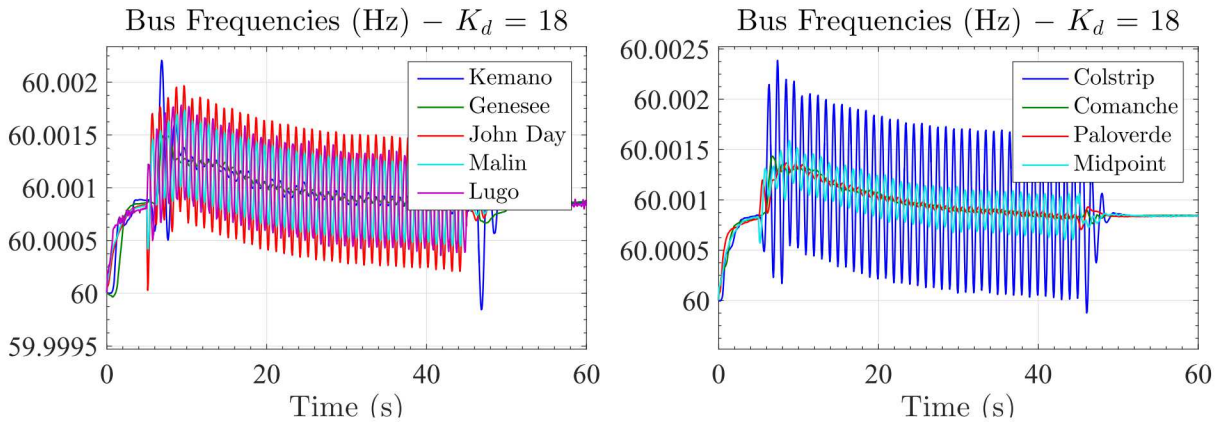


Figure 196. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

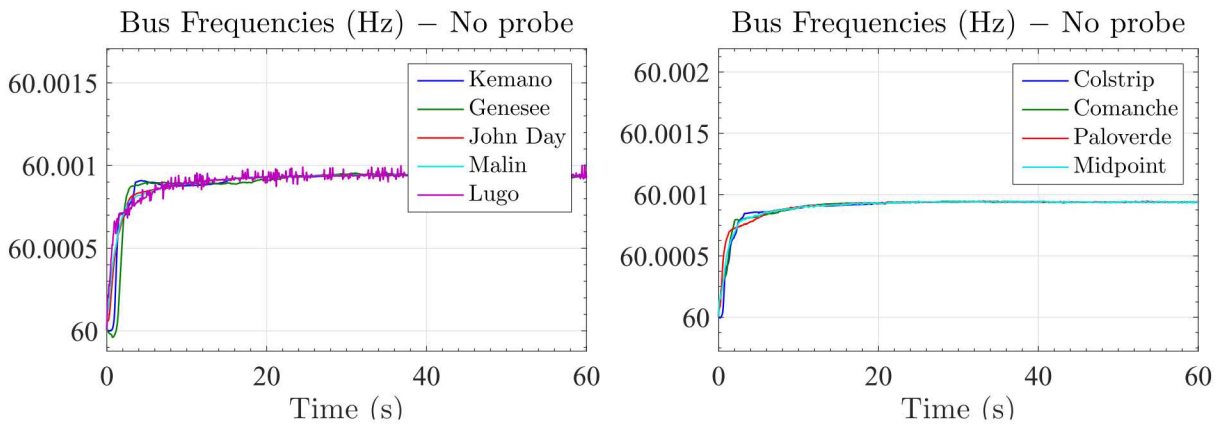


Figure 197. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

5.3. Test System: Heavy Summer 2016. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

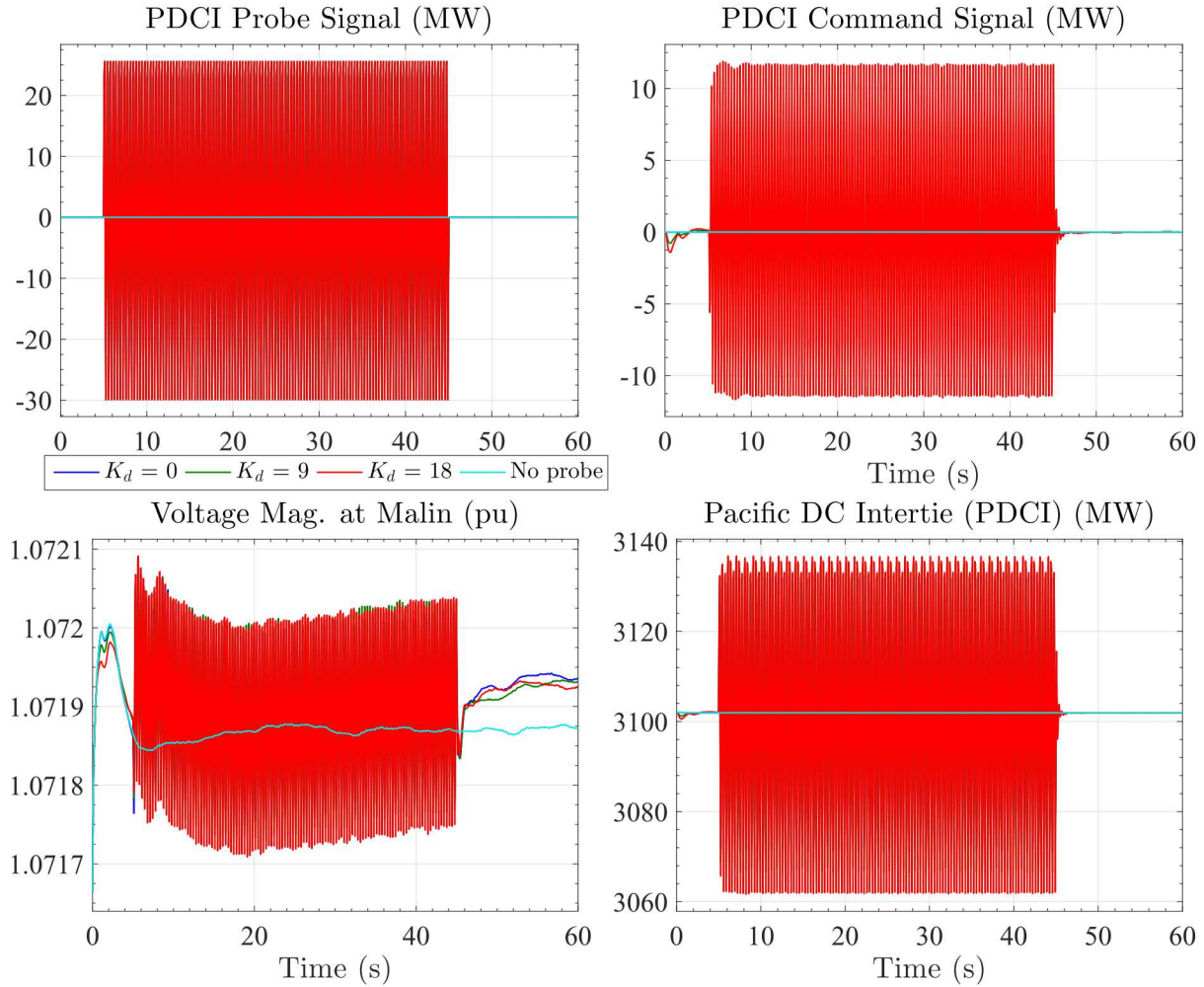
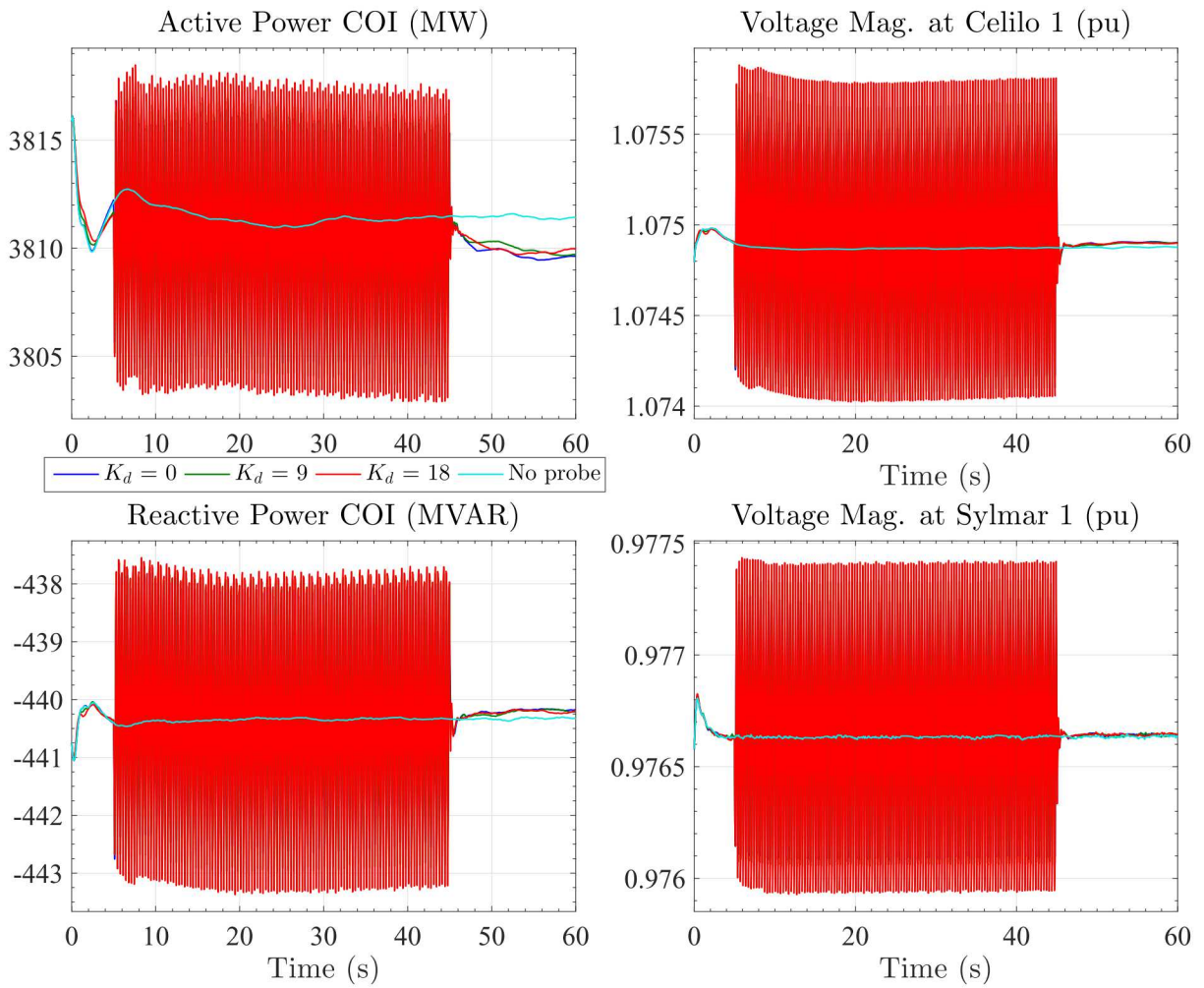
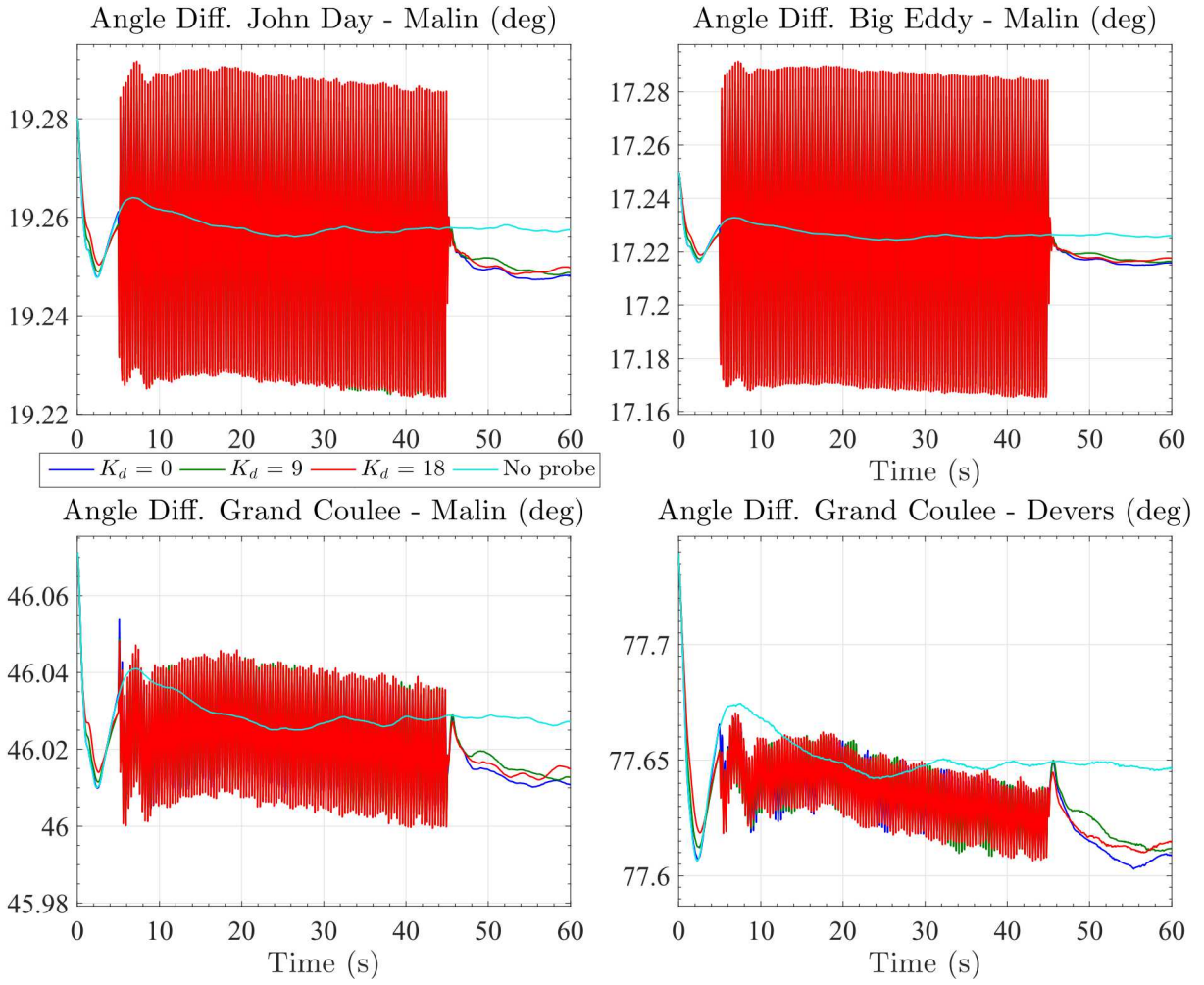


