

SANDIA REPORT

SAND2017-XXXX

Unlimited Release

Printed June 2017

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

Felipe Wilches-Bernal, Brian J. Pierre, Ryan T. Elliott, David A. Schoenwald,
Raymond H. Byrne, and Jason C. Neely
Sandia National Laboratories

Daniel J. Trudnowski and Matthew K. Donnelly
Montana Tech University

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multitechnology laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Approved for public release; further dissemination unlimited.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by NTESS, LLC.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online ordering: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



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

Felipe Wilches-Bernal, Brian J. Pierre, Ryan T. Elliott, David A. Schoenwald,
Raymond H. Byrne, and Jason C. Neely
Sandia National Laboratories
MS 1140, P.O. Box 5800
Albuquerque, NM 87185-1140

Daniel J. Trudnowski and Matthew K. Donnelly
Montana Tech University

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 light 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).

Sandia National Laboratories is a multitechnology laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

CONTENTS

1. INTRODUCTION	15
1.1. Background and Motivation	15
2. NEGATIVE GAIN TESTING	17
2.1. Test System: Light Summer 2016. Event: Chief Joe Brake	17
2.2. Test System: Light Summer 2016. Event: Double Palo Verde Trip	26
2.3. Test System: Light Summer 2016. Event: BC-US Separation	35
2.4. Test System: Light Summer 2016. Event: BC-AB Separation	44
2.5. Test System: Light Summer 2016. Event: CJB + 2PV	53
2.6. Test System: Light Summer 2016. Event: CJB + BCUS Separation	62
2.7. Test System: Light Summer 2016. Event: CJB + BCAB Separation	71
3. CONTROLLER LIMITS (HIGHER GAINS)	81
3.1. Test System: Light Summer 2016. Event: Chief Joe Brake	81
3.2. Test System: Light Summer 2016. Event: Double Palo Verde Trip	89
3.3. Test System: Light Summer 2016. Event: BC-US Separation	97
3.4. Test System: Light Summer 2016. Event: BC-AB Separation	105
3.5. Test System: Light Summer 2016. Event: CJB + 2PV	113
3.6. Test System: Light Summer 2016. Event: CJB + BCUS Separation	121
3.7. Test System: Light Summer 2016. Event: CJB + BCAB Separation	129
4. CHIEF JOSEPH BRAKE COMPARISON	137
4.1. Test System: Light Summer 2016. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	137
5. FORCED OSCILLATIONS (HIGHER FREQUENCIES)	147
5.1. Test System: Light Summer 2016. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	147
5.2. Test System: Light Summer 2016. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	155
5.3. Test System: Light Summer 2016. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	163
5.4. Test System: Light Summer 2016. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)	171
References	179
DISTRIBUTION	180

FIGURES

Figure 1.	Block diagram of the controller setup.	15
Figure 2.	PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake	17
Figure 3.	Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake	18
Figure 4.	Angle differences. Event: Chief Joe Brake	19
Figure 5.	Frequency differences. Event: Chief Joe Brake	20
Figure 6.	Frequency differences. Event: Chief Joe Brake	21
Figure 7.	Active power flows. Event: Chief Joe Brake	22
Figure 8.	Active power flows. Event: Chief Joe Brake	23
Figure 9.	Bus frequencies. Event: Chief Joe Brake	23
Figure 10.	Bus frequencies. Event: Chief Joe Brake	24
Figure 11.	Bus frequencies. Event: Chief Joe Brake	24
Figure 12.	Bus frequencies. Event: Chief Joe Brake	24
Figure 13.	Bus frequencies. Event: Chief Joe Brake	25
Figure 14.	PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Double Palo Verde Trip	26
Figure 15.	Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Double Palo Verde Trip	27
Figure 16.	Angle differences. Event: Double Palo Verde Trip	28
Figure 17.	Frequency differences. Event: Double Palo Verde Trip	29
Figure 18.	Frequency differences. Event: Double Palo Verde Trip	30
Figure 19.	Active power flows. Event: Double Palo Verde Trip	31
Figure 20.	Active power flows. Event: Double Palo Verde Trip	32
Figure 21.	Bus frequencies. Event: Double Palo Verde Trip	32
Figure 22.	Bus frequencies. Event: Double Palo Verde Trip	33
Figure 23.	Bus frequencies. Event: Double Palo Verde Trip	33
Figure 24.	Bus frequencies. Event: Double Palo Verde Trip	33
Figure 25.	Bus frequencies. Event: Double Palo Verde Trip	34
Figure 26.	PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-US Separation	35
Figure 27.	Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-US Separation	36
Figure 28.	Angle differences. Event: BC-US Separation	37
Figure 29.	Frequency differences. Event: BC-US Separation	38
Figure 30.	Frequency differences. Event: BC-US Separation	39
Figure 31.	Active power flows. Event: BC-US Separation	40
Figure 32.	Active power flows. Event: BC-US Separation	41
Figure 33.	Bus frequencies. Event: BC-US Separation	41
Figure 34.	Bus frequencies. Event: BC-US Separation	42
Figure 35.	Bus frequencies. Event: BC-US Separation	42
Figure 36.	Bus frequencies. Event: BC-US Separation	42
Figure 37.	Bus frequencies. Event: BC-US Separation	43
Figure 38.	PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-AB Separation	44
Figure 39.	Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-AB Separation	45
Figure 40.	Angle differences. Event: BC-AB Separation	46

Figure 41. Frequency differences. Event: BC-AB Separation	47
Figure 42. Frequency differences. Event: BC-AB Separation	48
Figure 43. Active power flows. Event: BC-AB Separation	49
Figure 44. Active power flows. Event: BC-AB Separation	50
Figure 45. Bus frequencies. Event: BC-AB Separation	50
Figure 46. Bus frequencies. Event: BC-AB Separation	51
Figure 47. Bus frequencies. Event: BC-AB Separation	51
Figure 48. Bus frequencies. Event: BC-AB Separation	51
Figure 49. Bus frequencies. Event: BC-AB Separation	52
Figure 50. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + 2PV	53
Figure 51. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + 2PV	54
Figure 52. Angle differences. Event: CJB + 2PV	55
Figure 53. Frequency differences. Event: CJB + 2PV	56
Figure 54. Frequency differences. Event: CJB + 2PV	57
Figure 55. Active power flows. Event: CJB + 2PV	58
Figure 56. Active power flows. Event: CJB + 2PV	59
Figure 57. Bus frequencies. Event: CJB + 2PV	59
Figure 58. Bus frequencies. Event: CJB + 2PV	60
Figure 59. Bus frequencies. Event: CJB + 2PV	60
Figure 60. Bus frequencies. Event: CJB + 2PV	60
Figure 61. Bus frequencies. Event: CJB + 2PV	61
Figure 62. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCUS Separation	62
Figure 63. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCUS Separation	63
Figure 64. Angle differences. Event: CJB + BCUS Separation	64
Figure 65. Frequency differences. Event: CJB + BCUS Separation	65
Figure 66. Frequency differences. Event: CJB + BCUS Separation	66
Figure 67. Active power flows. Event: CJB + BCUS Separation	67
Figure 68. Active power flows. Event: CJB + BCUS Separation	68
Figure 69. Bus frequencies. Event: CJB + BCUS Separation	68
Figure 70. Bus frequencies. Event: CJB + BCUS Separation	69
Figure 71. Bus frequencies. Event: CJB + BCUS Separation	69
Figure 72. Bus frequencies. Event: CJB + BCUS Separation	69
Figure 73. Bus frequencies. Event: CJB + BCUS Separation	70
Figure 74. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCAB Separation	71
Figure 75. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCAB Separation	72
Figure 76. Angle differences. Event: CJB + BCAB Separation	73
Figure 77. Frequency differences. Event: CJB + BCAB Separation	74
Figure 78. Frequency differences. Event: CJB + BCAB Separation	75
Figure 79. Active power flows. Event: CJB + BCAB Separation	76
Figure 80. Active power flows. Event: CJB + BCAB Separation	77
Figure 81. Bus frequencies. Event: CJB + BCAB Separation	77
Figure 82. Bus frequencies. Event: CJB + BCAB Separation	78
Figure 83. Bus frequencies. Event: CJB + BCAB Separation	78
Figure 84. Bus frequencies. Event: CJB + BCAB Separation	78

Figure 85. Bus frequencies. Event: CJB + BCAB Separation	79
Figure 86. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake	81
Figure 87. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake	82
Figure 88. Angle differences. Event: Chief Joe Brake	83
Figure 89. Frequency differences. Event: Chief Joe Brake	84
Figure 90. Frequency differences. Event: Chief Joe Brake	85
Figure 91. Active power flows. Event: Chief Joe Brake	86
Figure 92. Active power flows. Event: Chief Joe Brake	87
Figure 93. Bus frequencies. Event: Chief Joe Brake	87
Figure 94. Bus frequencies. Event: Chief Joe Brake	88
Figure 95. Bus frequencies. Event: Chief Joe Brake	88
Figure 96. Bus frequencies. Event: Chief Joe Brake	88
Figure 97. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Double Palo Verde Trip	89
Figure 98. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Double Palo Verde Trip	90
Figure 99. Angle differences. Event: Double Palo Verde Trip	91
Figure 100. Frequency differences. Event: Double Palo Verde Trip	92
Figure 101. Frequency differences. Event: Double Palo Verde Trip	93
Figure 102. Active power flows. Event: Double Palo Verde Trip	94
Figure 103. Active power flows. Event: Double Palo Verde Trip	95
Figure 104. Bus frequencies. Event: Double Palo Verde Trip	95
Figure 105. Bus frequencies. Event: Double Palo Verde Trip	96
Figure 106. Bus frequencies. Event: Double Palo Verde Trip	96
Figure 107. Bus frequencies. Event: Double Palo Verde Trip	96
Figure 108. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-US Separation	97
Figure 109. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-US Separation	98
Figure 110. Angle differences. Event: BC-US Separation	99
Figure 111. Frequency differences. Event: BC-US Separation	100
Figure 112. Frequency differences. Event: BC-US Separation	101
Figure 113. Active power flows. Event: BC-US Separation	102
Figure 114. Active power flows. Event: BC-US Separation	103
Figure 115. Bus frequencies. Event: BC-US Separation	103
Figure 116. Bus frequencies. Event: BC-US Separation	104
Figure 117. Bus frequencies. Event: BC-US Separation	104
Figure 118. Bus frequencies. Event: BC-US Separation	104
Figure 119. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-AB Separation	105
Figure 120. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-AB Separation	106
Figure 121. Angle differences. Event: BC-AB Separation	107
Figure 122. Frequency differences. Event: BC-AB Separation	108
Figure 123. Frequency differences. Event: BC-AB Separation	109
Figure 124. Active power flows. Event: BC-AB Separation	110
Figure 125. Active power flows. Event: BC-AB Separation	111
Figure 126. Bus frequencies. Event: BC-AB Separation	111

Figure 127. Bus frequencies. Event: BC-AB Separation	112
Figure 128. Bus frequencies. Event: BC-AB Separation	112
Figure 129. Bus frequencies. Event: BC-AB Separation	112
Figure 130. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + 2PV	113
Figure 131. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + 2PV	114
Figure 132. Angle differences. Event: CJB + 2PV	115
Figure 133. Frequency differences. Event: CJB + 2PV	116
Figure 134. Frequency differences. Event: CJB + 2PV	117
Figure 135. Active power flows. Event: CJB + 2PV	118
Figure 136. Active power flows. Event: CJB + 2PV	119
Figure 137. Bus frequencies. Event: CJB + 2PV	119
Figure 138. Bus frequencies. Event: CJB + 2PV	120
Figure 139. Bus frequencies. Event: CJB + 2PV	120
Figure 140. Bus frequencies. Event: CJB + 2PV	120
Figure 141. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCUS Separation	121
Figure 142. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCUS Separation	122
Figure 143. Angle differences. Event: CJB + BCUS Separation	123
Figure 144. Frequency differences. Event: CJB + BCUS Separation	124
Figure 145. Frequency differences. Event: CJB + BCUS Separation	125
Figure 146. Active power flows. Event: CJB + BCUS Separation	126
Figure 147. Active power flows. Event: CJB + BCUS Separation	127
Figure 148. Bus frequencies. Event: CJB + BCUS Separation	127
Figure 149. Bus frequencies. Event: CJB + BCUS Separation	128
Figure 150. Bus frequencies. Event: CJB + BCUS Separation	128
Figure 151. Bus frequencies. Event: CJB + BCUS Separation	128
Figure 152. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCAB Separation	129
Figure 153. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCAB Separation	130
Figure 154. Angle differences. Event: CJB + BCAB Separation	131
Figure 155. Frequency differences. Event: CJB + BCAB Separation	132
Figure 156. Frequency differences. Event: CJB + BCAB Separation	133
Figure 157. Active power flows. Event: CJB + BCAB Separation	134
Figure 158. Active power flows. Event: CJB + BCAB Separation	135
Figure 159. Bus frequencies. Event: CJB + BCAB Separation	135
Figure 160. Bus frequencies. Event: CJB + BCAB Separation	136
Figure 161. Bus frequencies. Event: CJB + BCAB Separation	136
Figure 162. Bus frequencies. Event: CJB + BCAB Separation	136
Figure 163. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	137
Figure 164. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	138
Figure 165. Angle differences. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	139
Figure 166. Frequency differences. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	140
Figure 167. Frequency differences. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	141
Figure 168. Active power flows. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	142

Figure 169. Active power flows. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	143
Figure 170. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	143
Figure 171. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	144
Figure 172. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	144
Figure 173. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	144
Figure 174. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	145
Figure 175. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$	145
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)	147
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)	148
Figure 178. Angle differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	149
Figure 179. Frequency differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	150
Figure 180. Frequency differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	151
Figure 181. Active power flows. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	152
Figure 182. Active power flows. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	153
Figure 183. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	153
Figure 184. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	154
Figure 185. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)	154
Figure 186. 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)	155
Figure 187. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	156
Figure 188. Angle differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	157
Figure 189. Frequency differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	158
Figure 190. Frequency differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	159
Figure 191. Active power flows. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	160
Figure 192. Active power flows. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	161
Figure 193. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	161
Figure 194. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	162
Figure 195. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)	162
Figure 196. 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)	163
Figure 197. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	164
Figure 198. Angle differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	165
Figure 199. Frequency differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	166
Figure 200. Frequency differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	167
Figure 201. Active power flows. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	168
Figure 202. Active power flows. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	169
Figure 203. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	169
Figure 204. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	170
Figure 205. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)	170
Figure 206. 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)	171
Figure 207. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)	172
Figure 208. Angle differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)	173
Figure 209. Frequency differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)	174
Figure 210. Frequency differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)	175

Figure 211. Active power flows. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)		176
Figure 212. Active power flows. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)		177
Figure 213. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)		177
Figure 214. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)		178
Figure 215. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)		178

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 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 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.

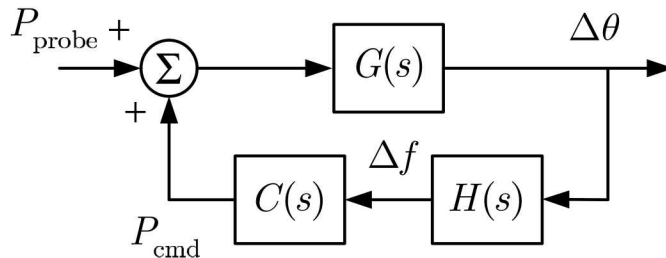


Figure 1. Block diagram of the controller setup.

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 Light Summer 2016 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 light summer base case.