Figure 198. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

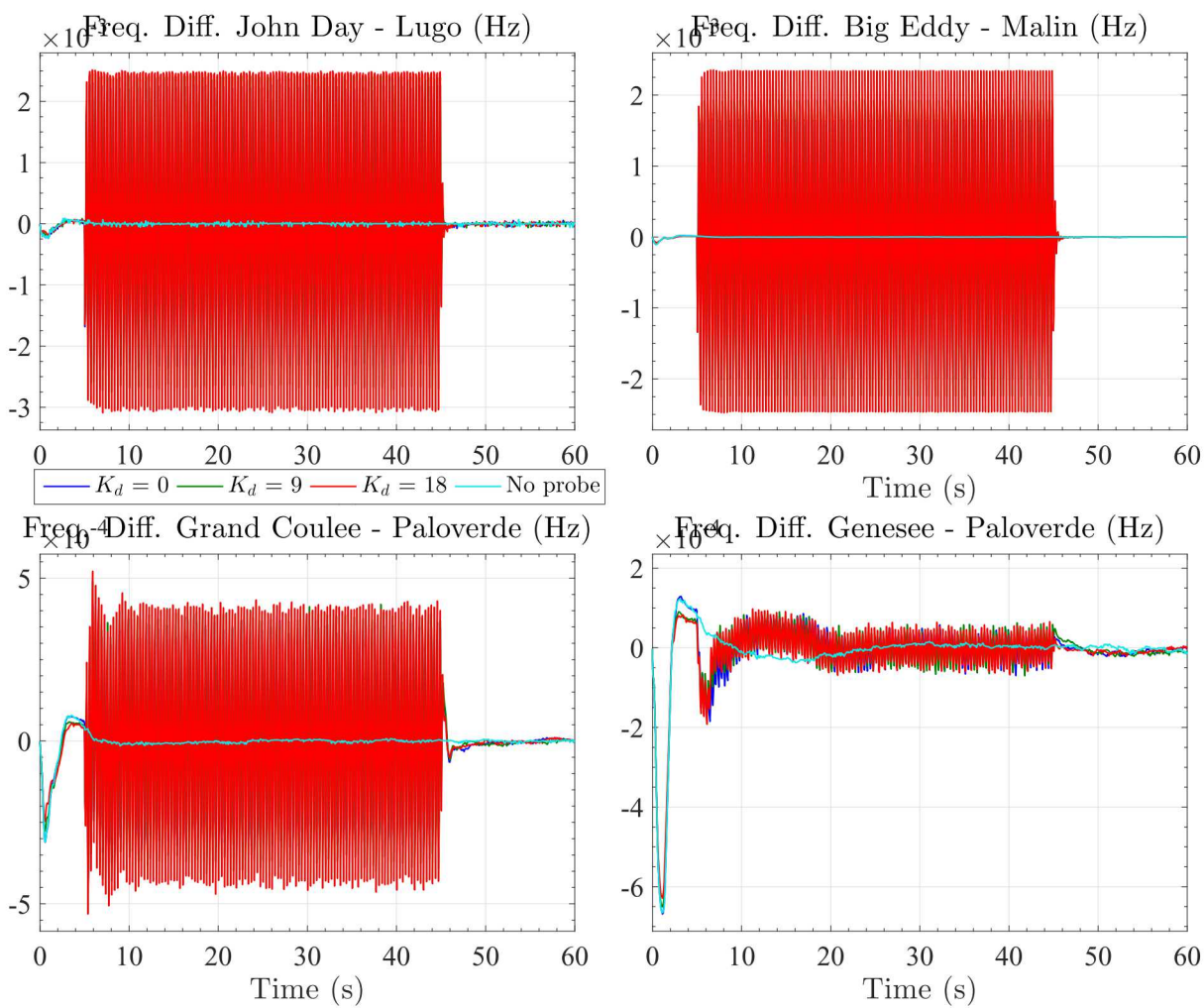


**Figure 199. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)**

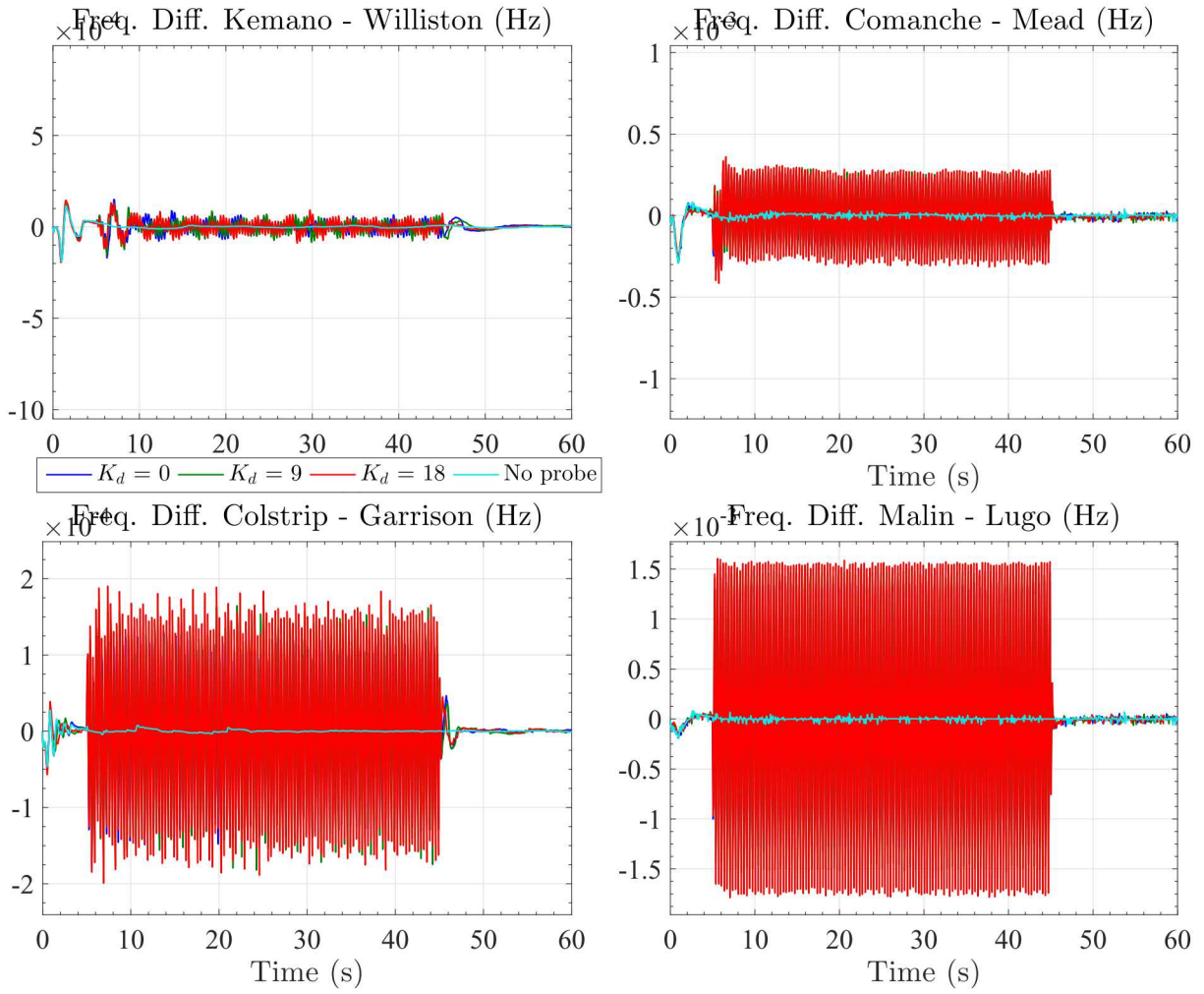


**Figure 200. Angle differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)**



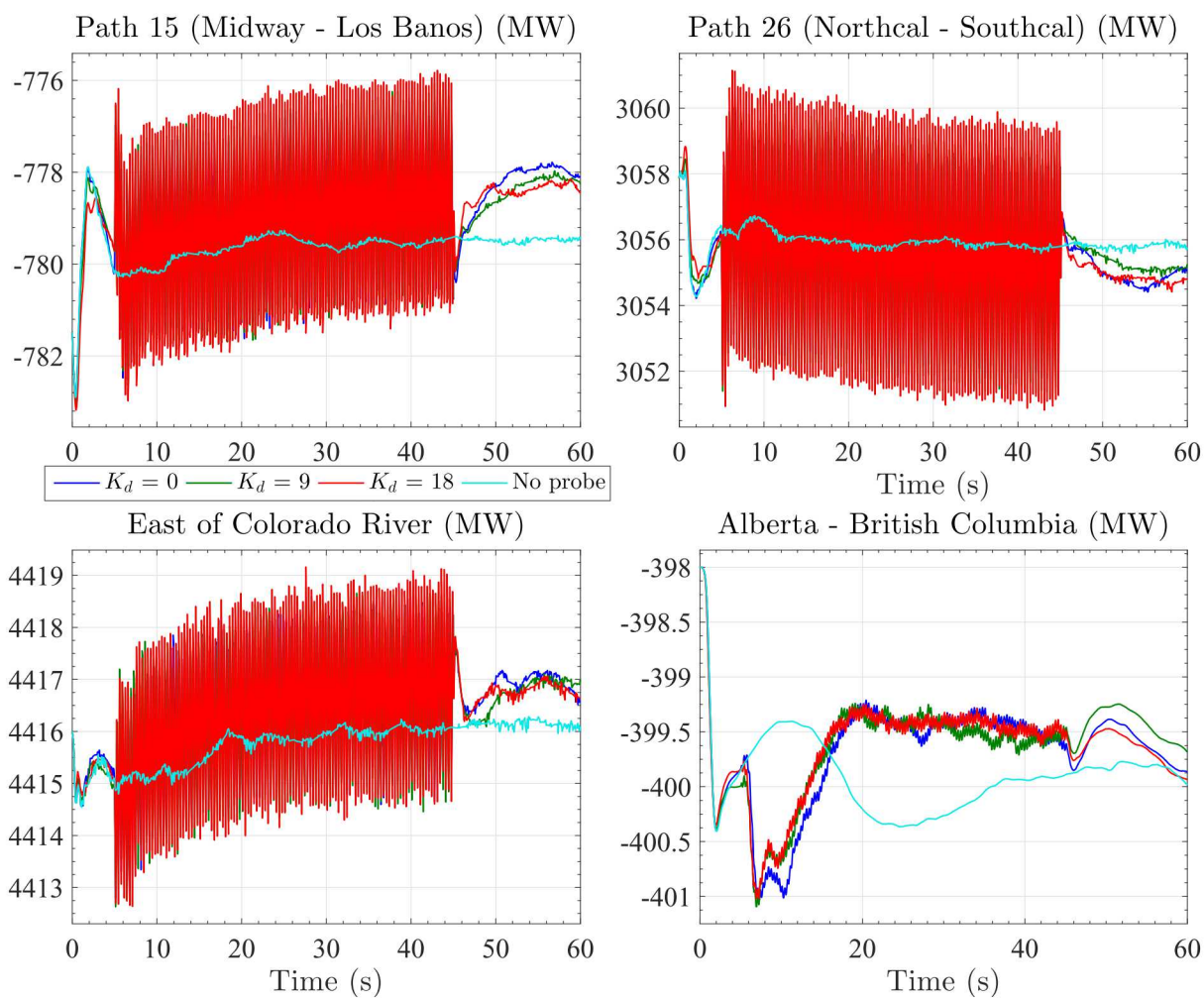


**Figure 201. Frequency differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)**



**Figure 202. Frequency differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)**





**Figure 203. Active power flows. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)**

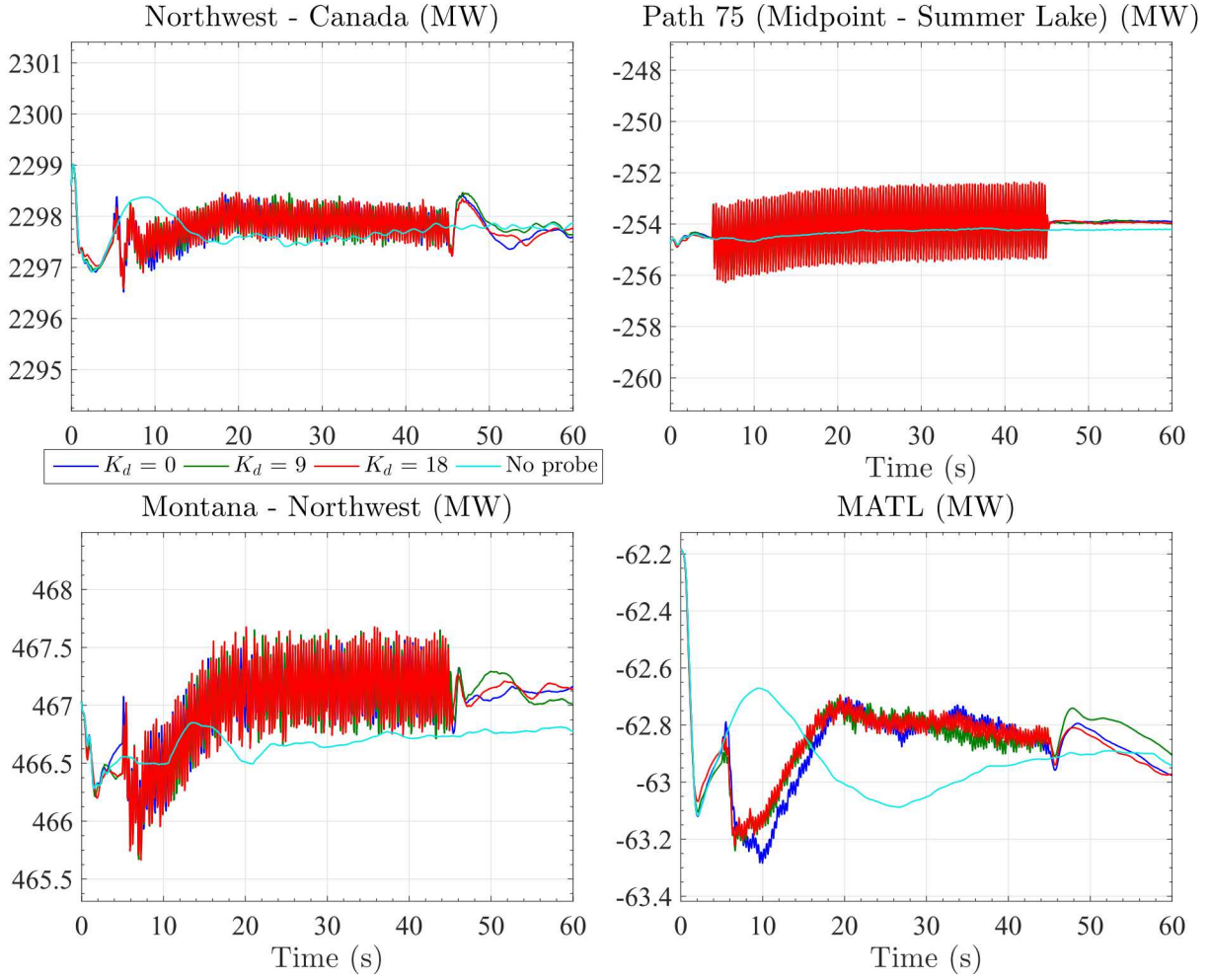


Figure 204. Active power flows. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