2. NEGATIVE GAIN TESTING

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

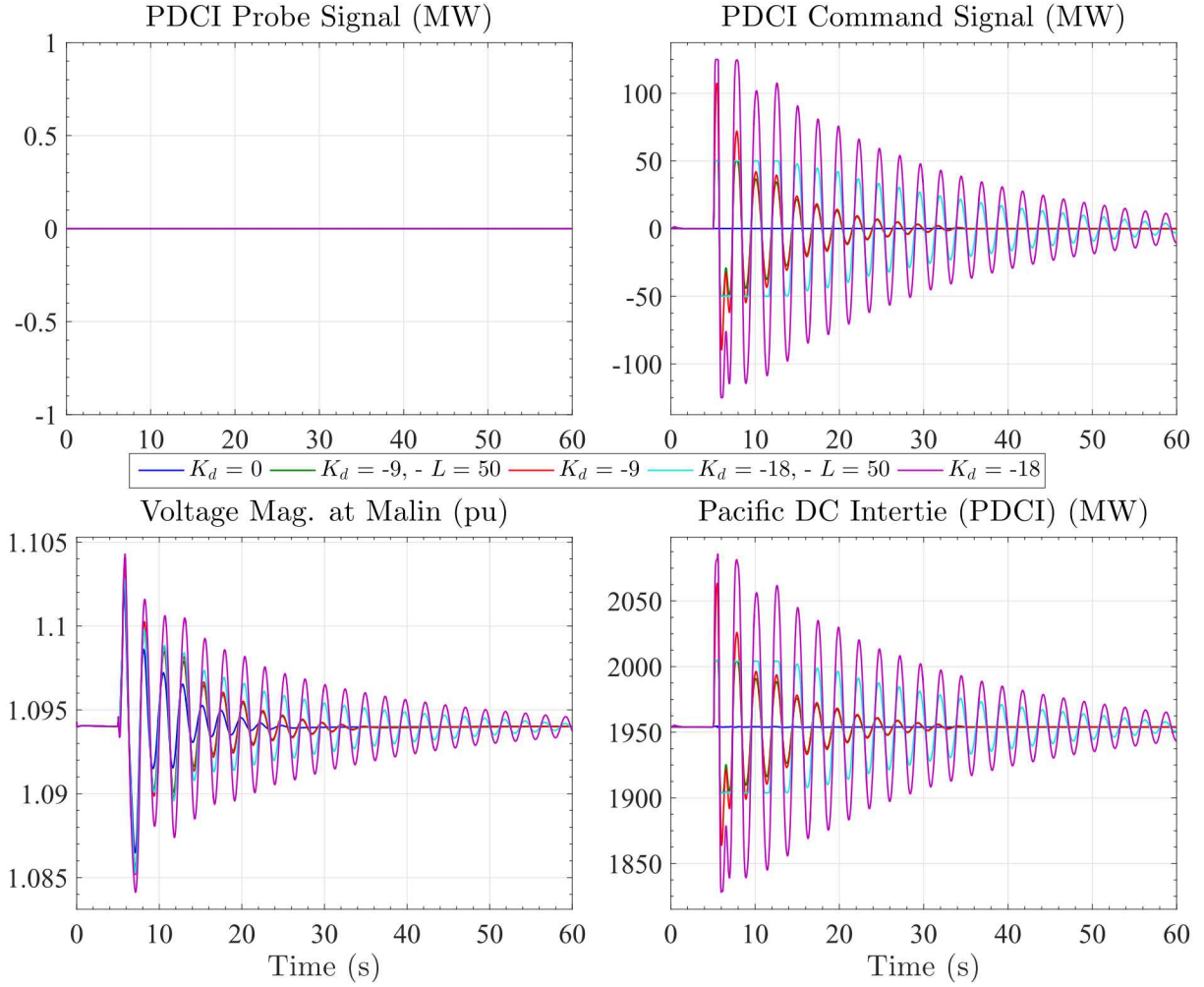


Figure 2. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake

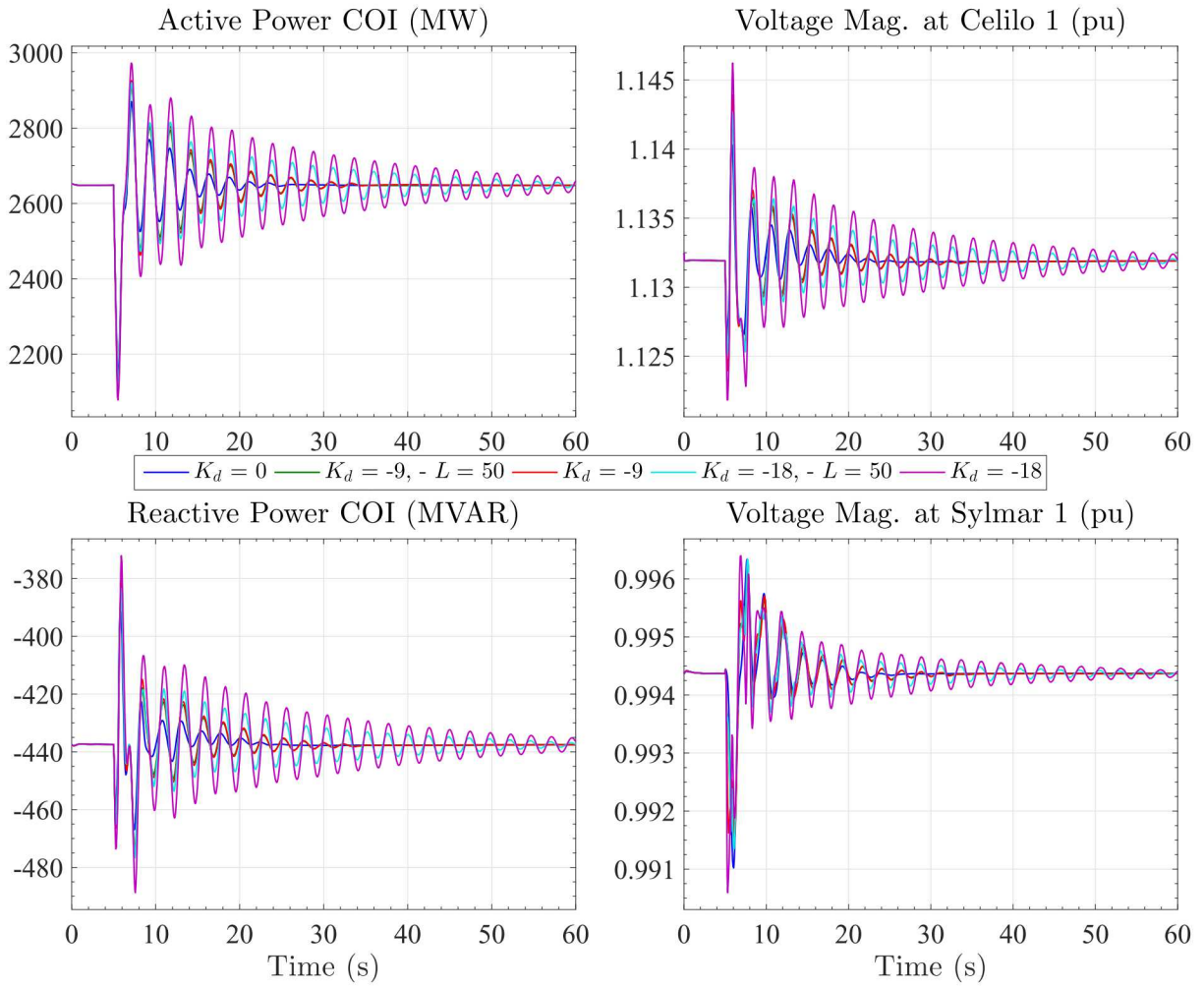


Figure 3. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake

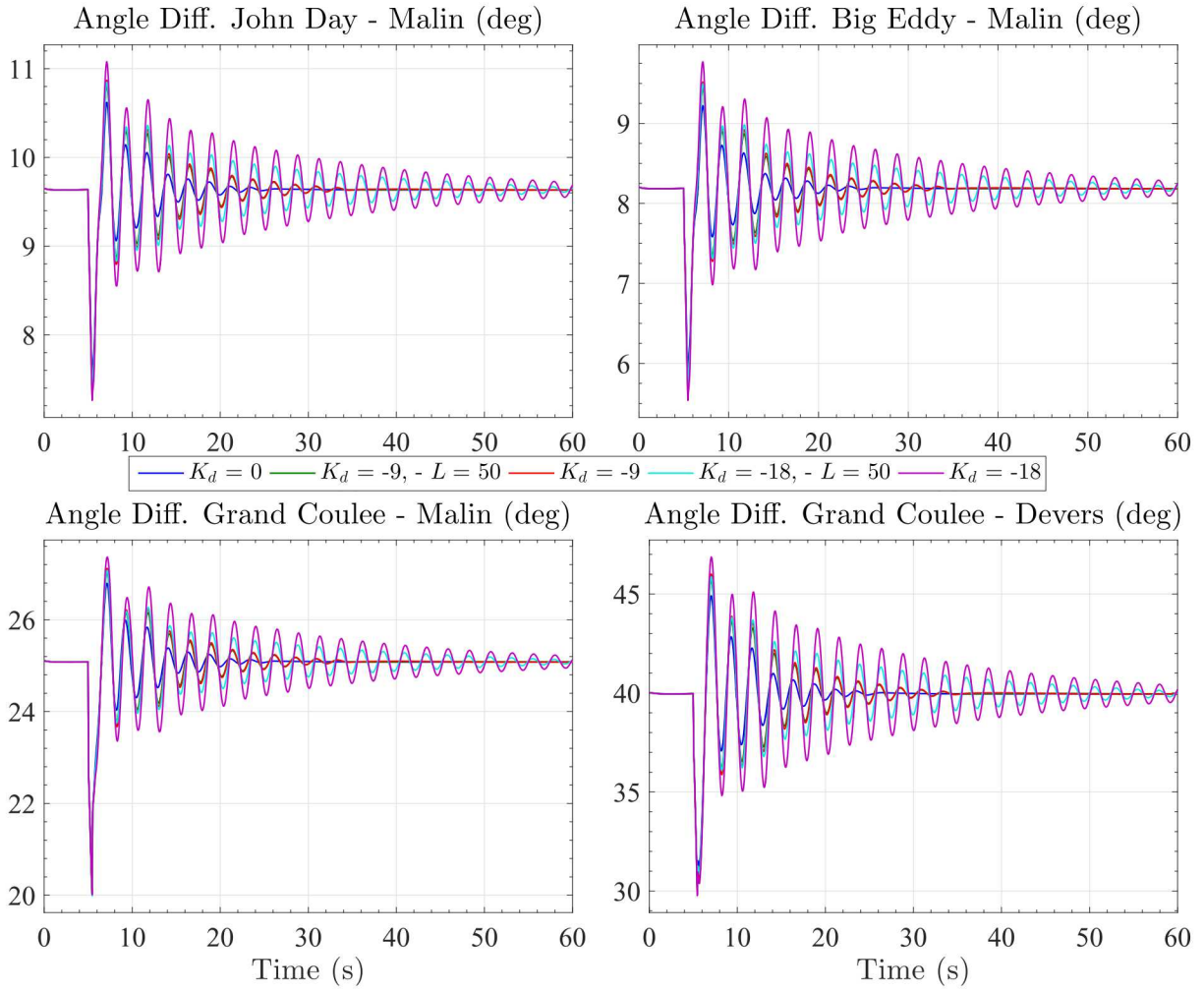


Figure 4. Angle differences. Event: Chief Joe Brake

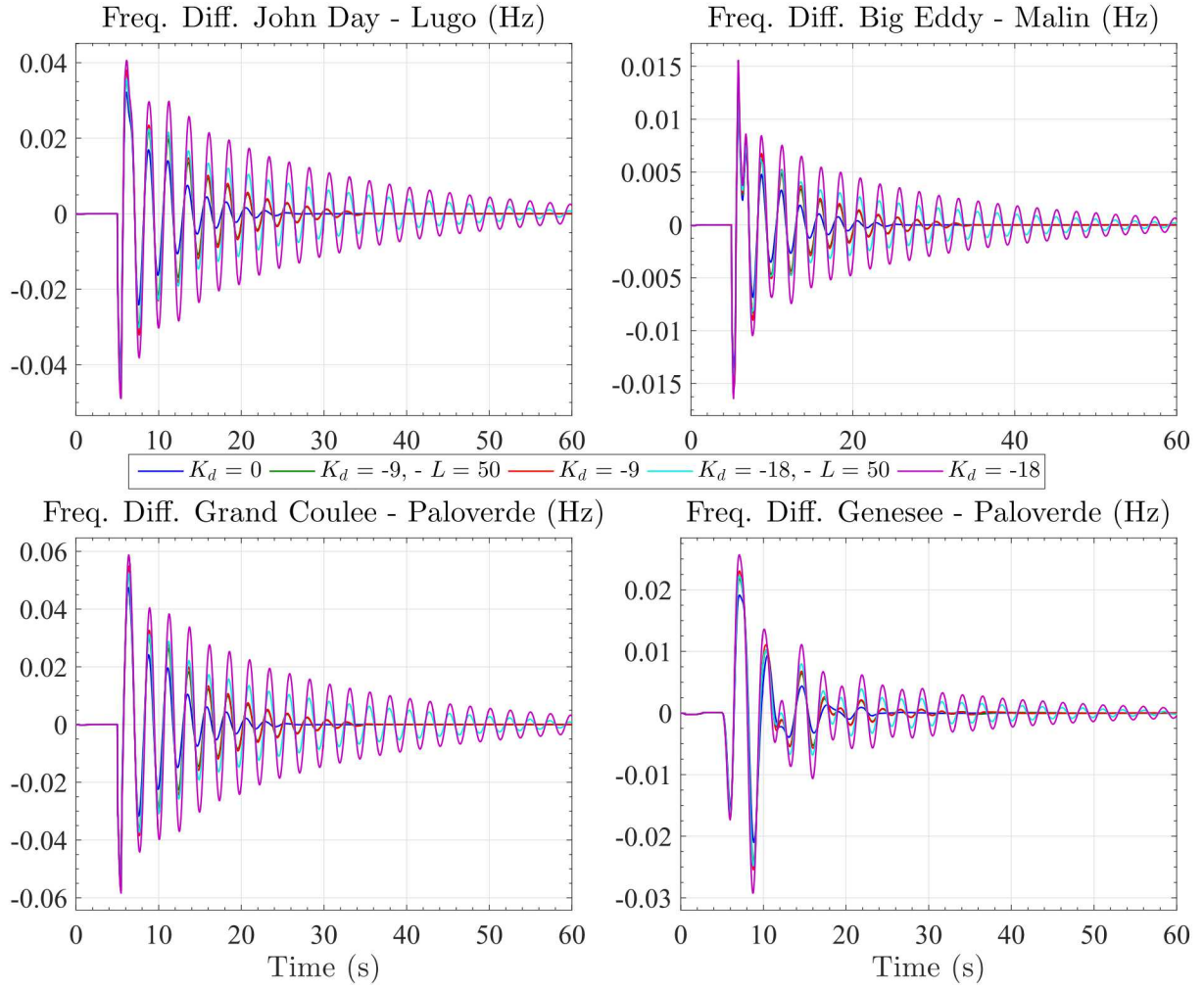


Figure 5. Frequency differences. Event: Chief Joe Brake

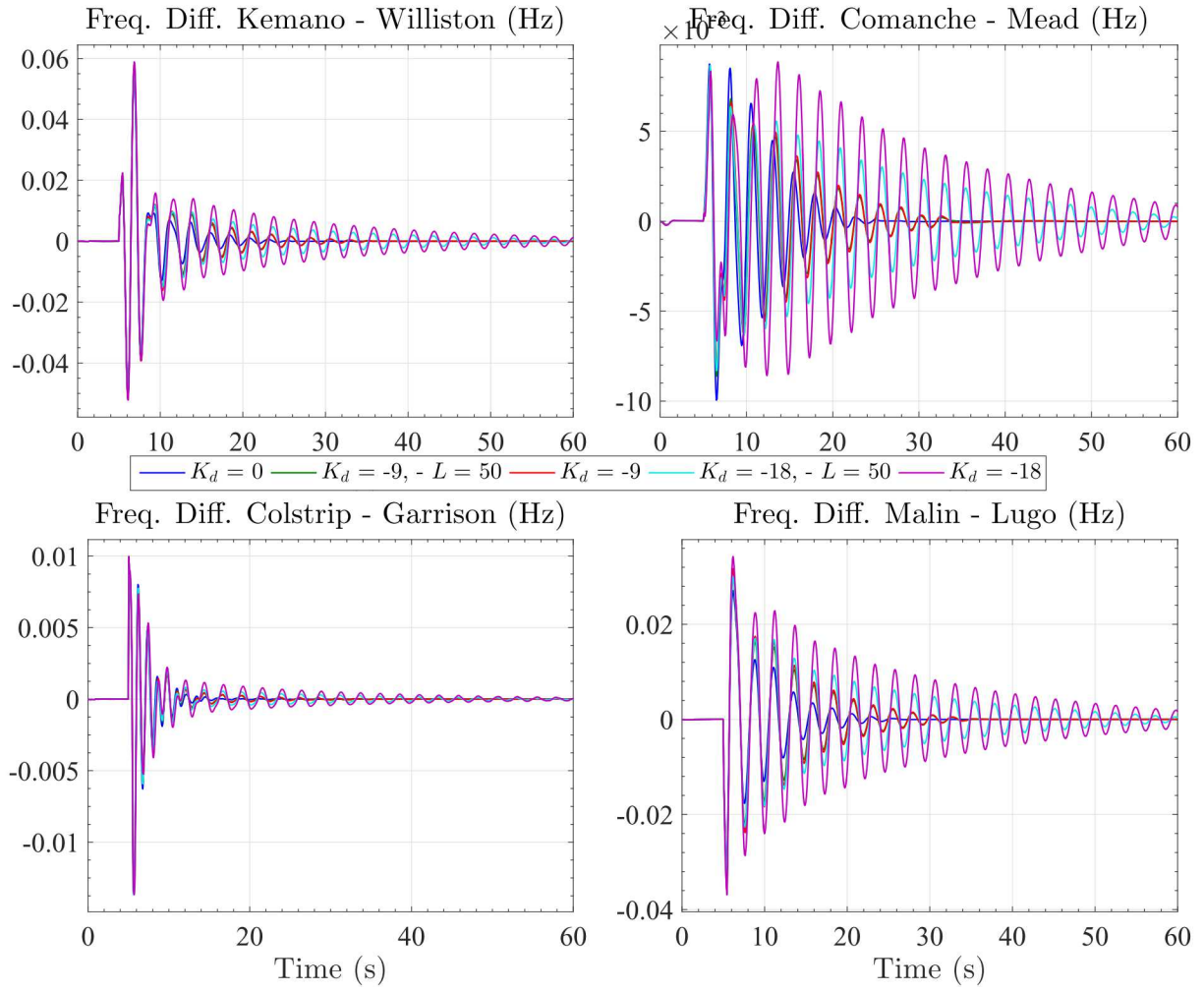


Figure 6. Frequency differences. Event: Chief Joe Brake

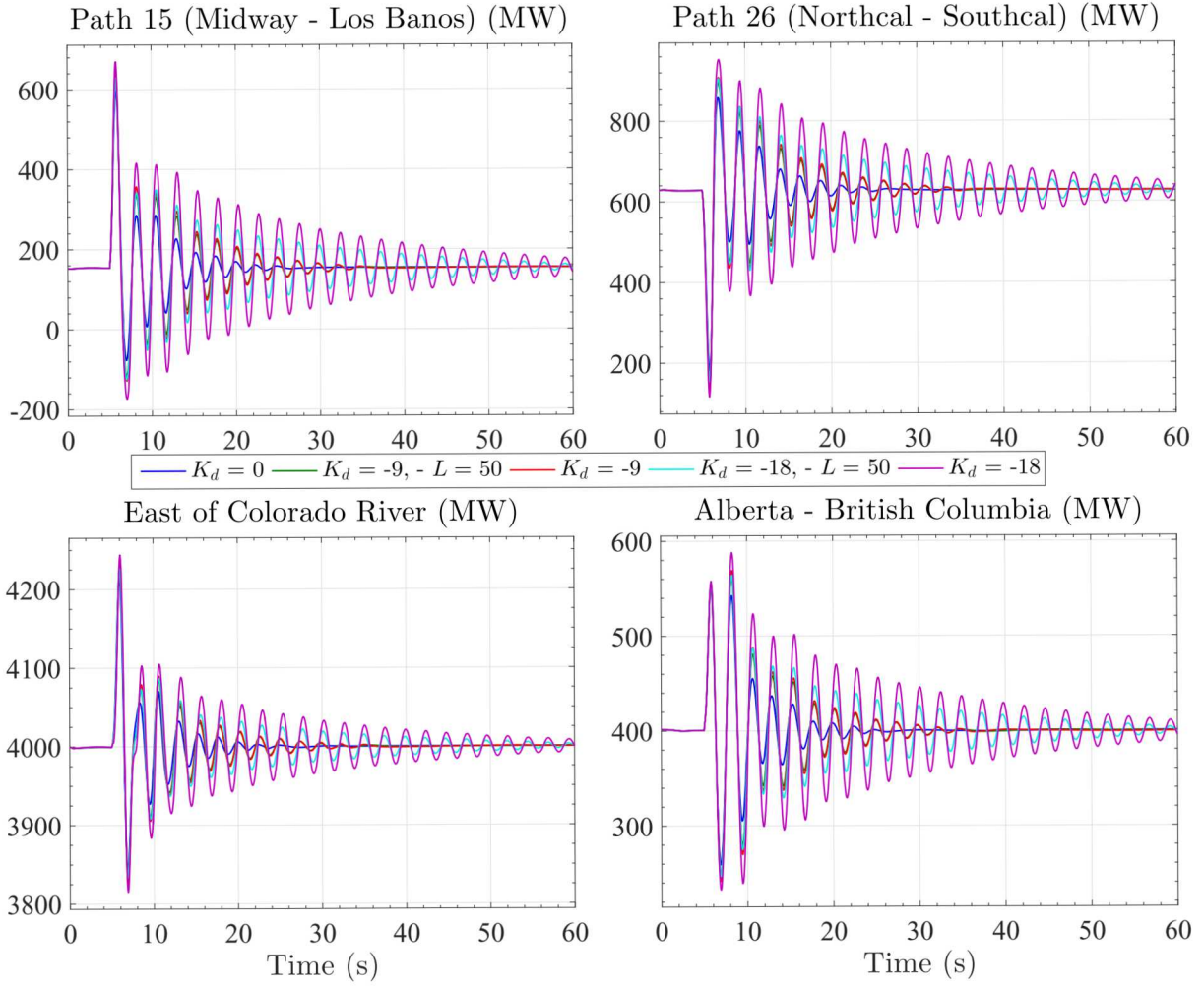


Figure 7. Active power flows. Event: Chief Joe Brake

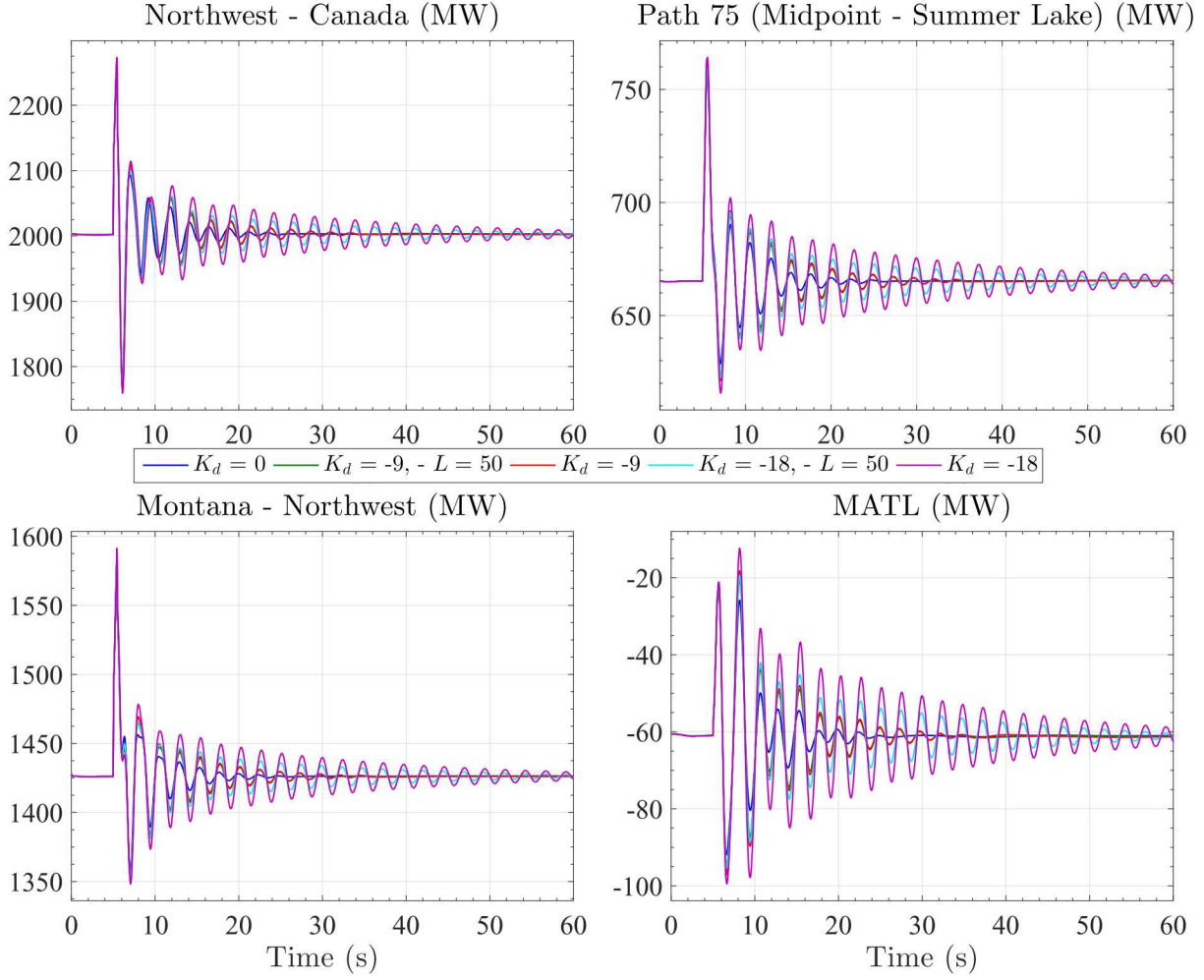


Figure 8. Active power flows. Event: Chief Joe Brake

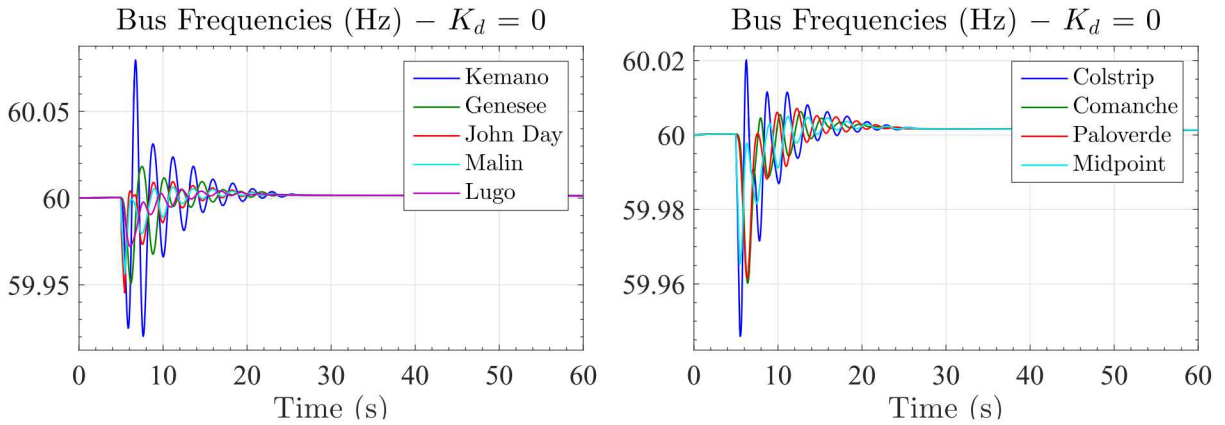


Figure 9. Bus frequencies. Event: Chief Joe Brake

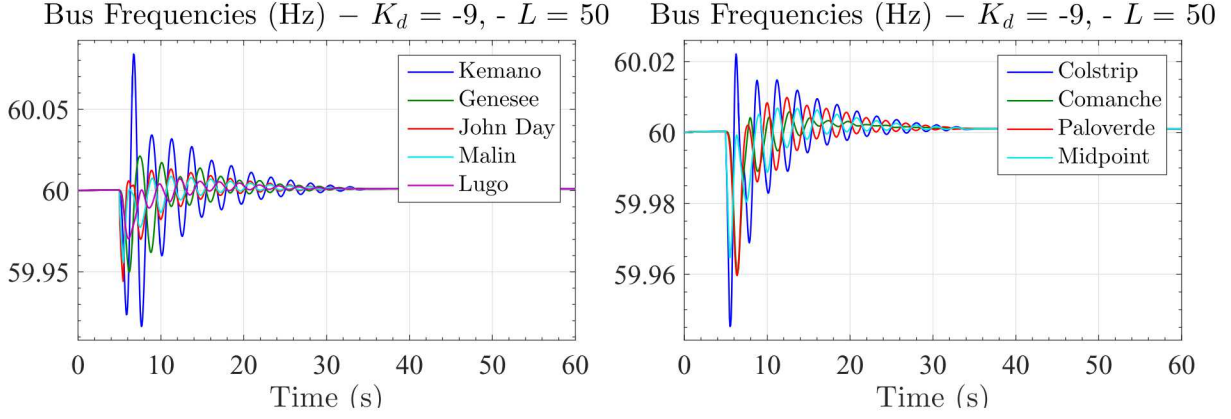


Figure 10. Bus frequencies. Event: Chief Joe Brake

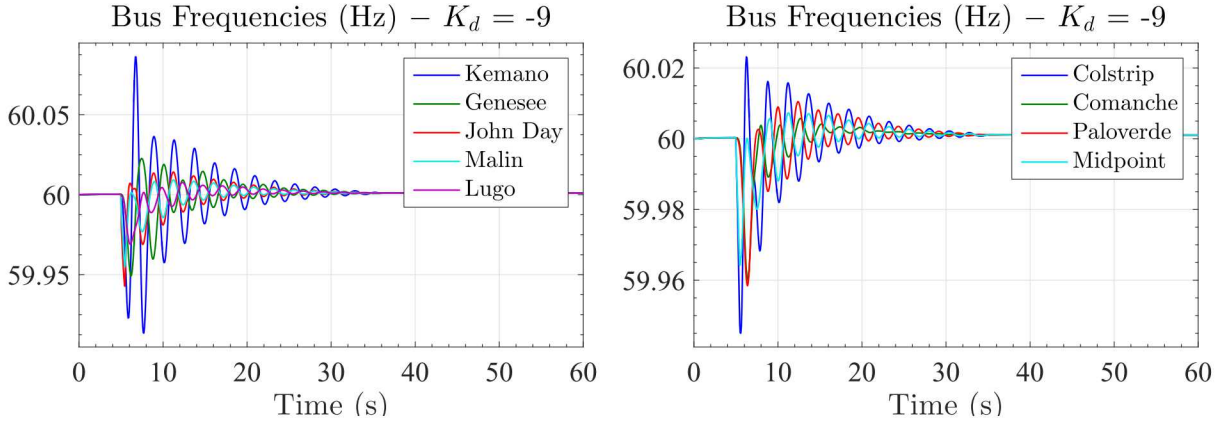


Figure 11. Bus frequencies. Event: Chief Joe Brake

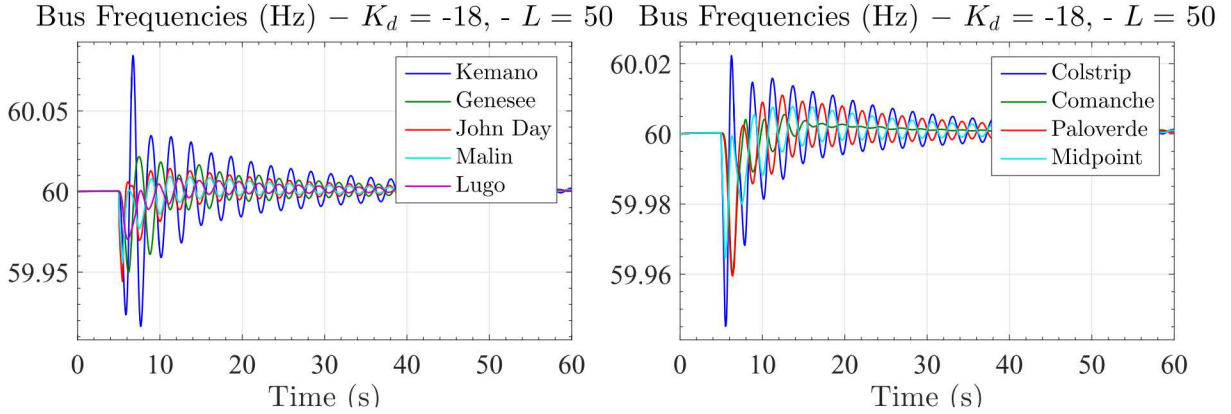


Figure 12. Bus frequencies. Event: Chief Joe Brake

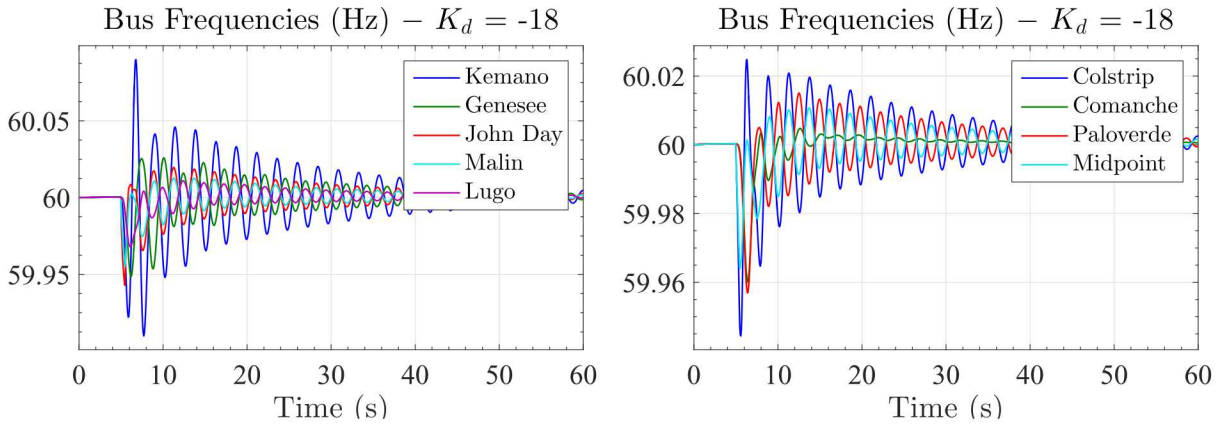


Figure 13. Bus frequencies. Event: Chief Joe Brake

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

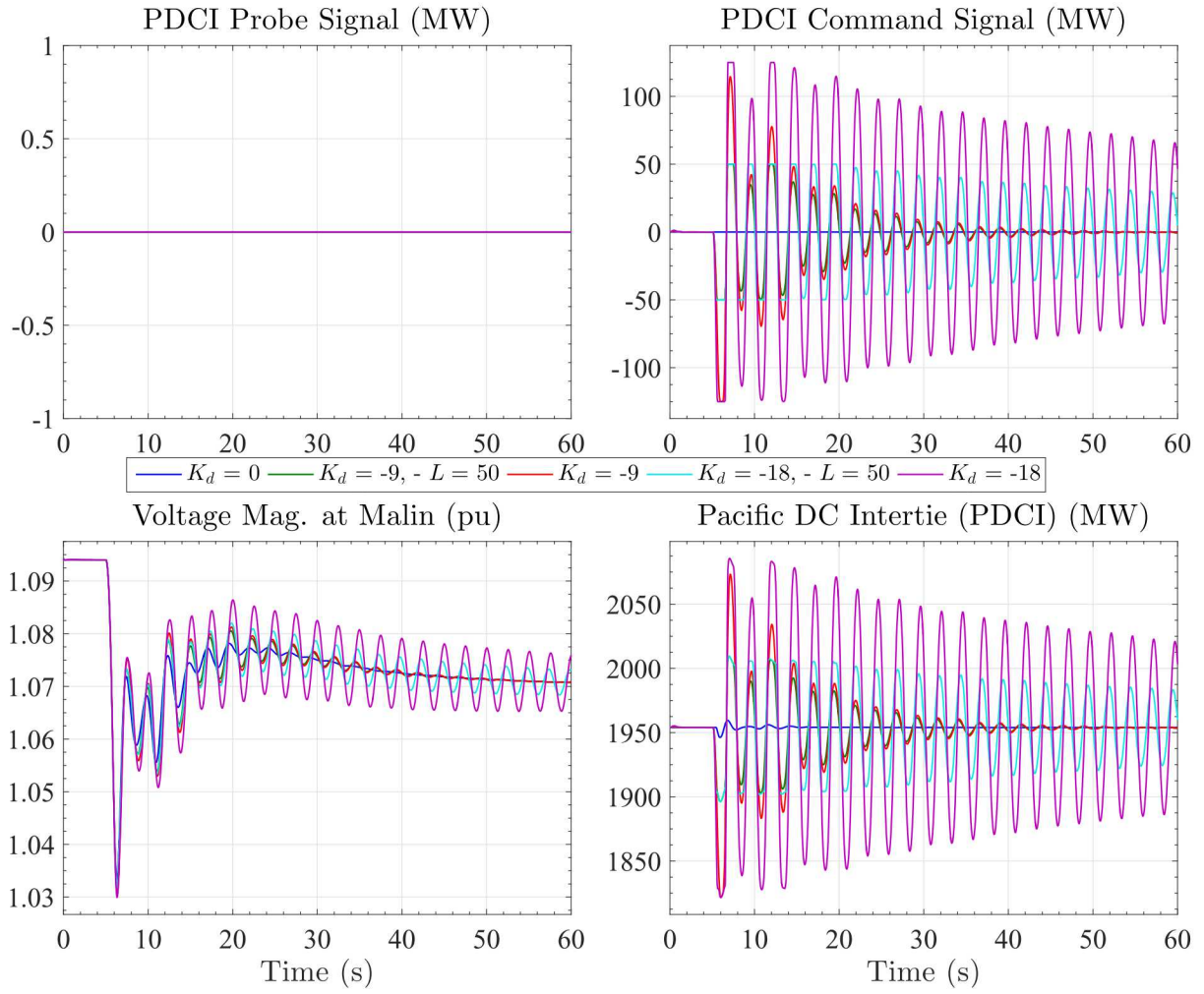


Figure 14. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Double Palo Verde Trip