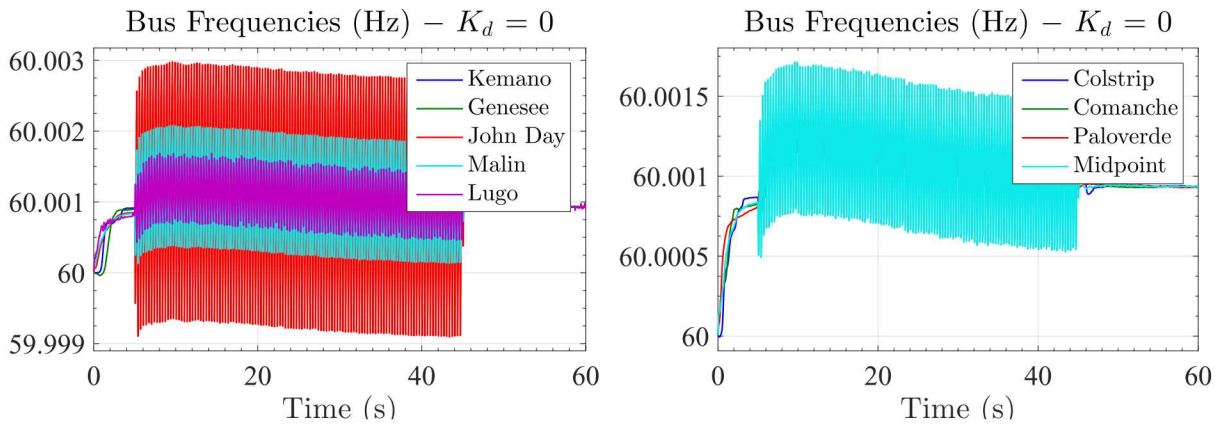


Figure 205. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

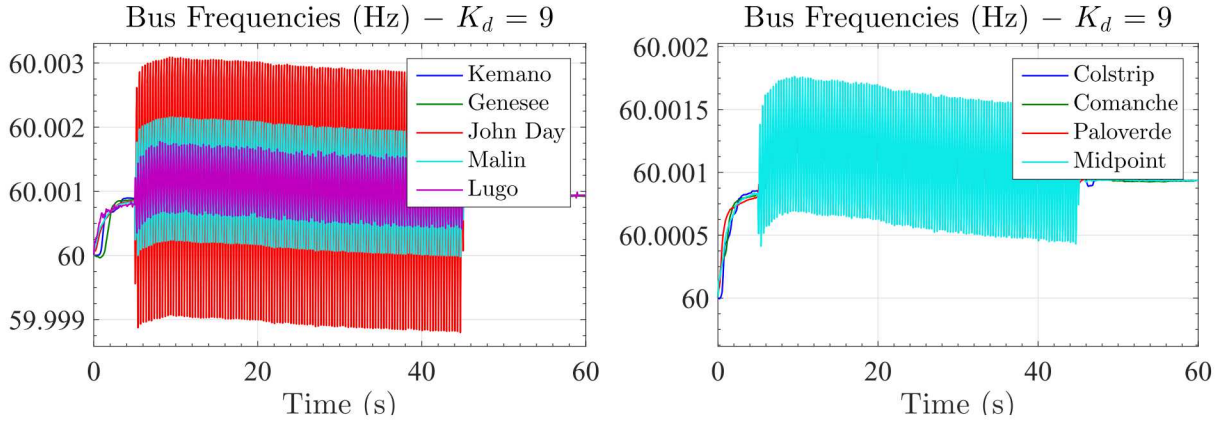


Figure 206. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

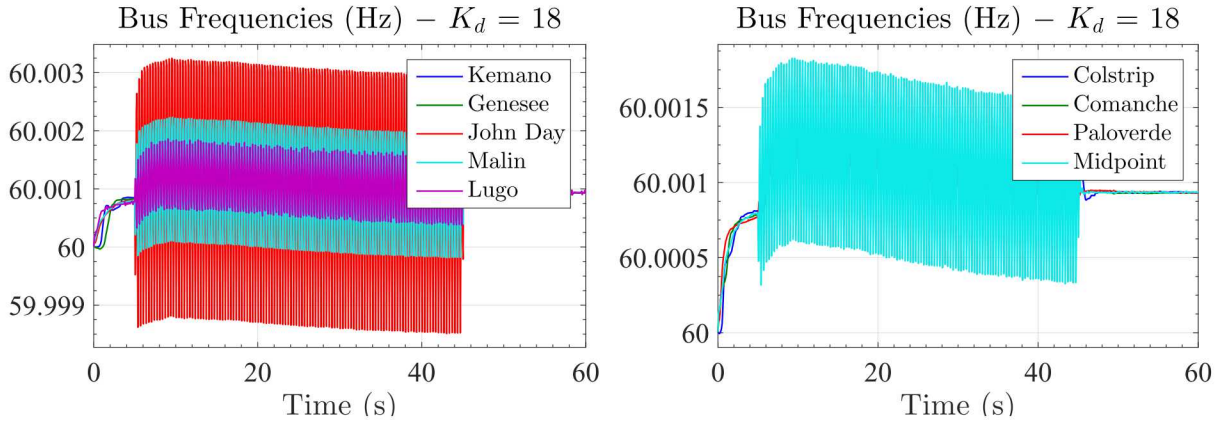


Figure 207. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

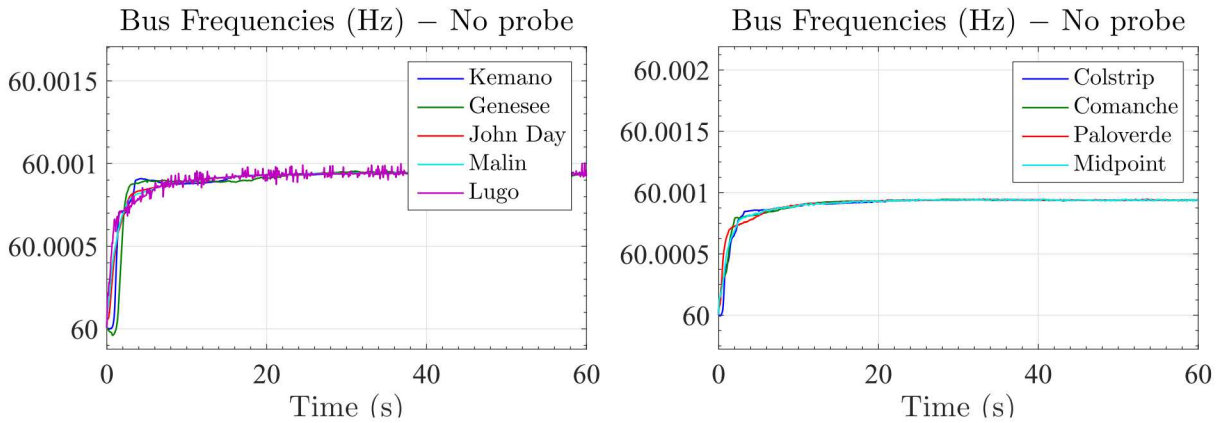


Figure 208. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

5.4. Test System: Heavy Summer 2016. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

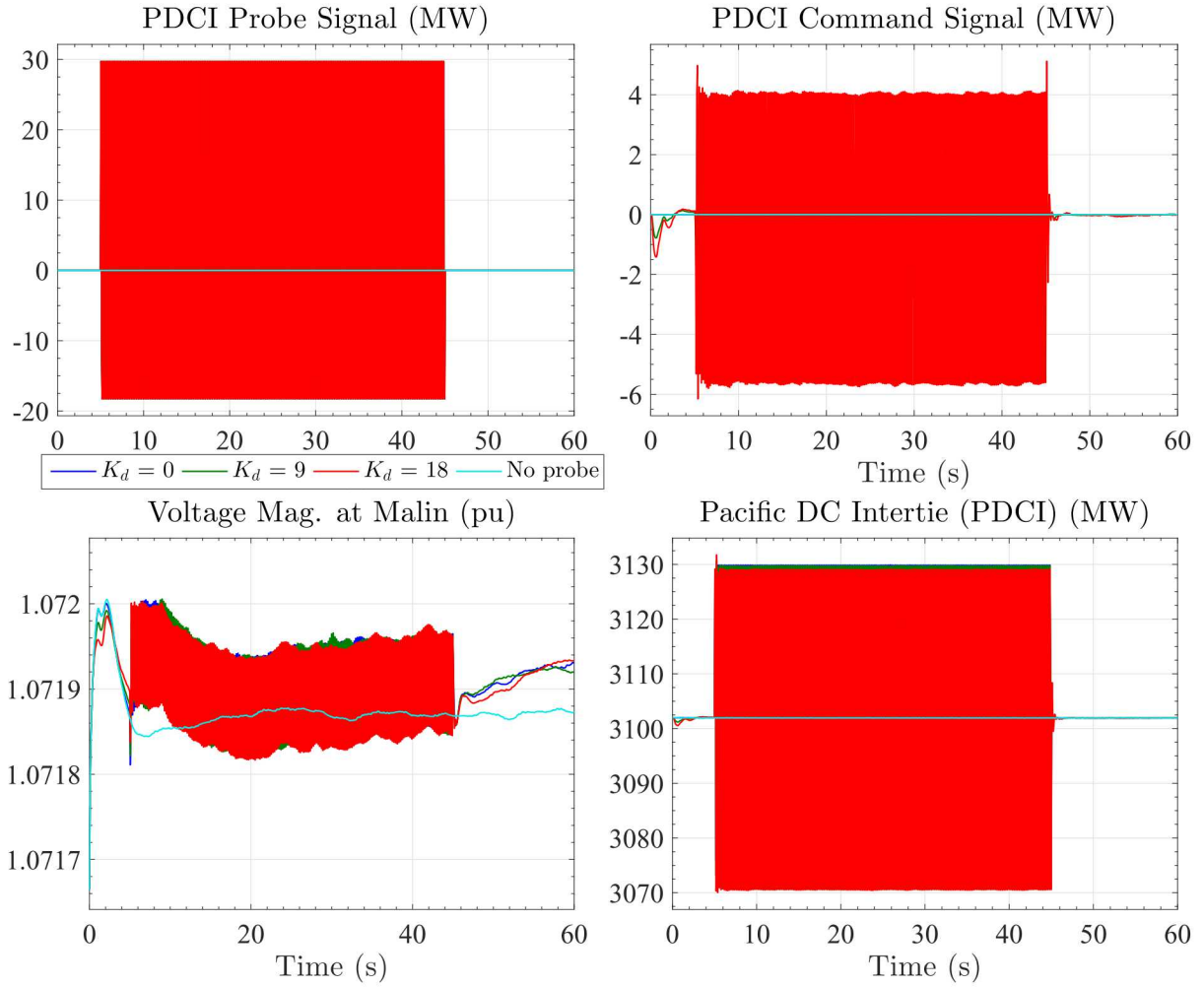
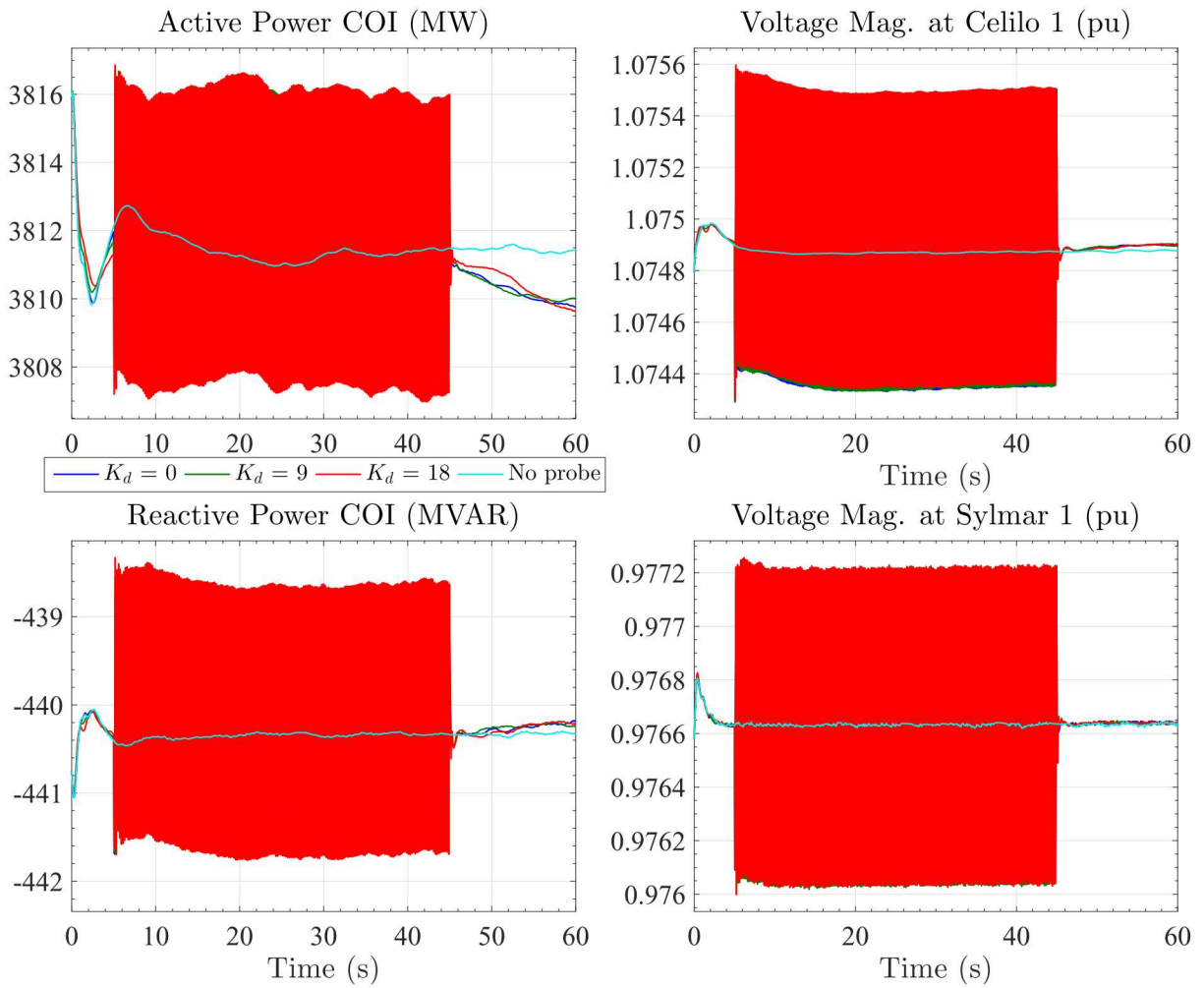
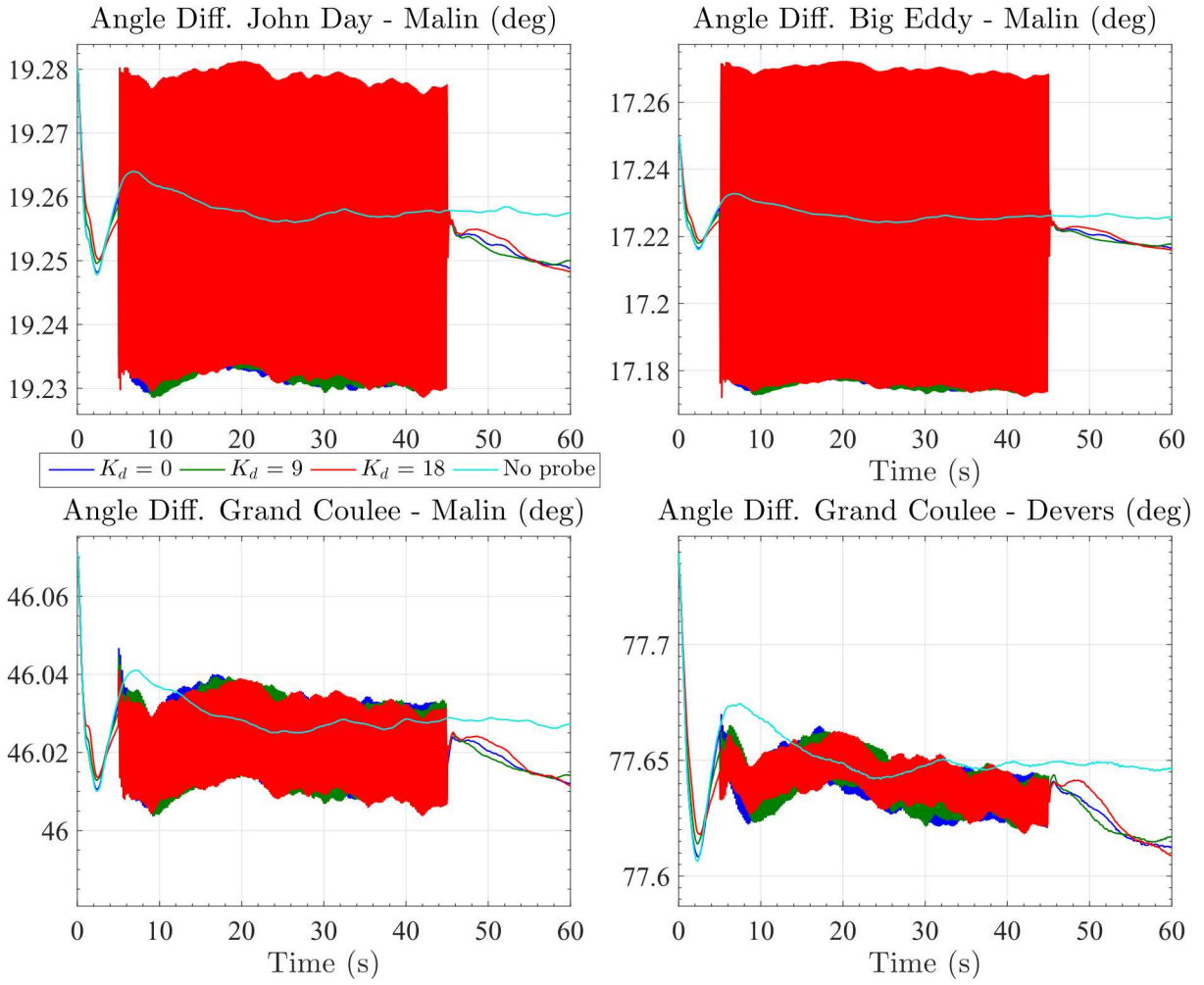