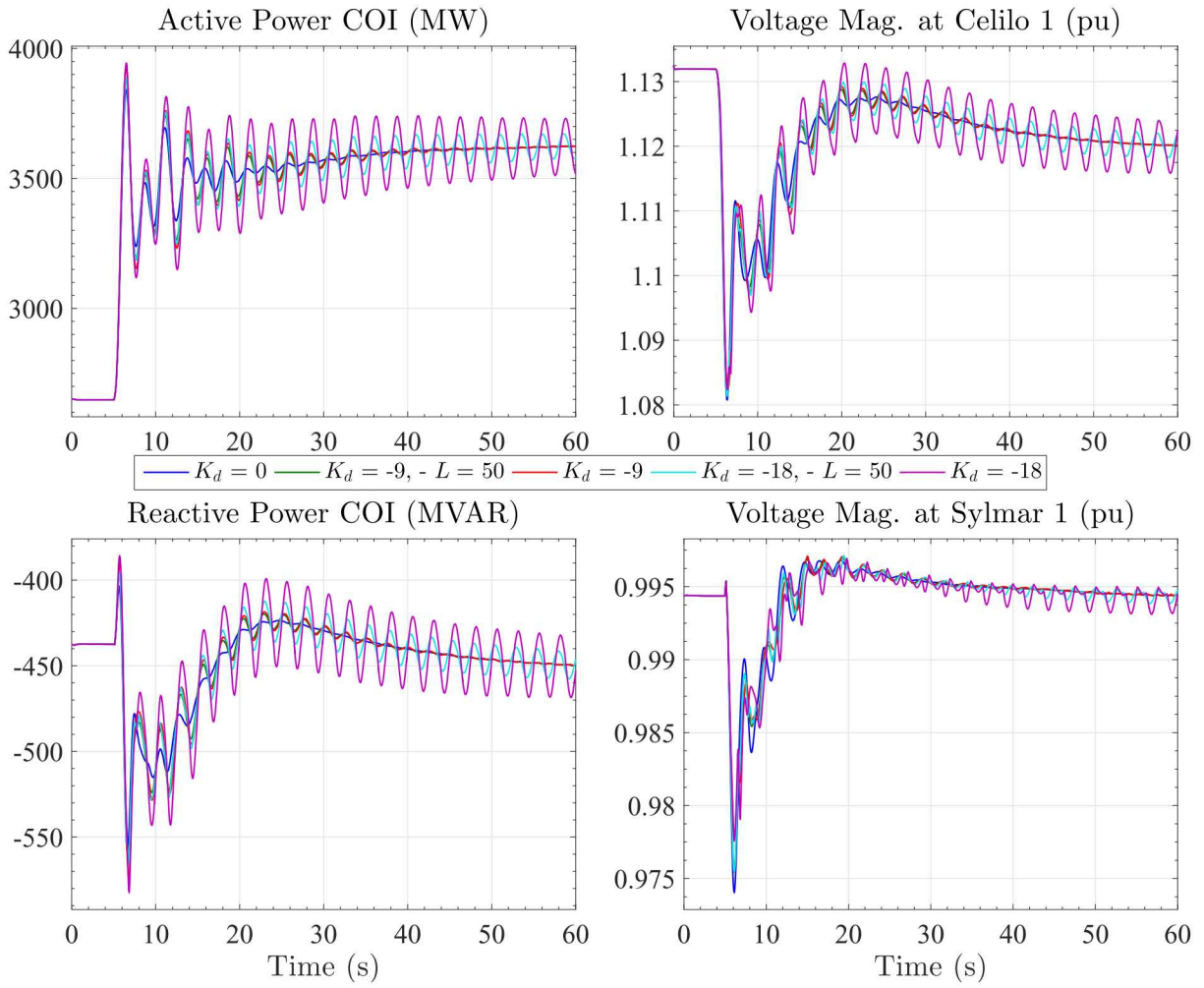


Figure 15. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Double Palo Verde Trip