Figure 209. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)



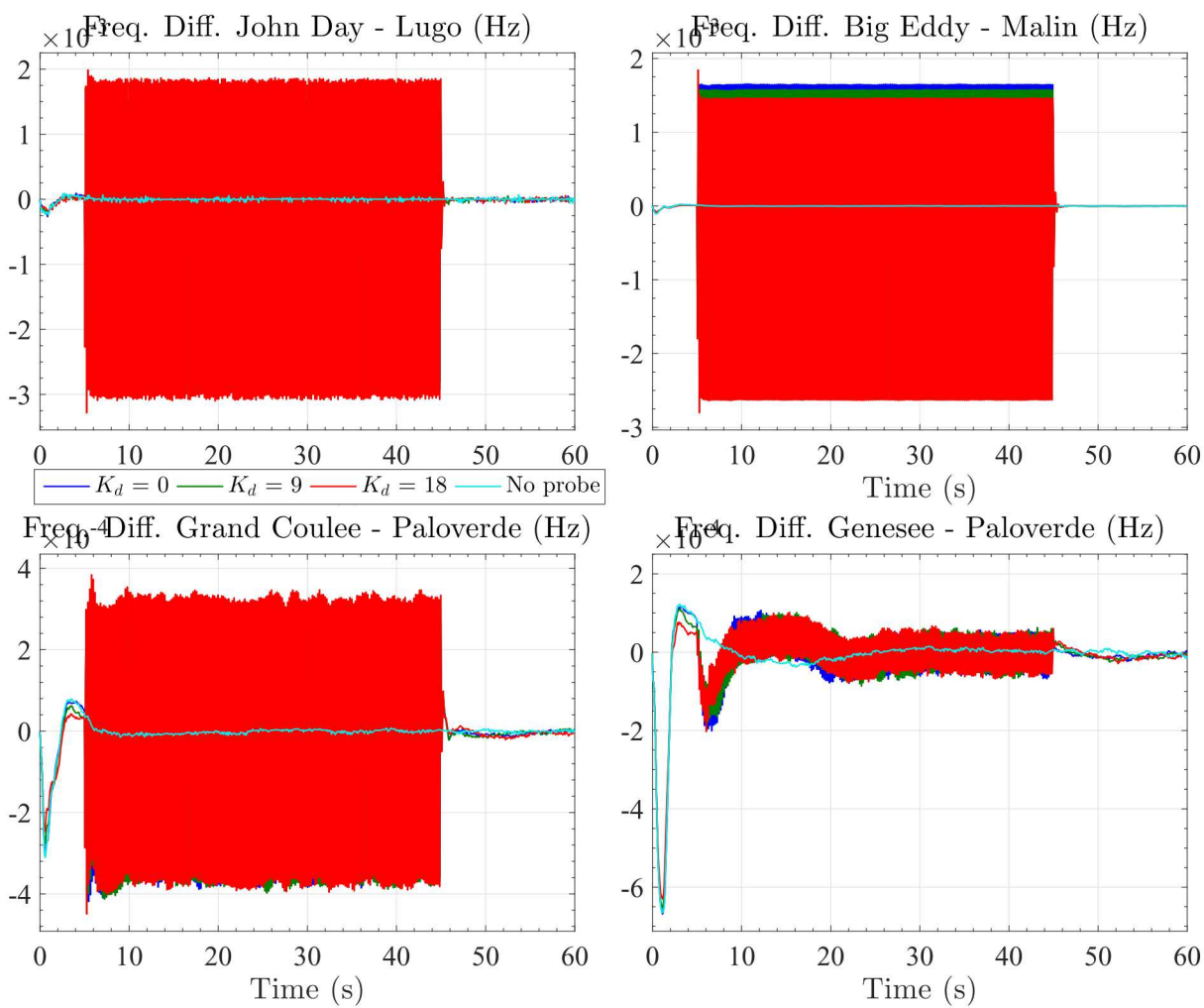
**Figure 210. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)**



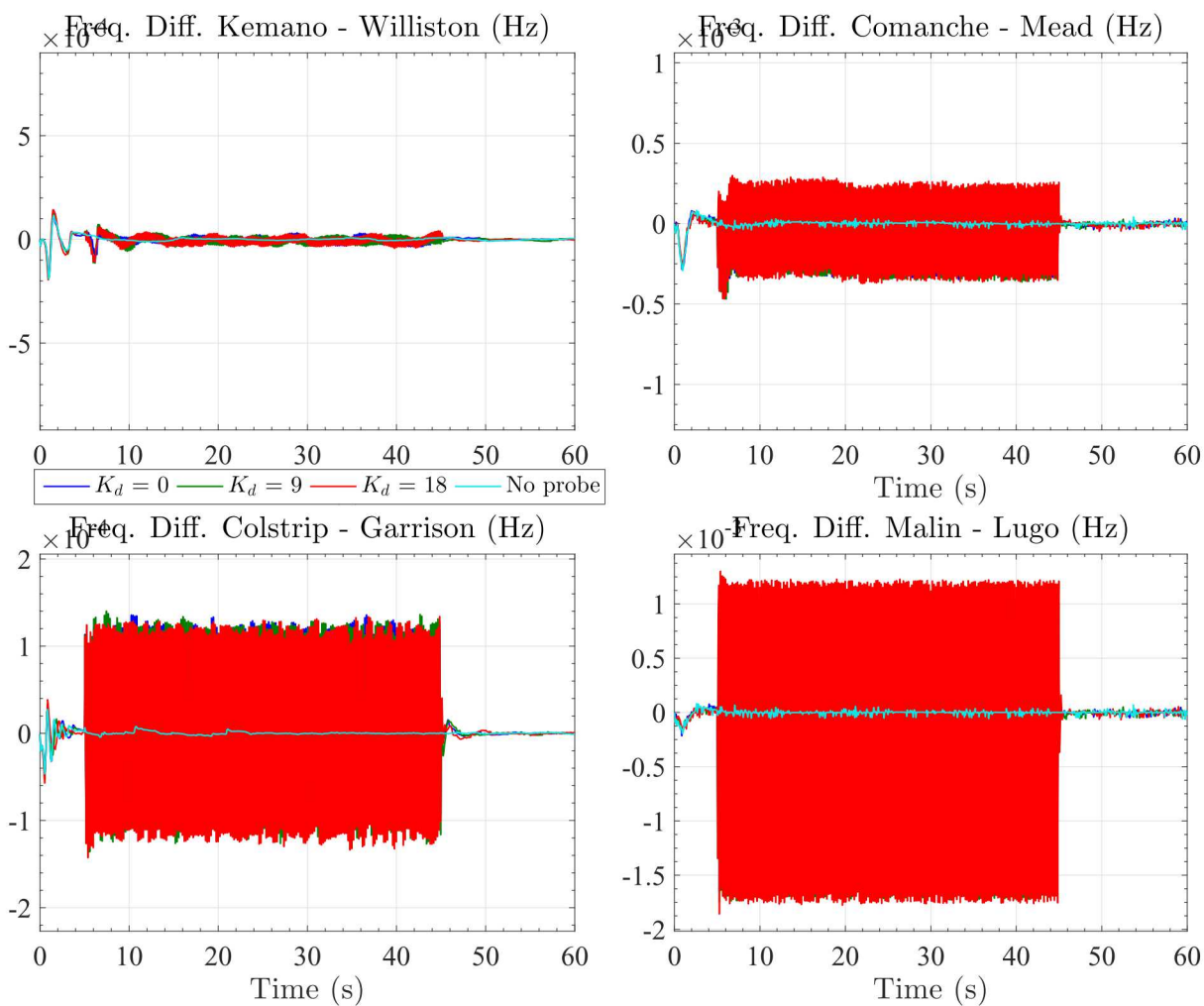


**Figure 211. Angle differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)**

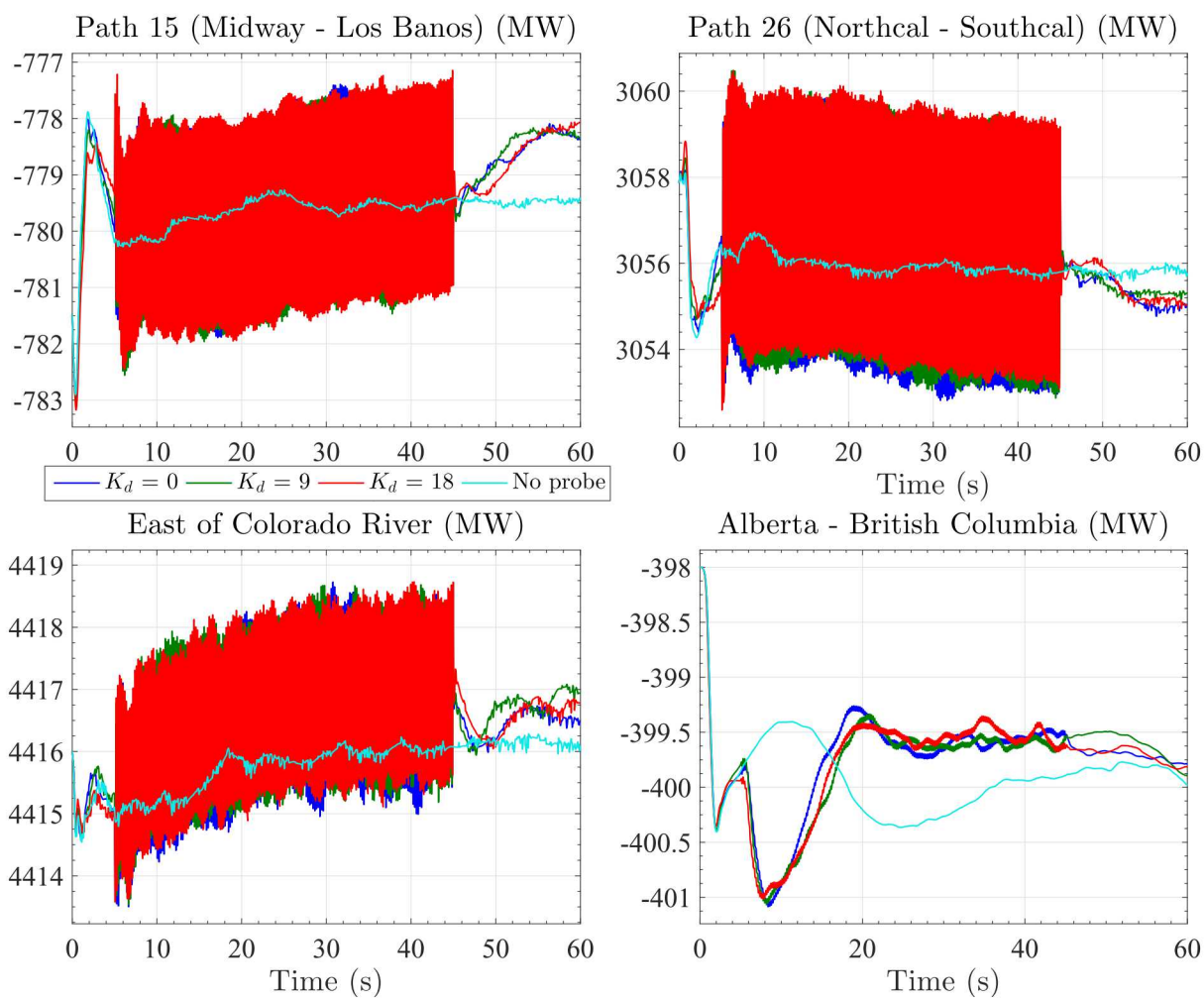




**Figure 212. Frequency differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)**



**Figure 213. Frequency differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)**



**Figure 214. Active power flows. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)**

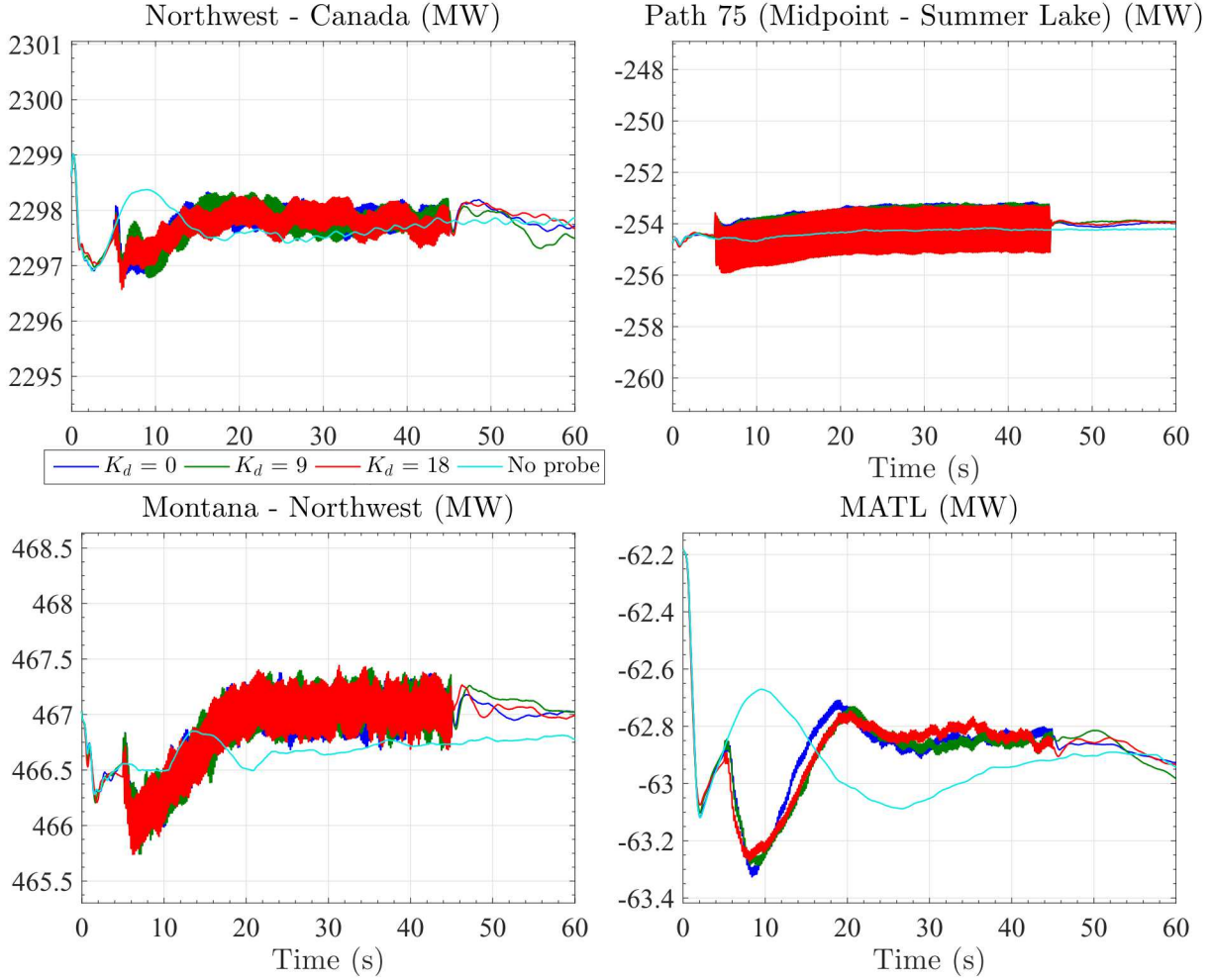


Figure 215. Active power flows. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