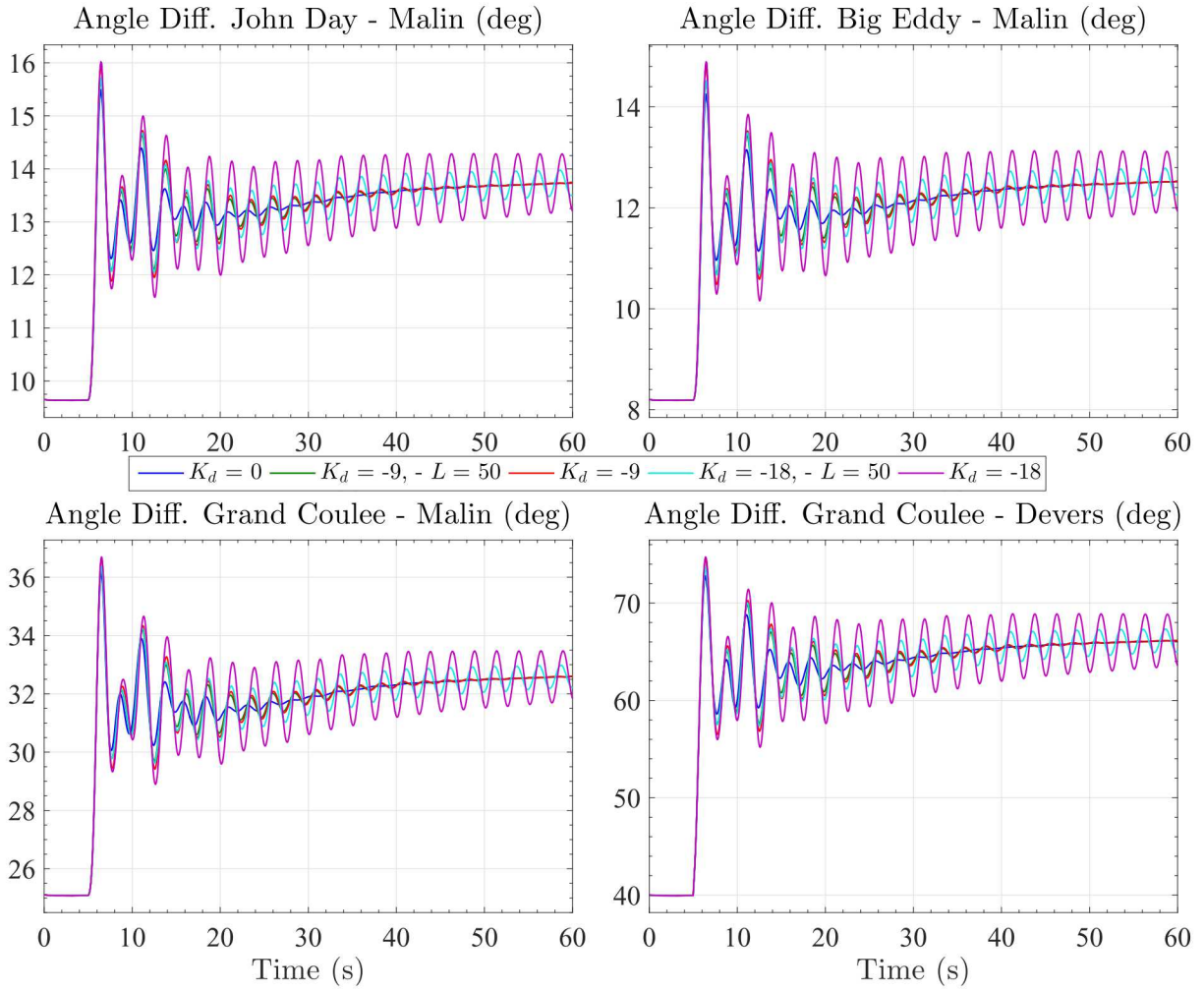


Figure 16. Angle differences. Event: Double Palo Verde Trip

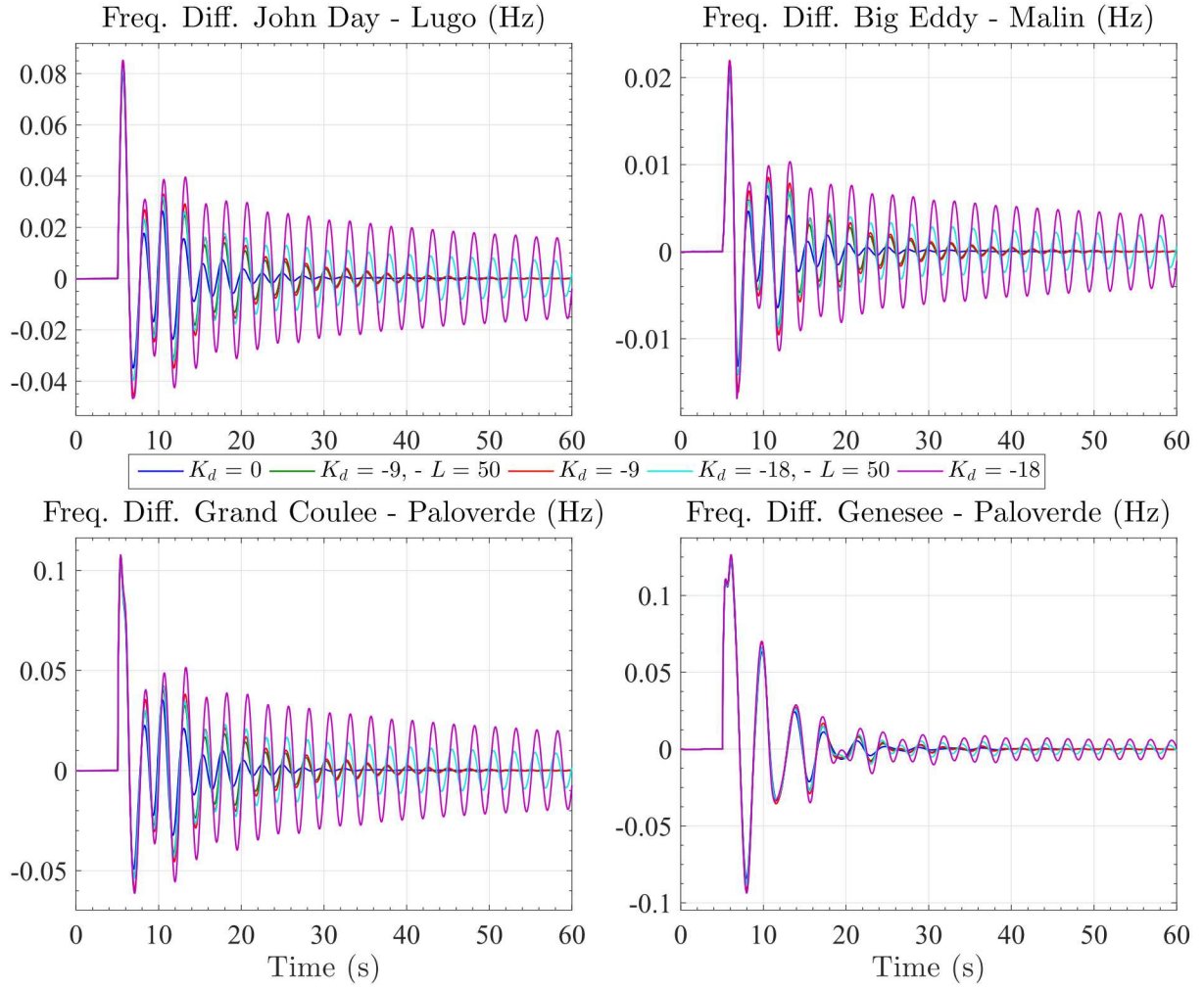


Figure 17. Frequency differences. Event: Double Palo Verde Trip

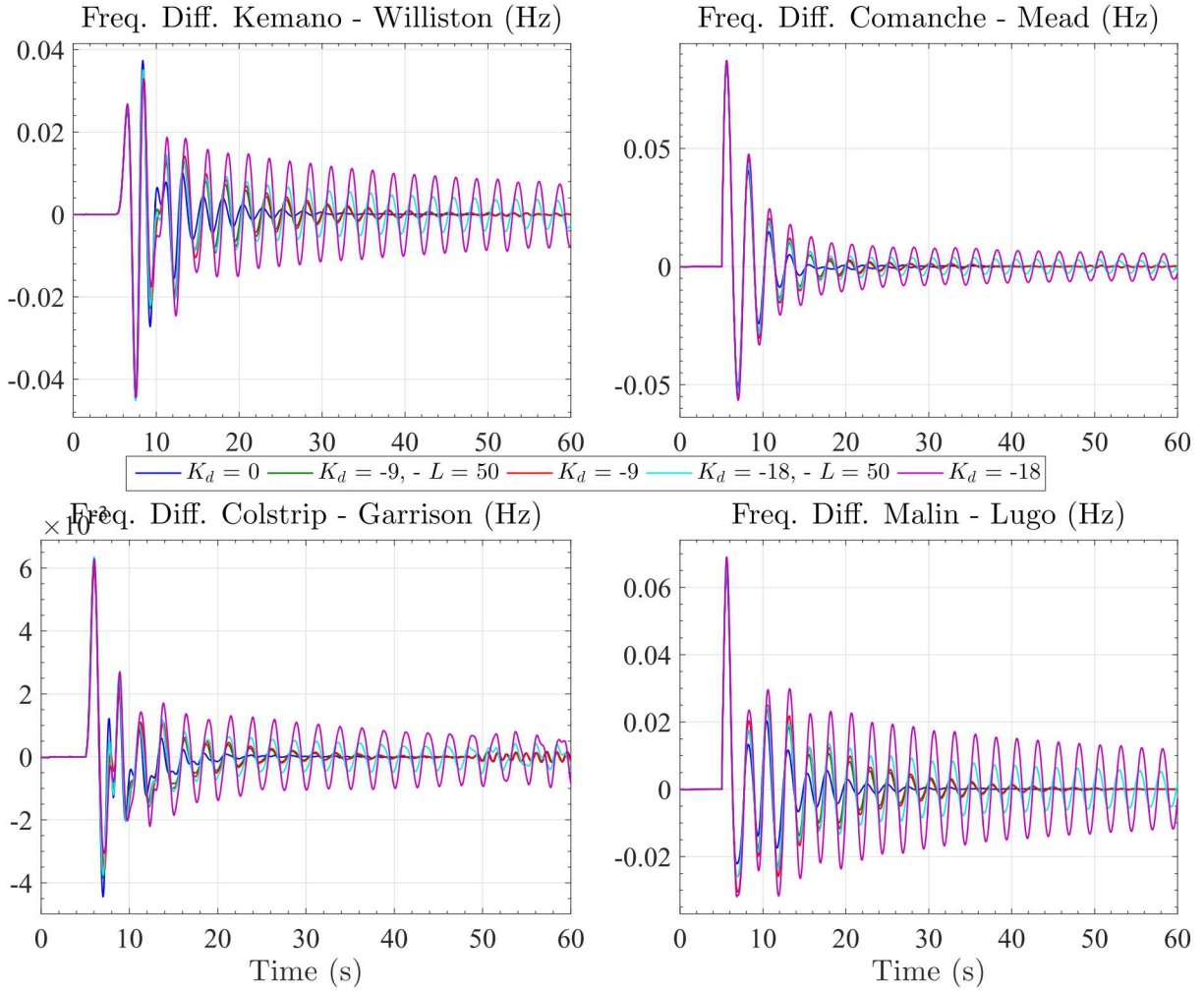


Figure 18. Frequency differences. Event: Double Palo Verde Trip

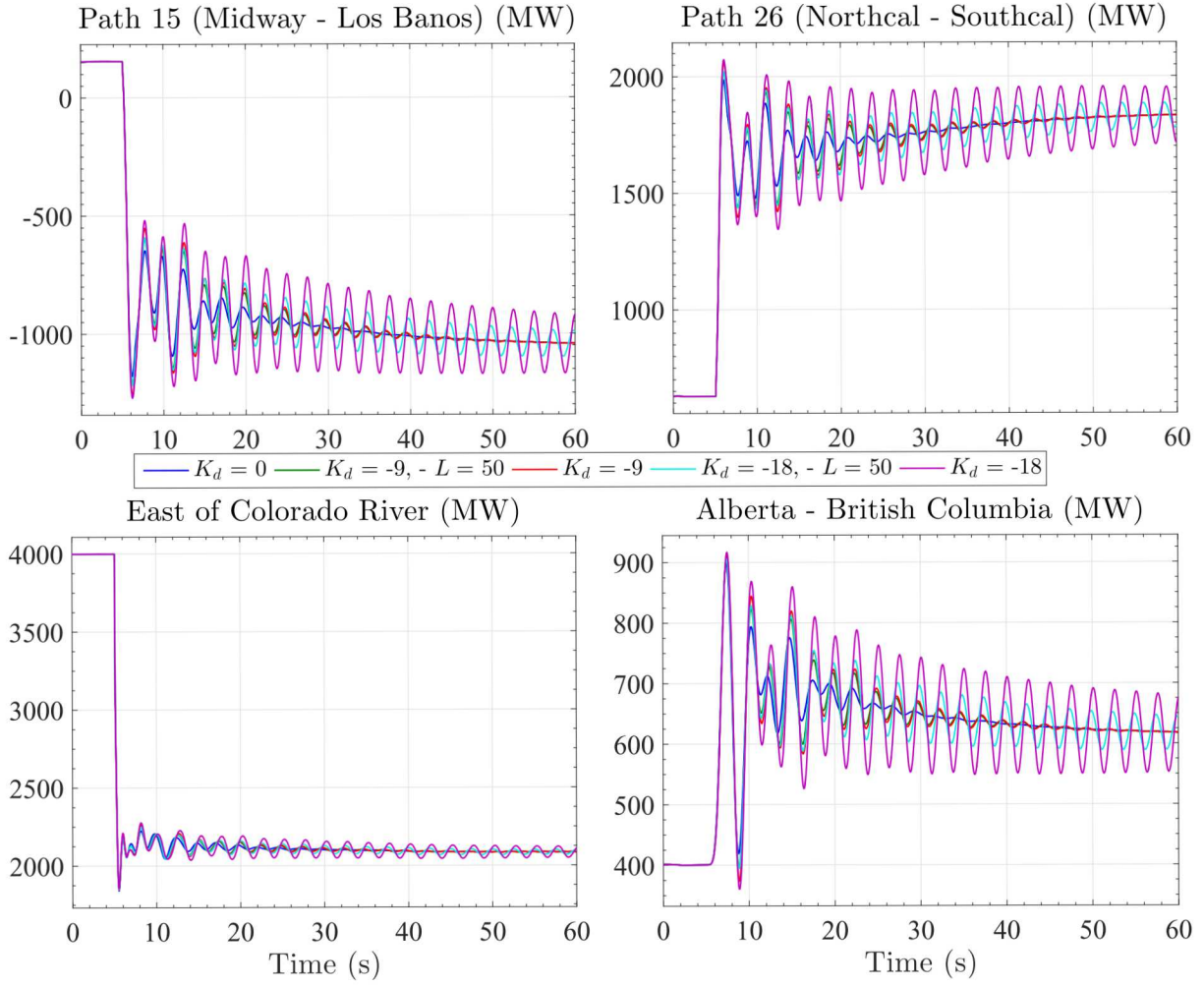


Figure 19. Active power flows. Event: Double Palo Verde Trip

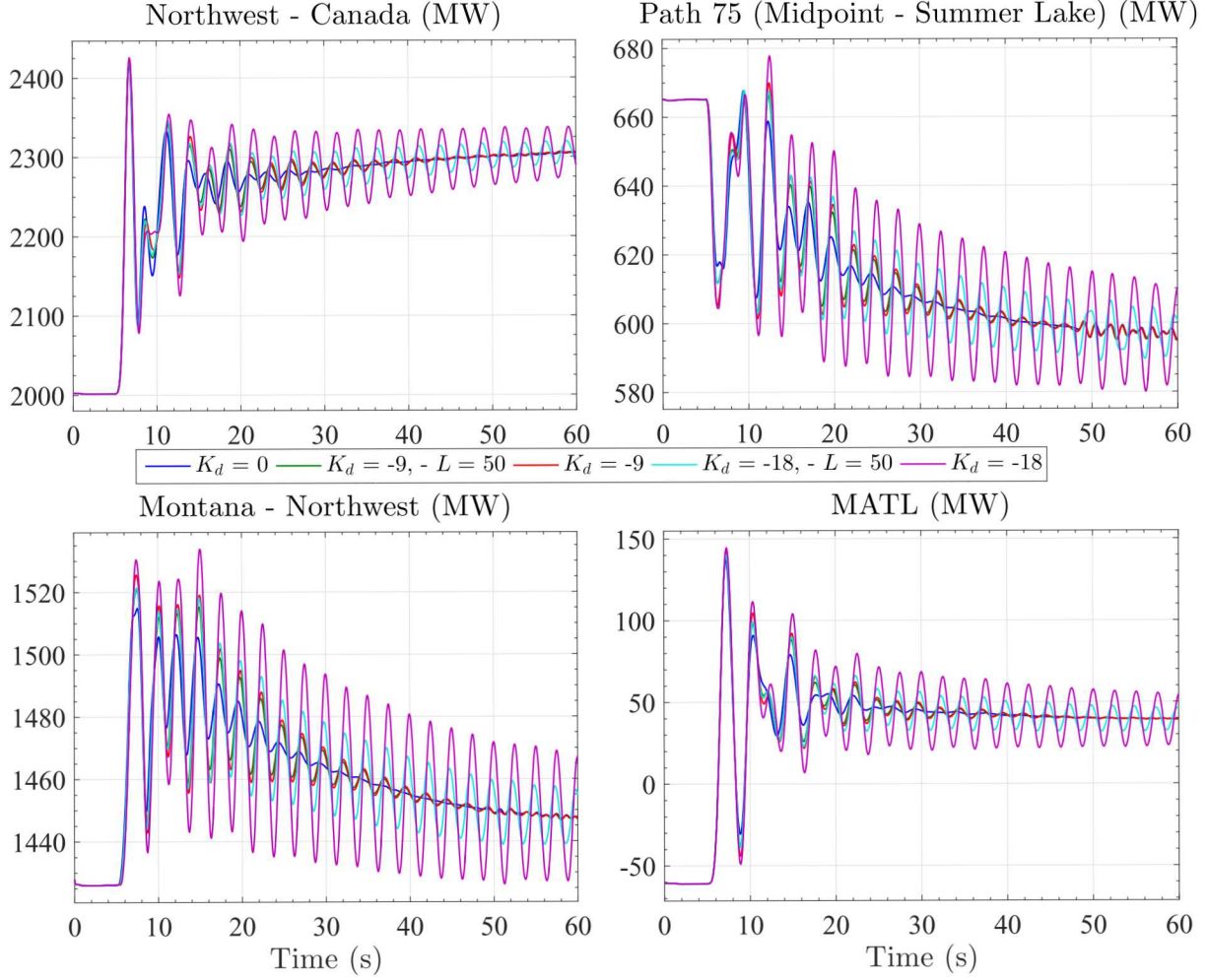


Figure 20. Active power flows. Event: Double Palo Verde Trip

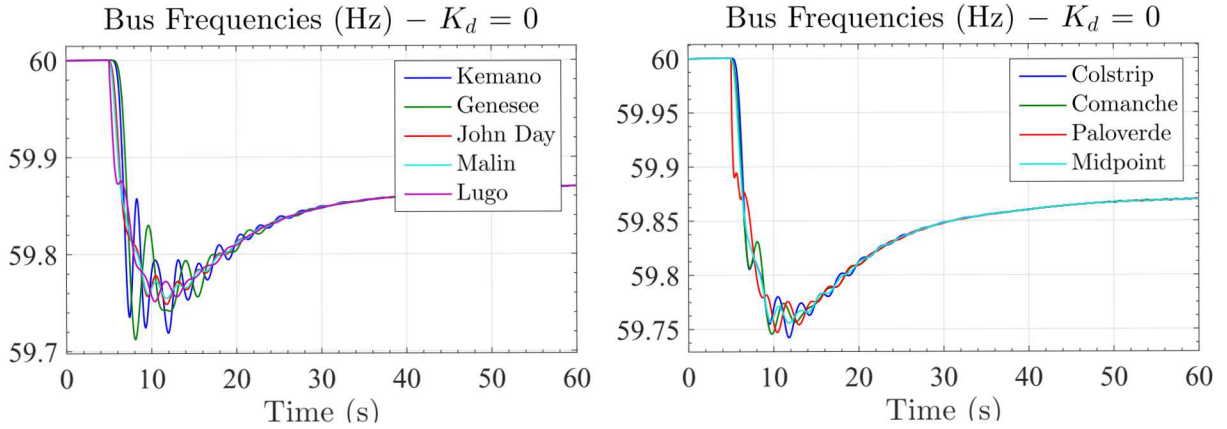


Figure 21. Bus frequencies. Event: Double Palo Verde Trip

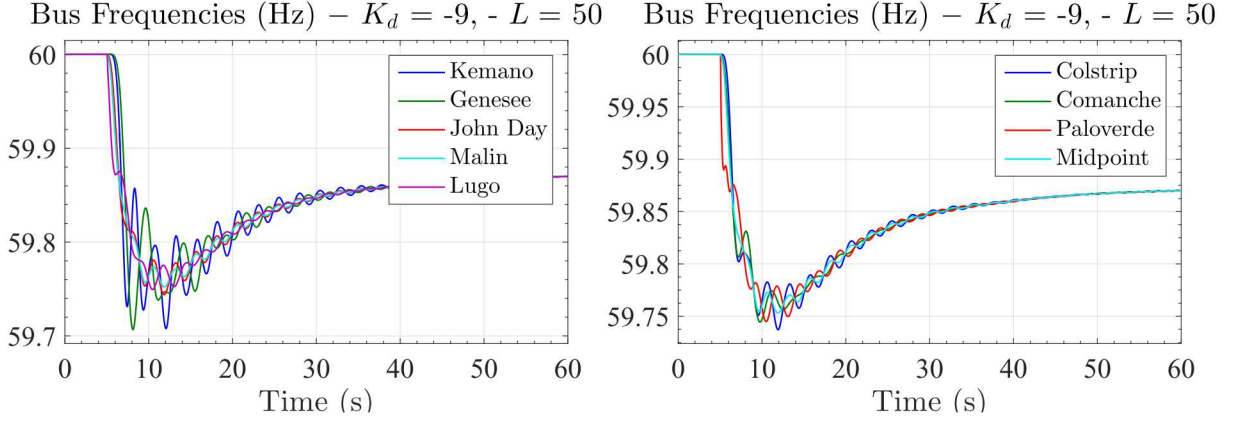


Figure 22. Bus frequencies. Event: Double Palo Verde Trip

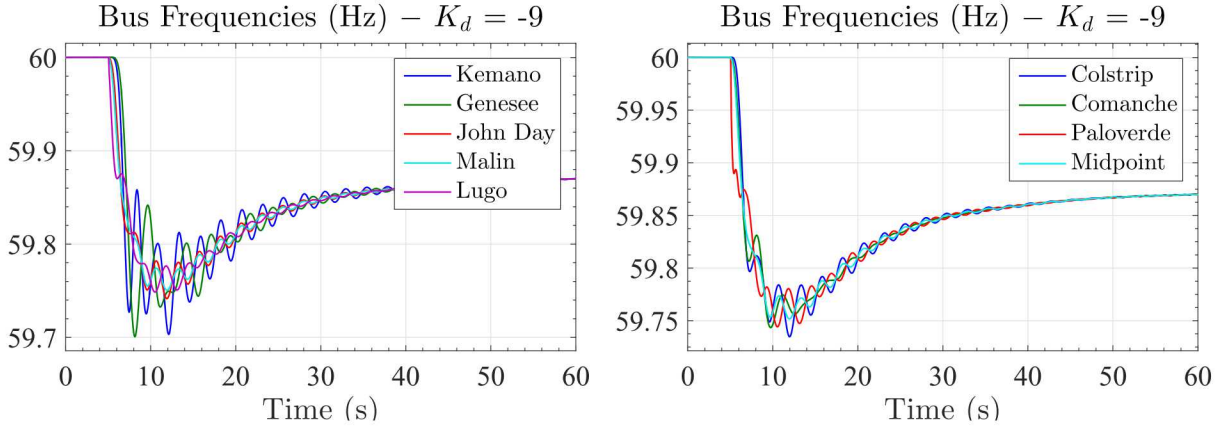


Figure 23. Bus frequencies. Event: Double Palo Verde Trip

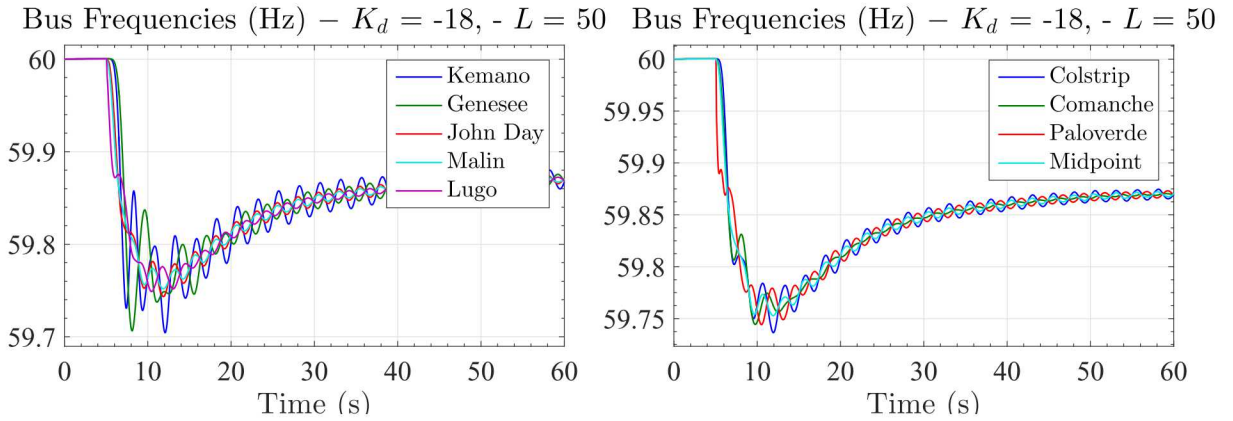


Figure 24. Bus frequencies. Event: Double Palo Verde Trip

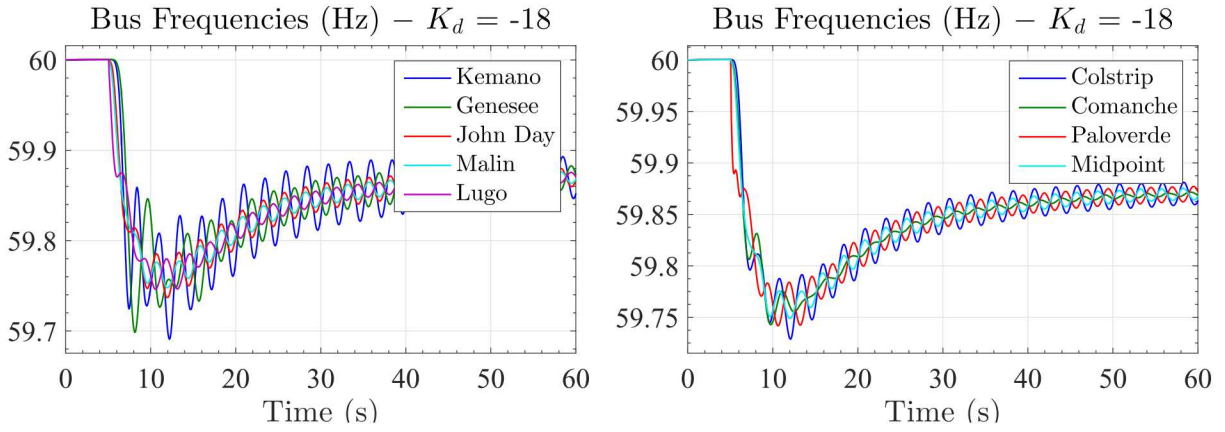


Figure 25. Bus frequencies. Event: Double Palo Verde Trip

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

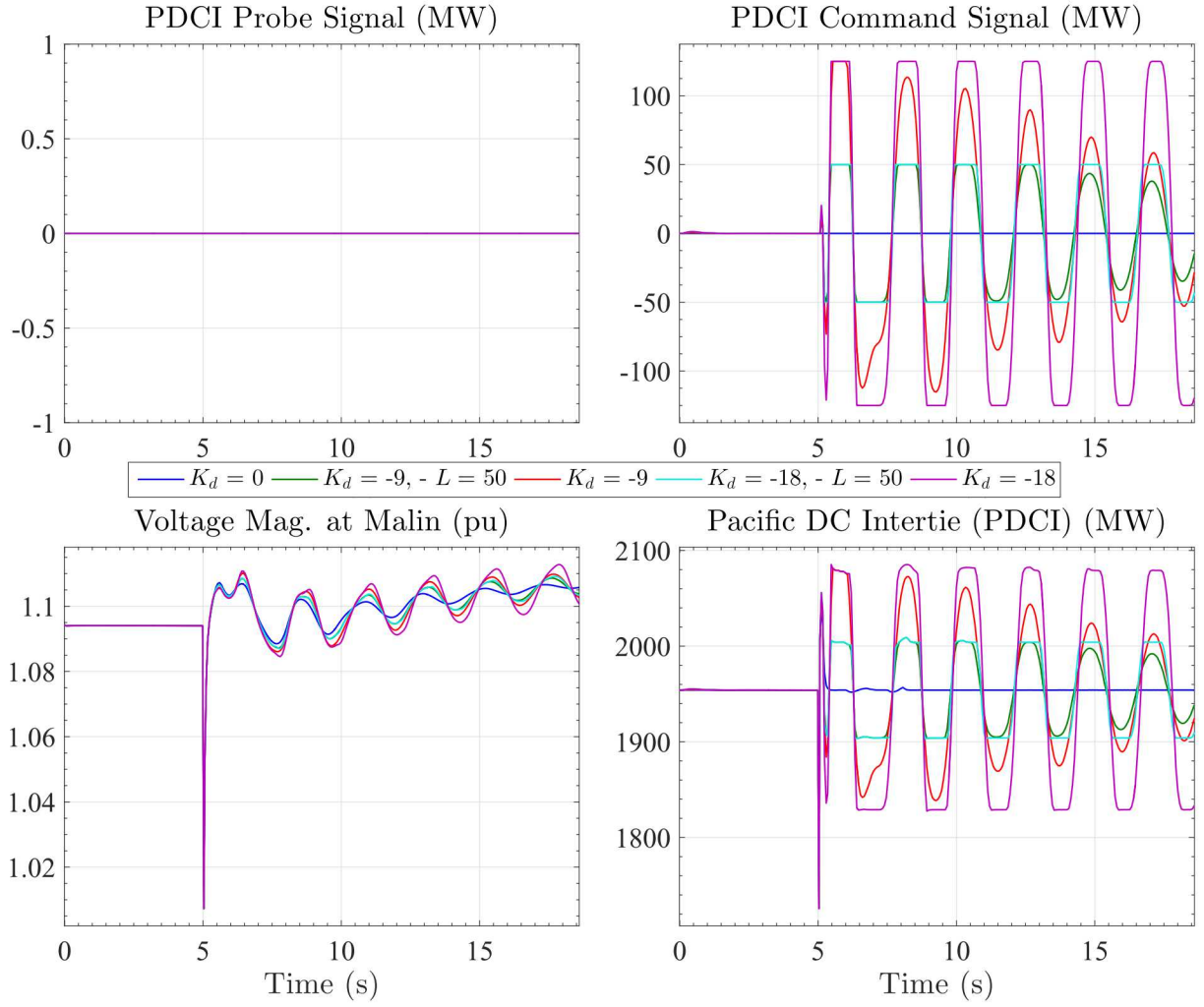


Figure 26. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-US Separation

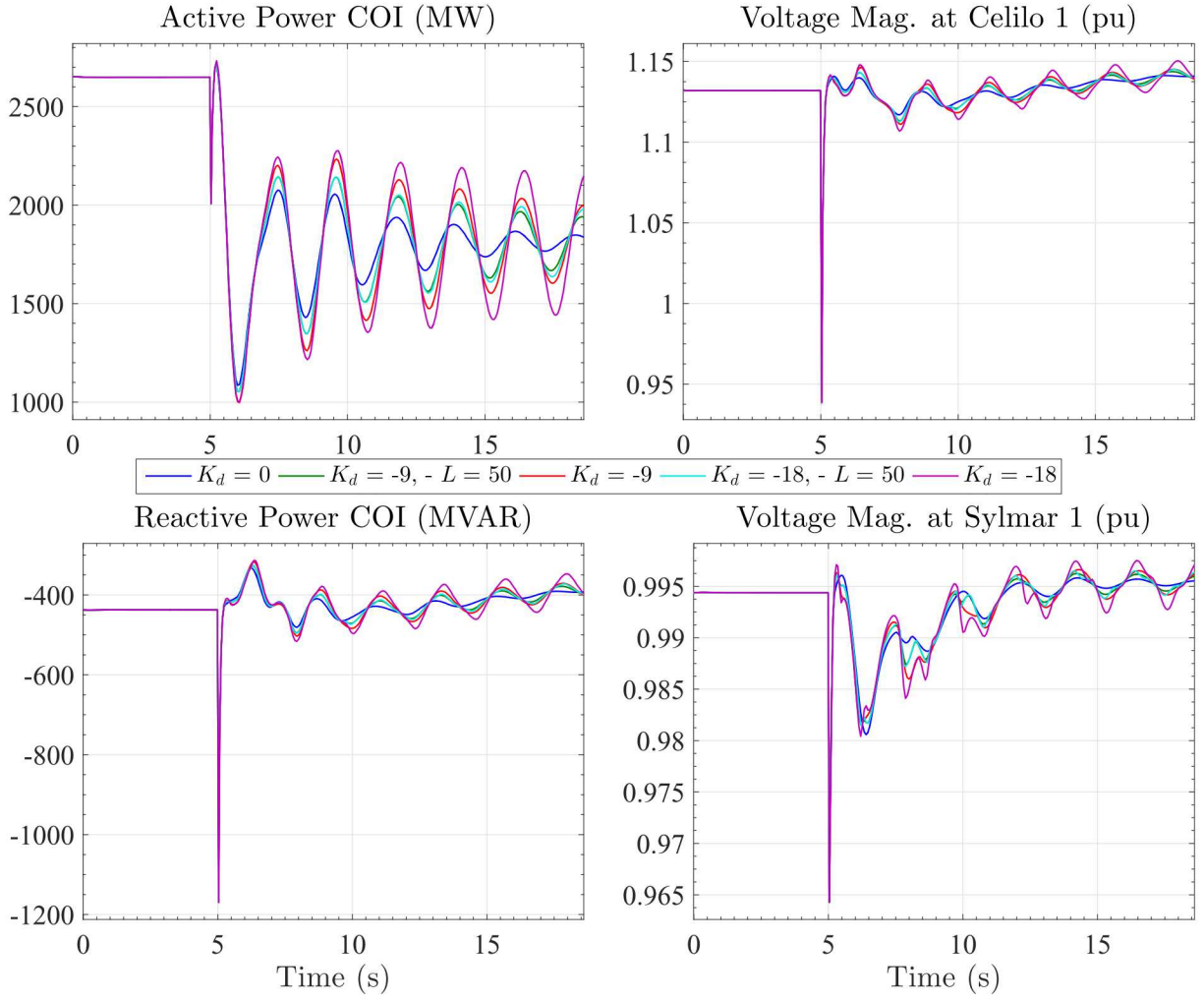


Figure 27. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-US Separation

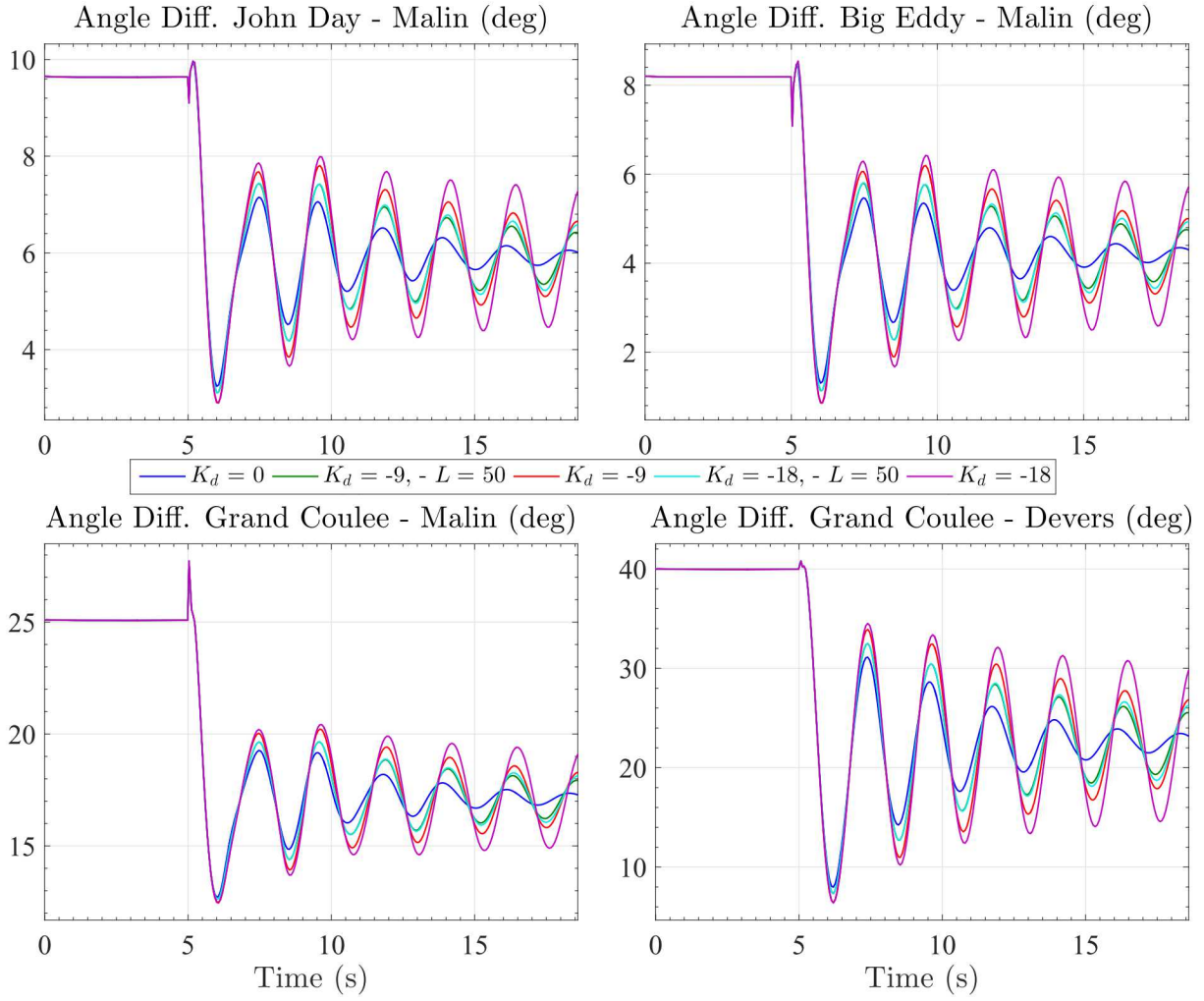


Figure 28. Angle differences. Event: BC-US Separation

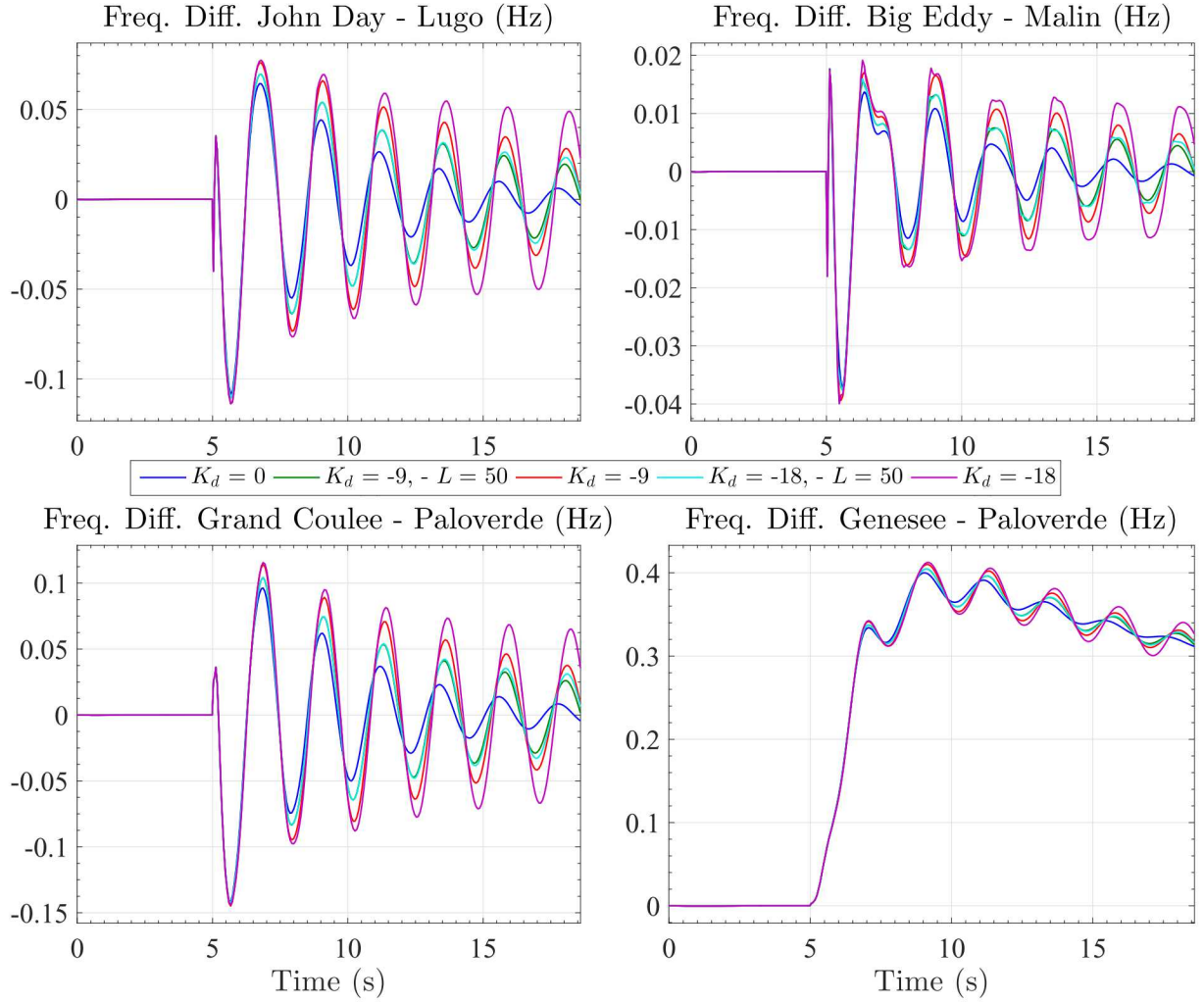


Figure 29. Frequency differences. Event: BC-US Separation