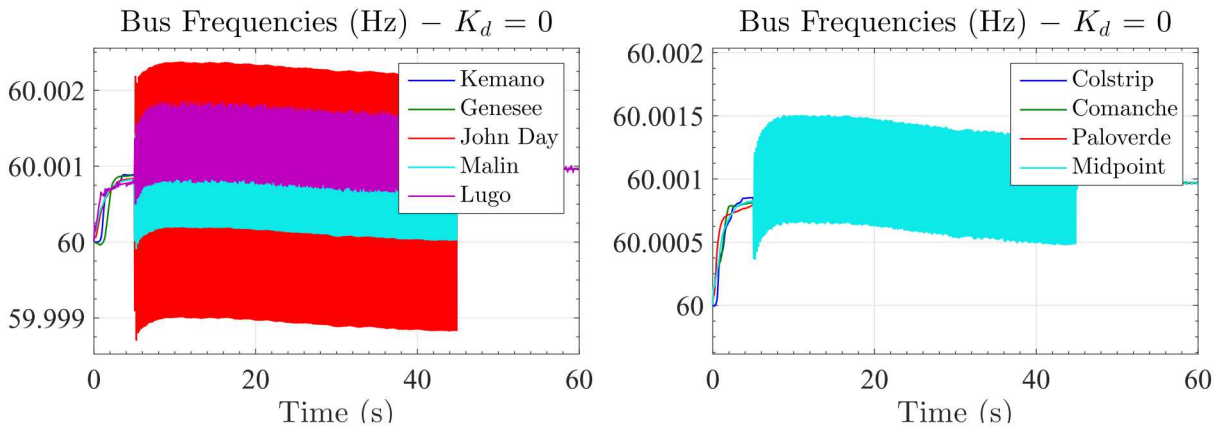


Figure 216. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

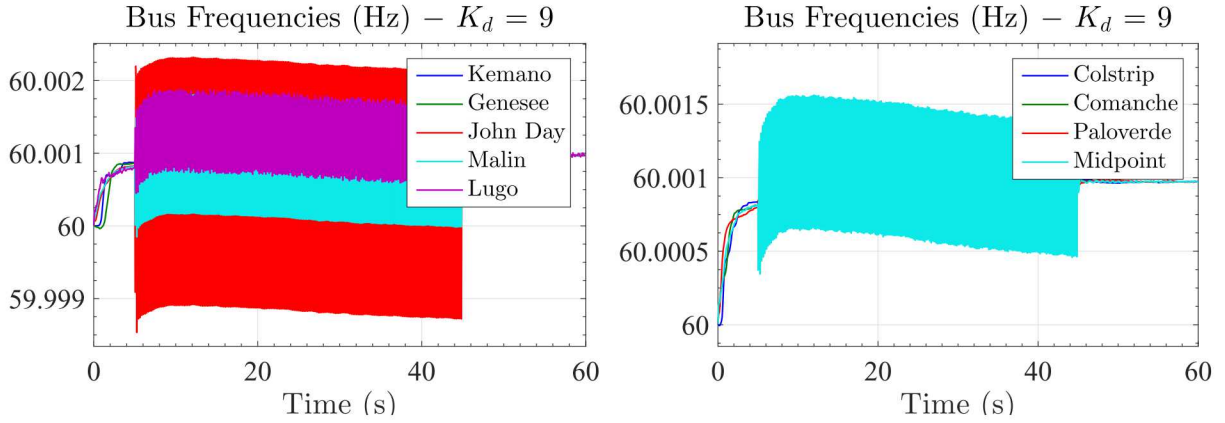


Figure 217. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

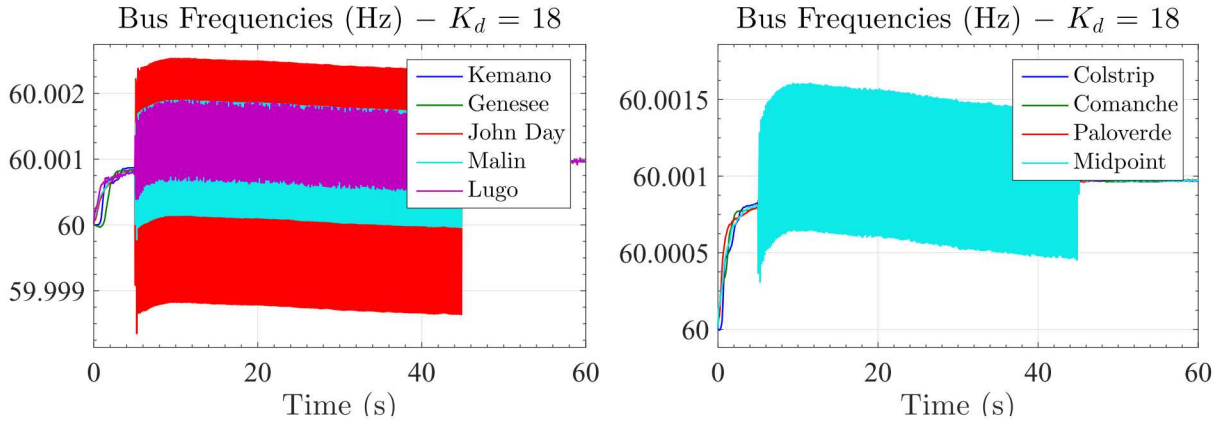


Figure 218. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

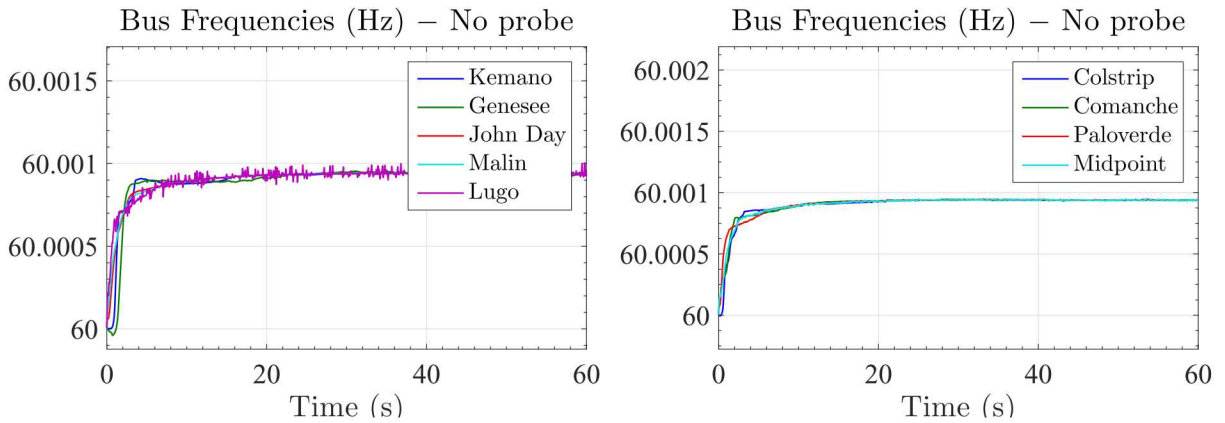


Figure 219. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

## References

- [1] F. Wilches-Bernal, B. J. Pierre, R. T. Elliott, D. A. Schoenwald, R. H. Byrne, J. C. Neely, D. J. Trudnowski, and M. K. Donnelly, "PDCI Wide-Area Damping Control: PSLF Simulations of the 2016 Open and Closed Loop Test Plan," Sandia National Laboratories, Albuquerque, NM, Tech. Rep. SAND2017-2755, Mar. 2017.
- [2] F. Wilches-Bernal, B. J. Pierre, R. T. Elliott, D. A. Schoenwald, R. H. Byrne, J. C. Neely, and D. J. Trudnowski, "Time Delay Definitions and Characterization in the Pacific DC Intertie Wide Area Damping Controller," in *Power and Energy Soc. General Meeting, 2017. IEEE*, Chicago, IL, 2017, pp. 1–5.
- [3] B. J. Pierre, F. Wilches-Bernal, R. T. Elliott, D. A. Schoenwald, J. C. Neely, R. H. Byrne, and D. J. Trudnowski, "Simulation Results for the Pacific DC Intertie Wide Area Damping Controller," in *Power and Energy Soc. General Meeting, 2017. IEEE*, Chicago, IL, 2017, pp. 1–5.
- [4] D. A. Schoenwald, B. J. Pierre, F. Wilches-Bernal, and D. J. Trudnowski, "Design and Implementation of a Wide-Area Damping Controller Using High Voltage DC Modulation and Synchrophasor Feedback," in *2017 IFAC World Congress*, Toulouse, France, 2017, pp. 1–6.
- [5] D. J. Trudnowski, B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, J. C. Neely, R. H. Byrne, and D. Kosterev, "Initial Closed-Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller," in *Power and Energy Soc. General Meeting, 2017. IEEE*, Chicago, IL, 2017, pp. 1–5.
- [6] B. J. Pierre, F. Wilches-Bernal, R. T. Elliott, D. A. Schoenwald, J. C. Neely, R. H. Byrne, and D. J. Trudnowski, "Open Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller," in *the 12th IEEE PES PowerTech Conference*, Manchester, UK, 2017, pp. 1–6.



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