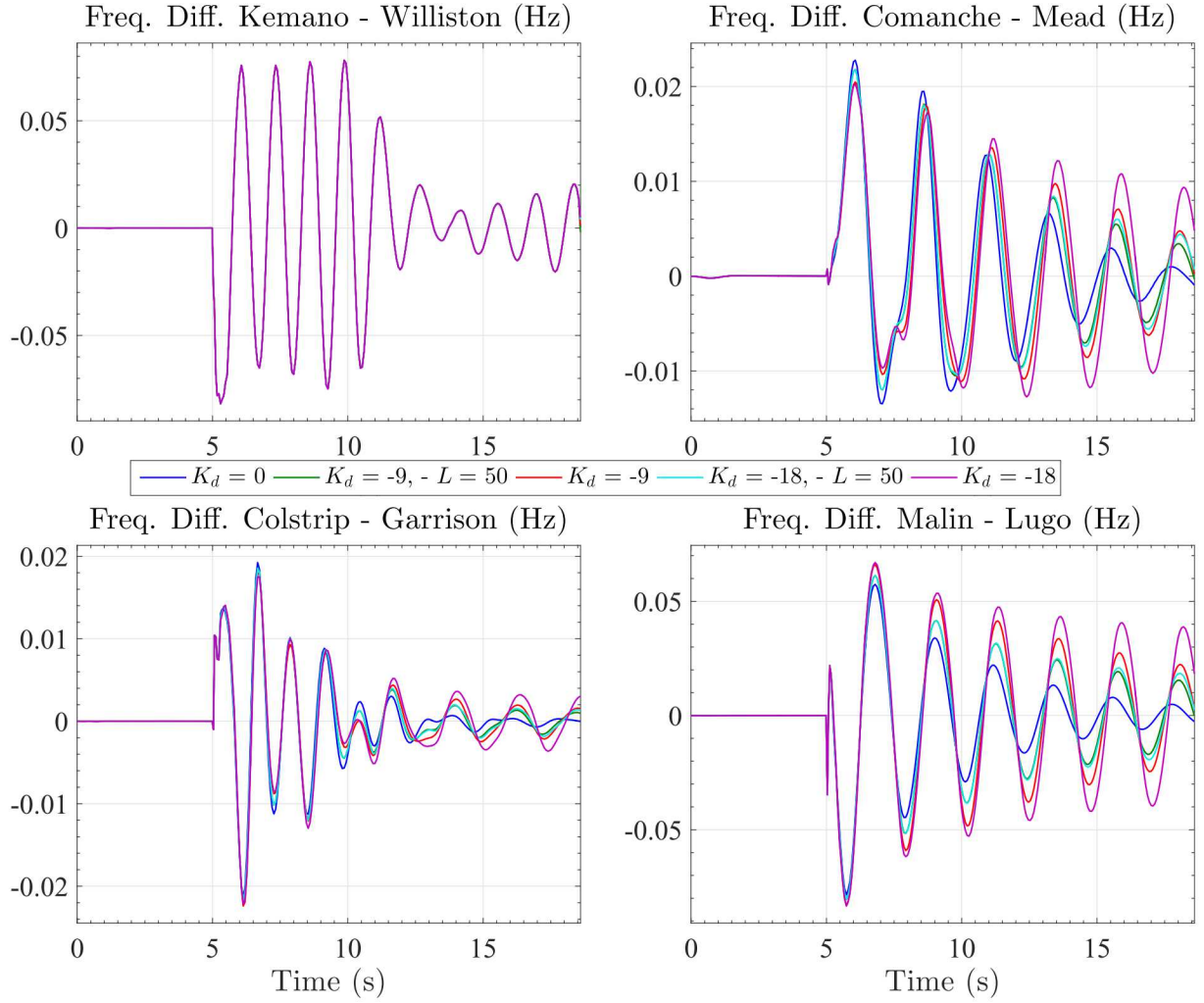


Figure 30. Frequency differences. Event: BC-US Separation

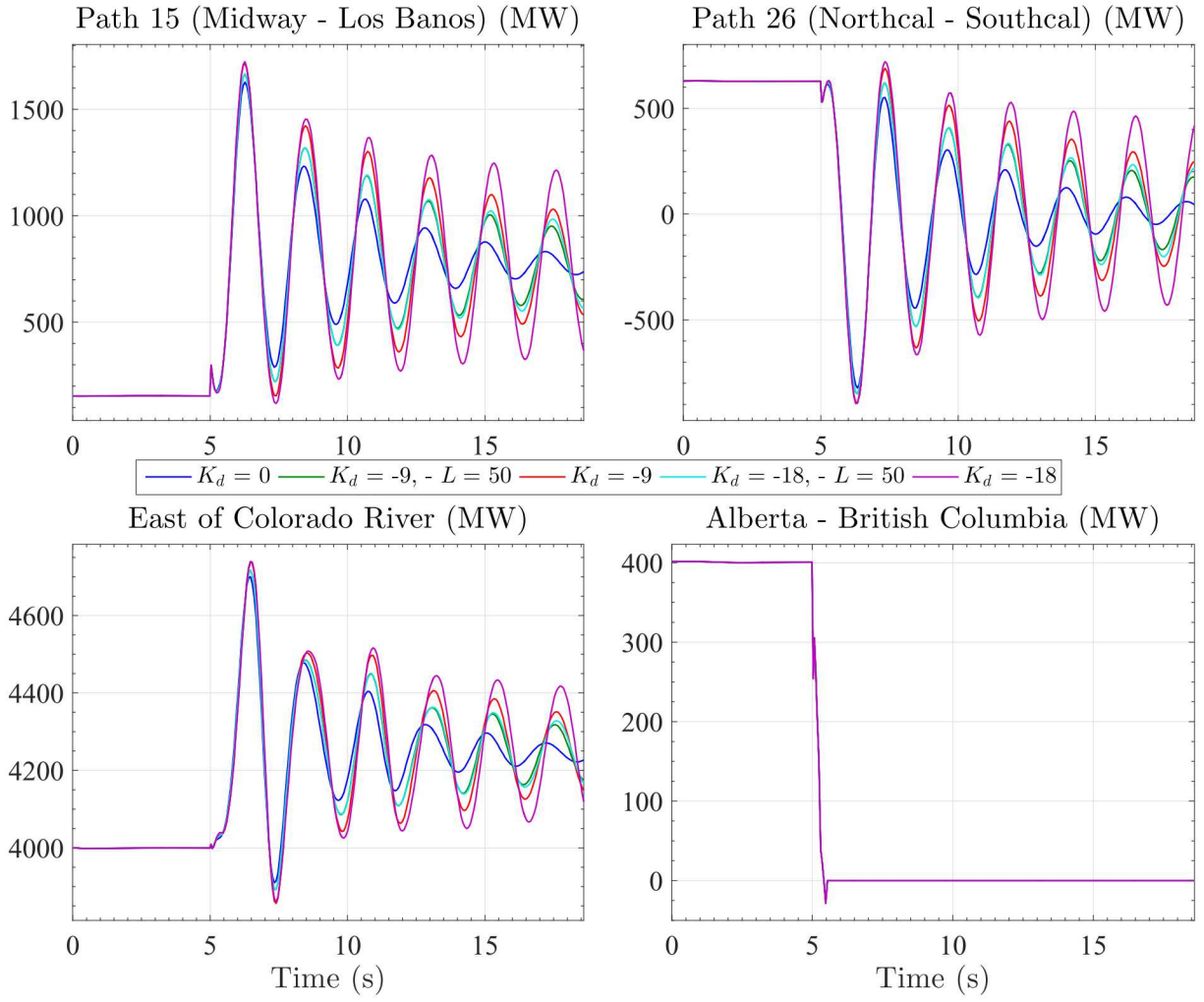


Figure 31. Active power flows. Event: BC-US Separation

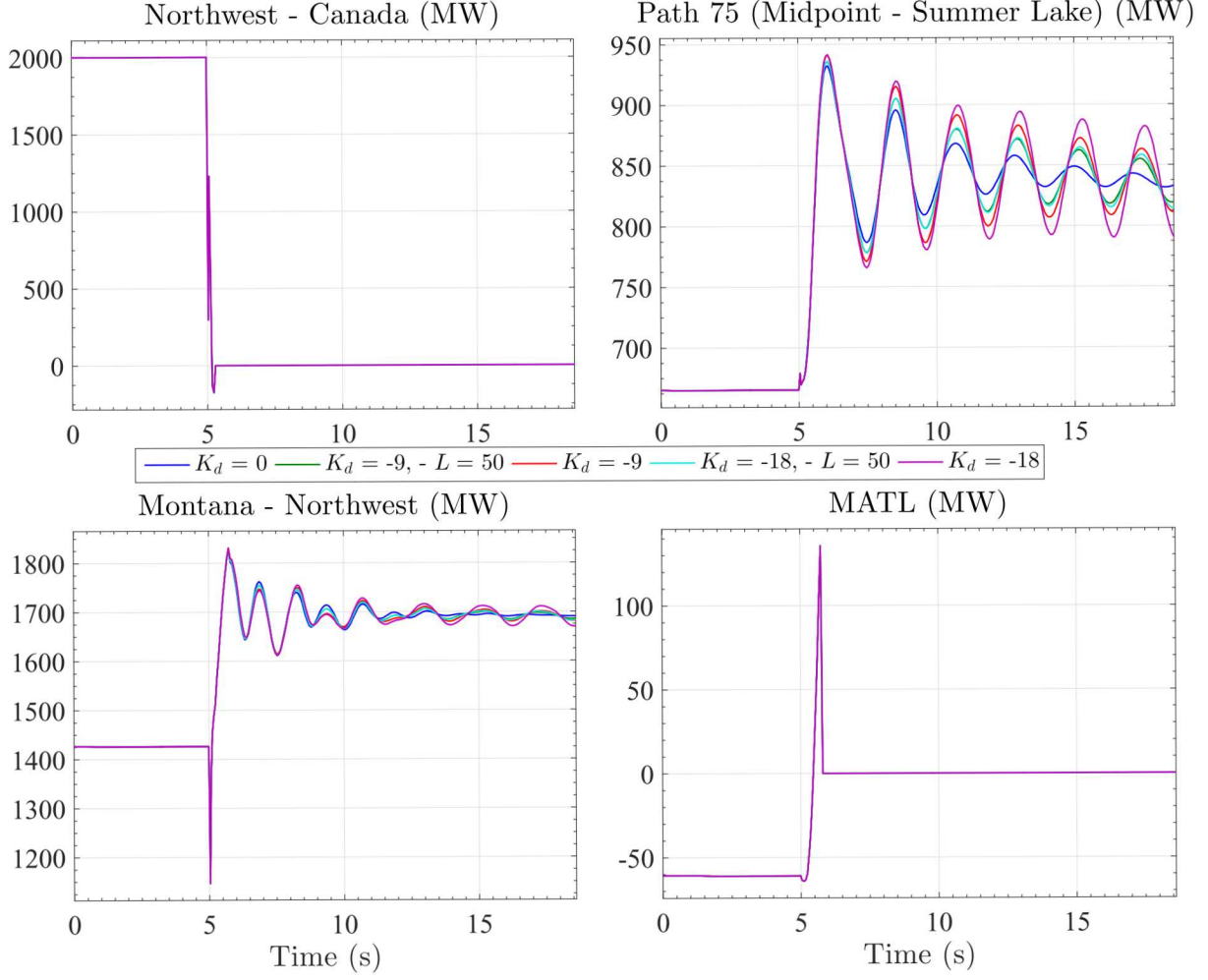


Figure 32. Active power flows. Event: BC-US Separation

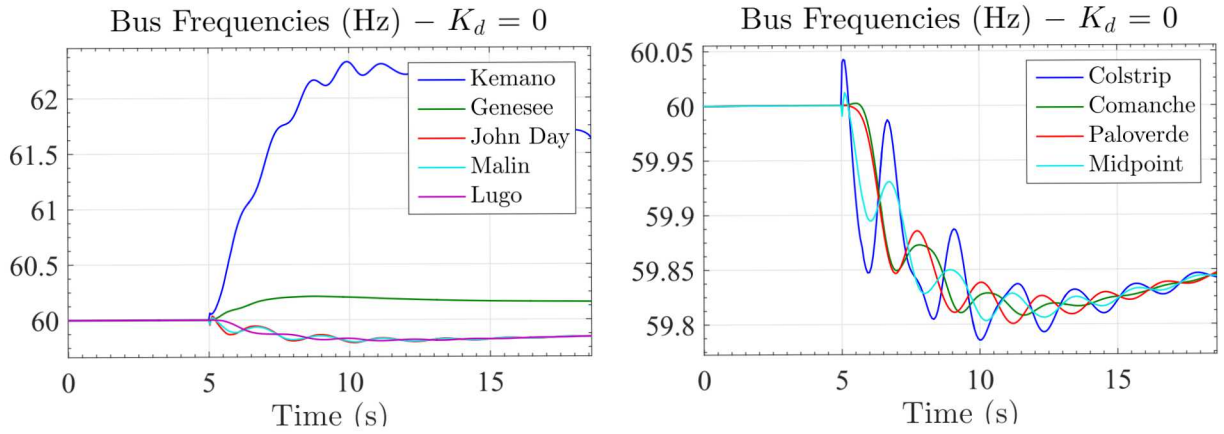


Figure 33. Bus frequencies. Event: BC-US Separation

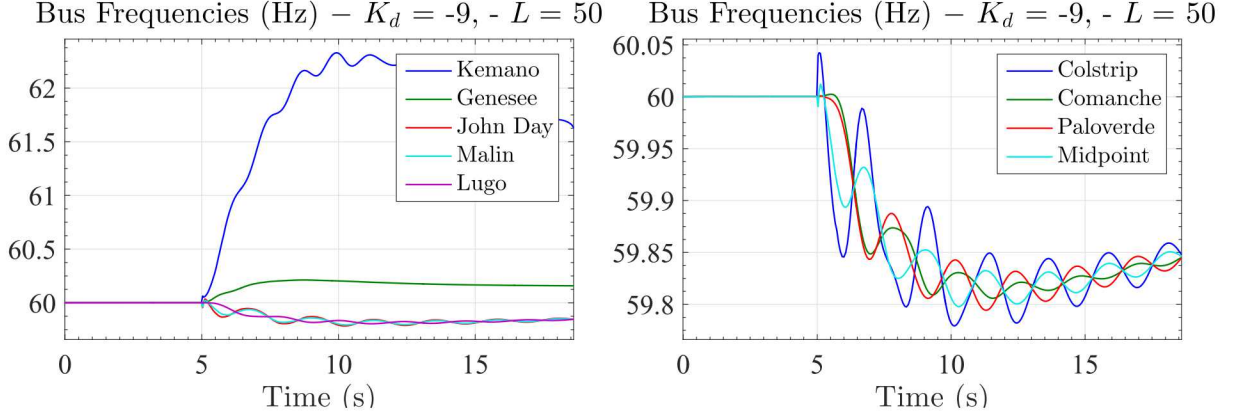


Figure 34. Bus frequencies. Event: BC-US Separation

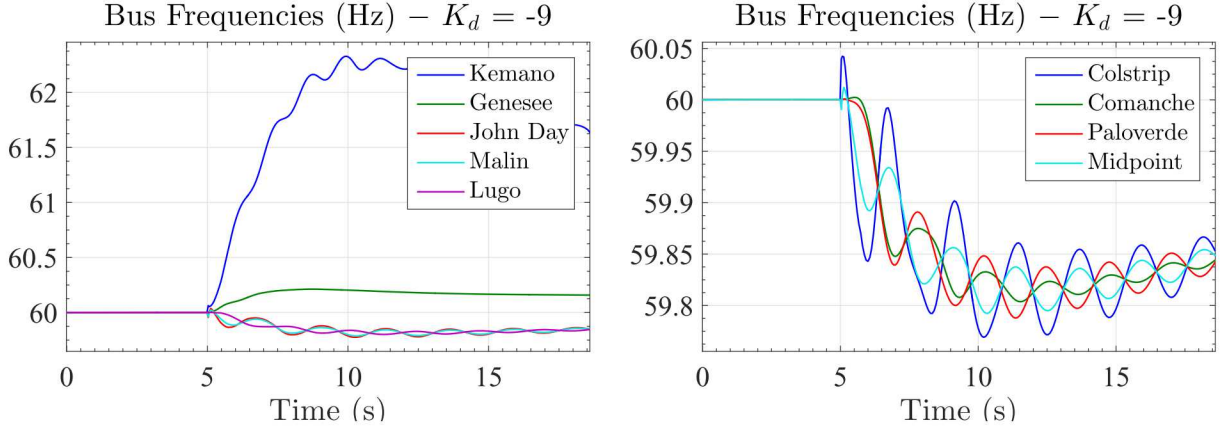


Figure 35. Bus frequencies. Event: BC-US Separation

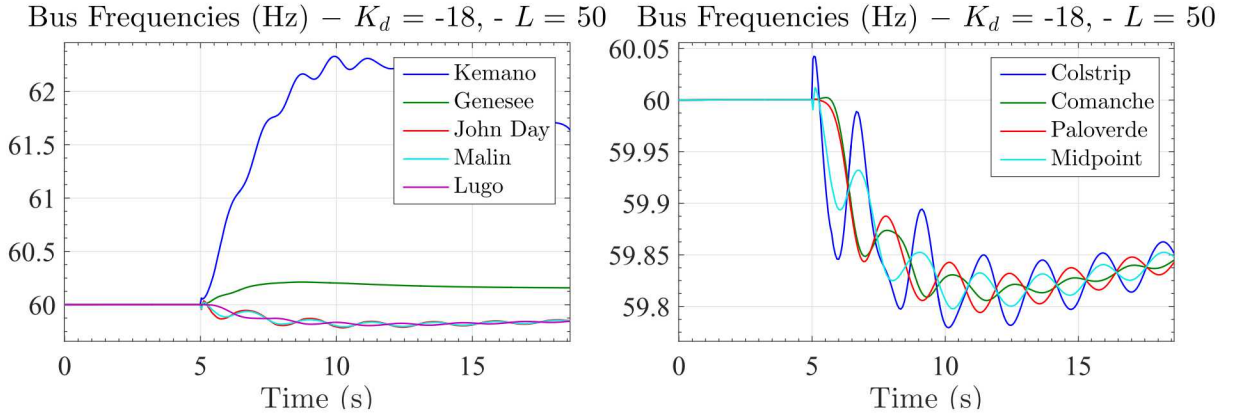


Figure 36. Bus frequencies. Event: BC-US Separation

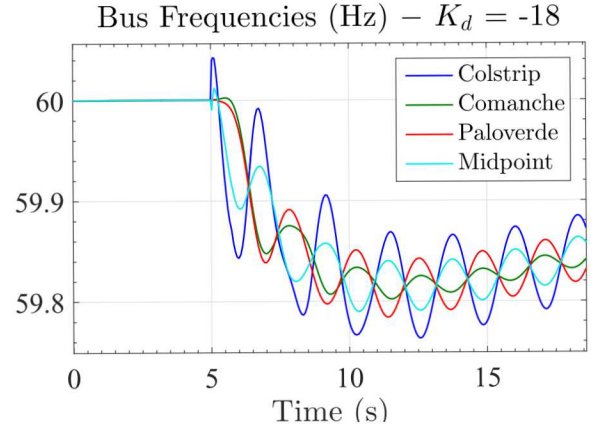
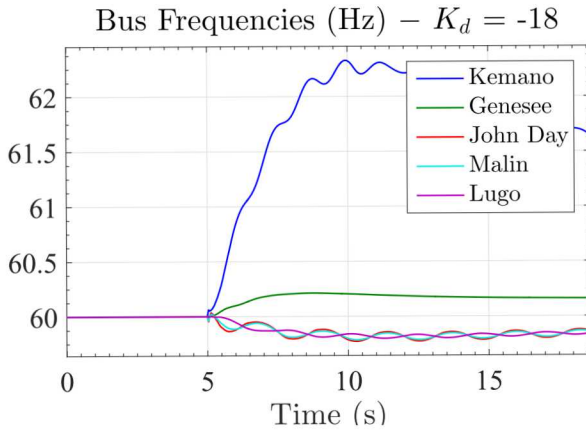


Figure 37. Bus frequencies. Event: BC-US Separation

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

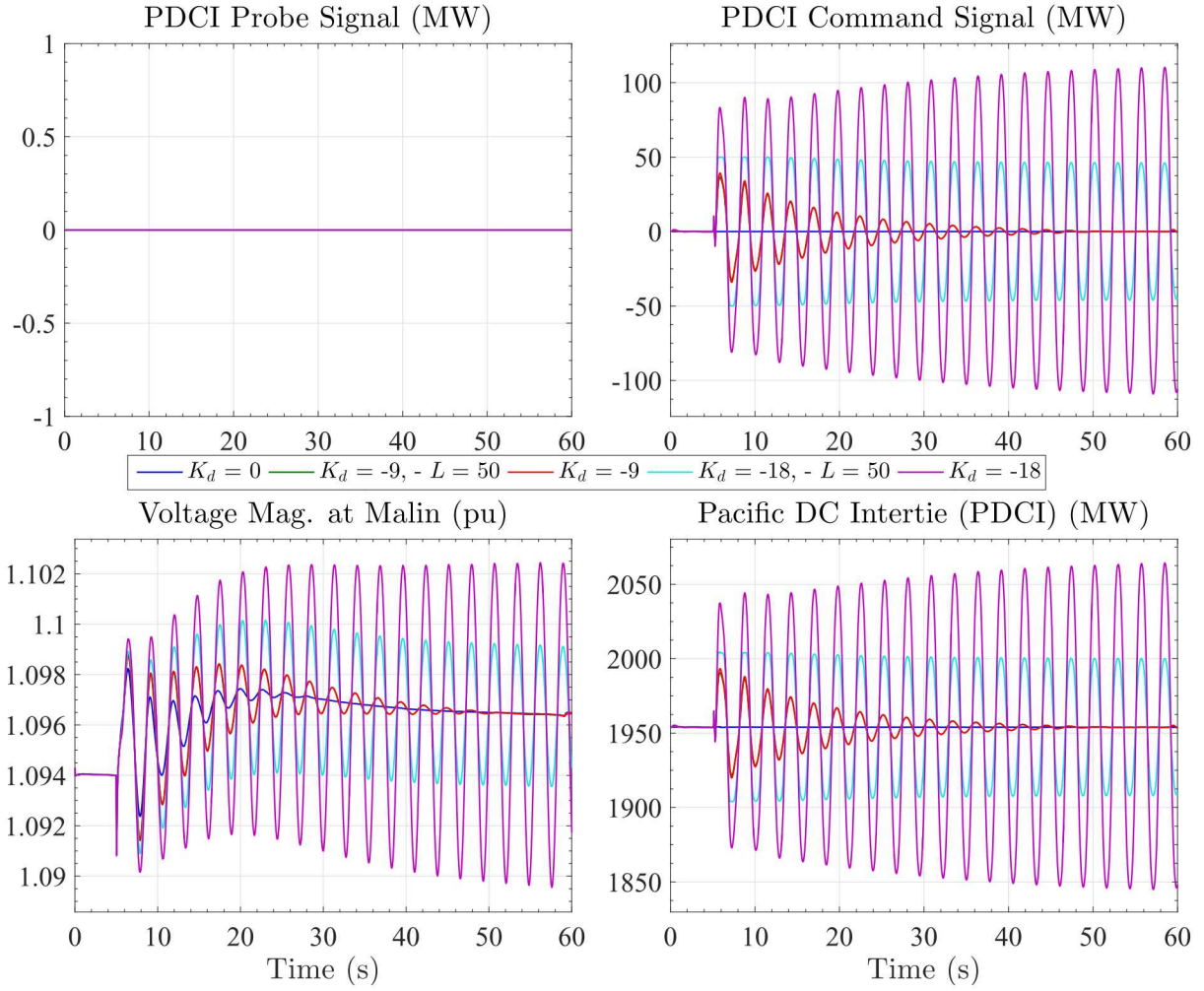


Figure 38. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-AB Separation

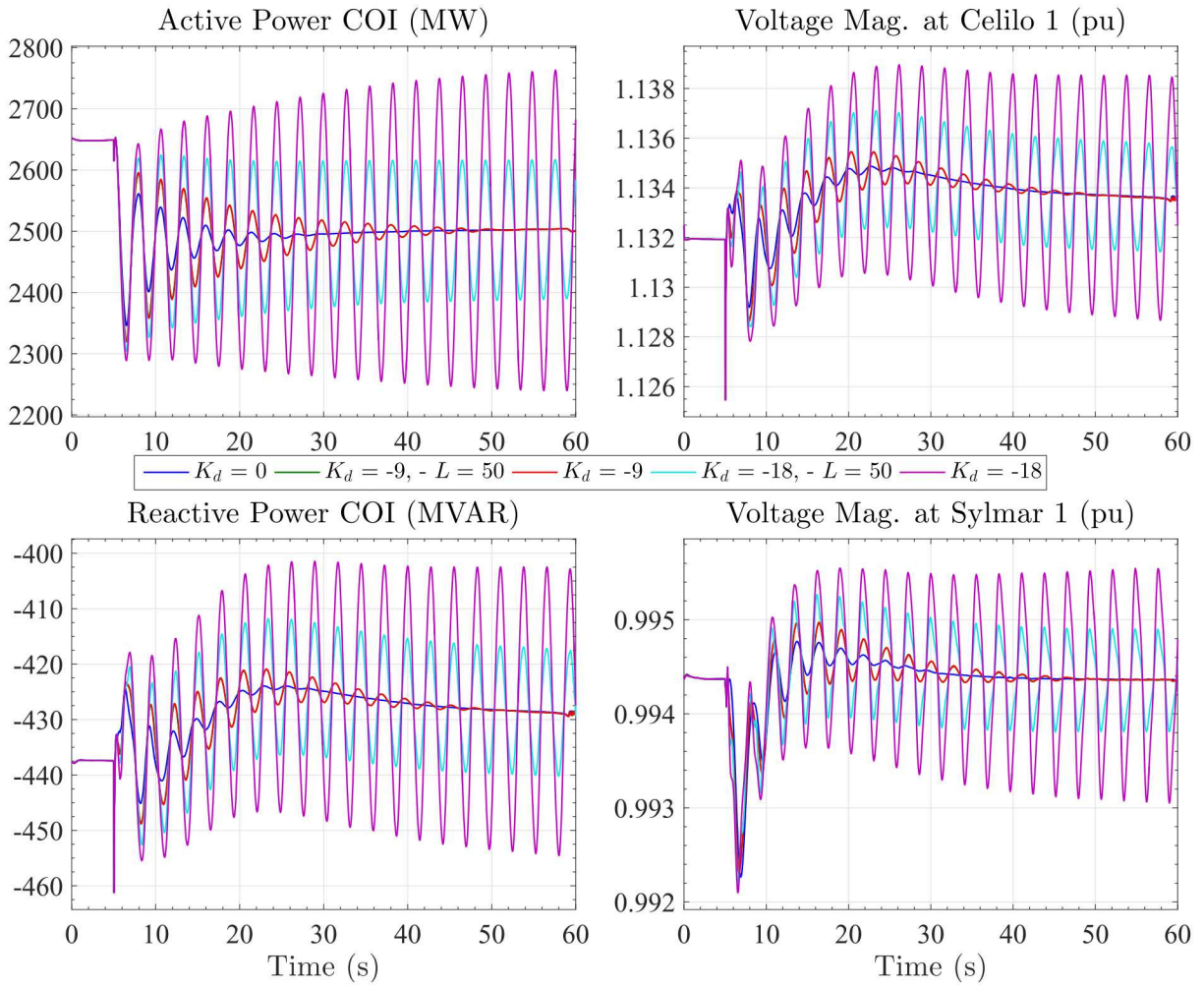


Figure 39. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-AB Separation

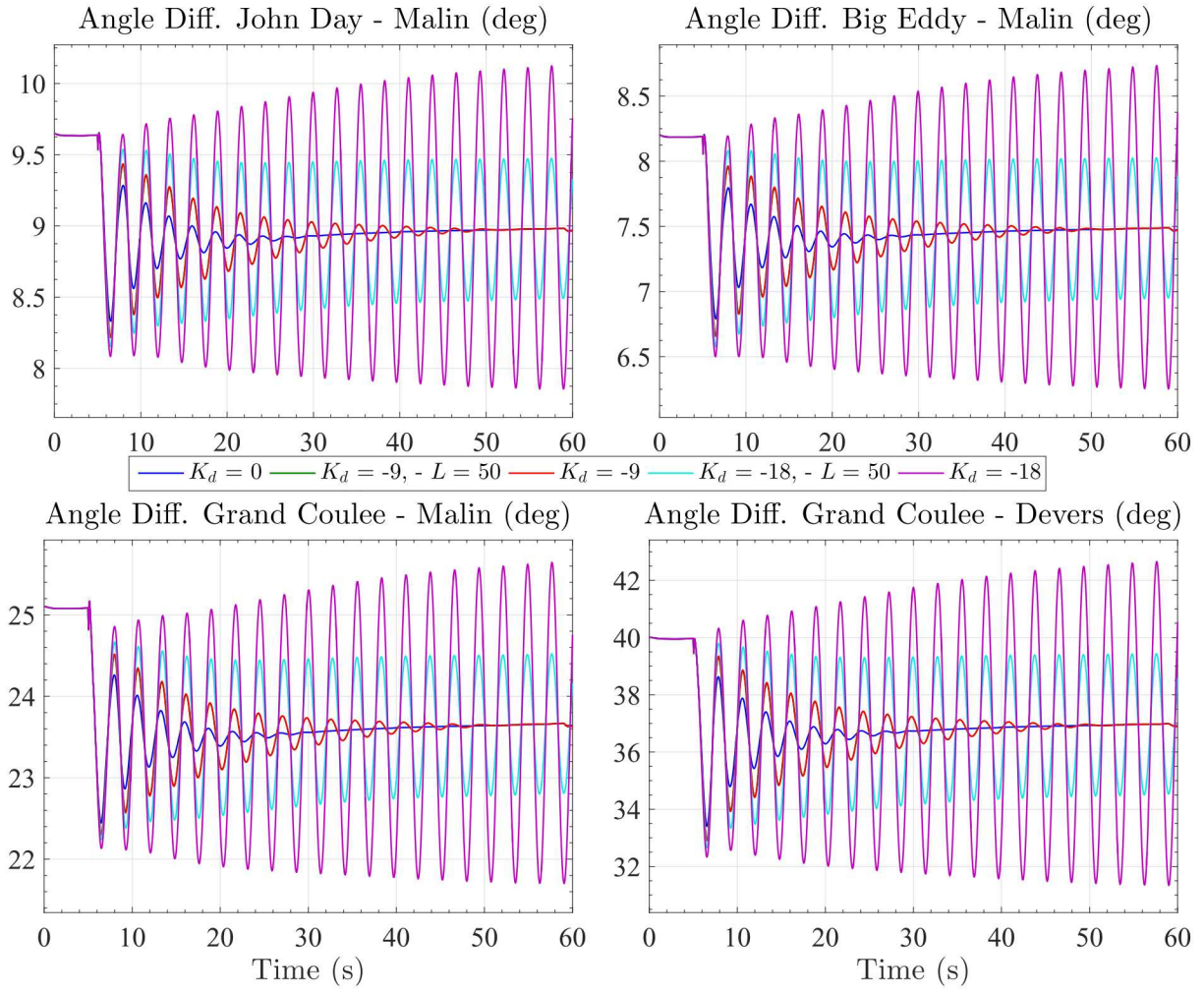


Figure 40. Angle differences. Event: BC-AB Separation

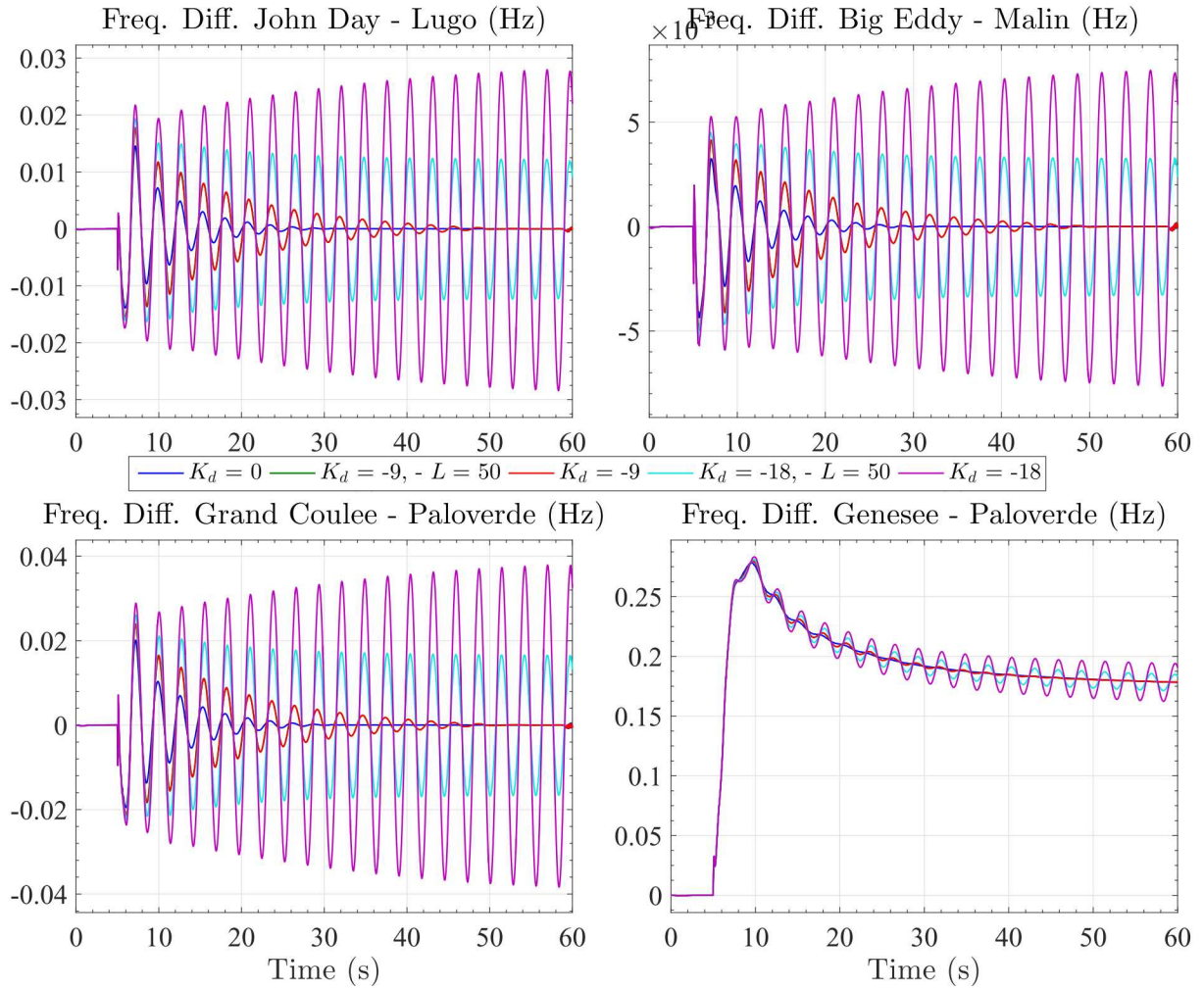


Figure 41. Frequency differences. Event: BC-AB Separation

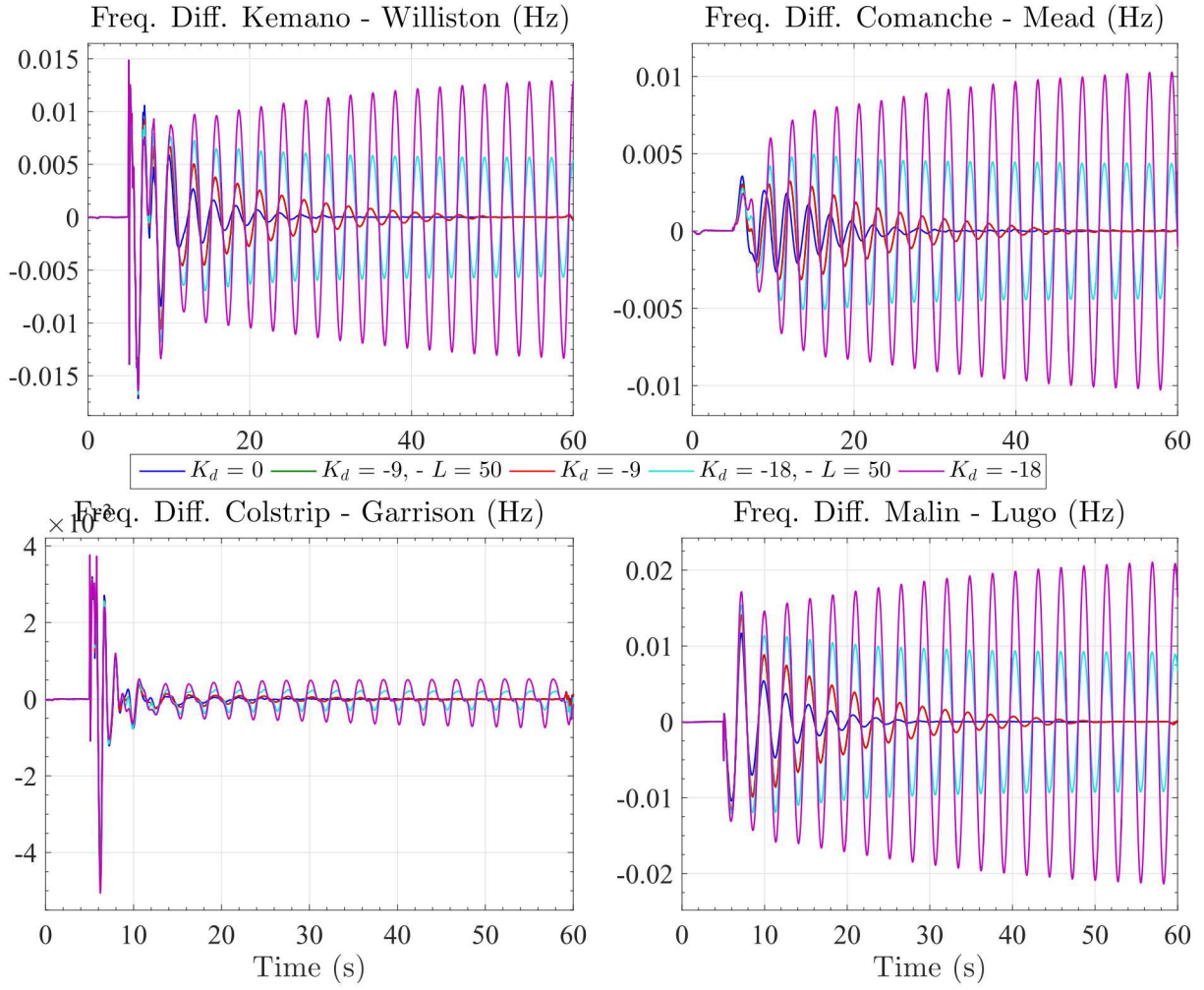


Figure 42. Frequency differences. Event: BC-AB Separation

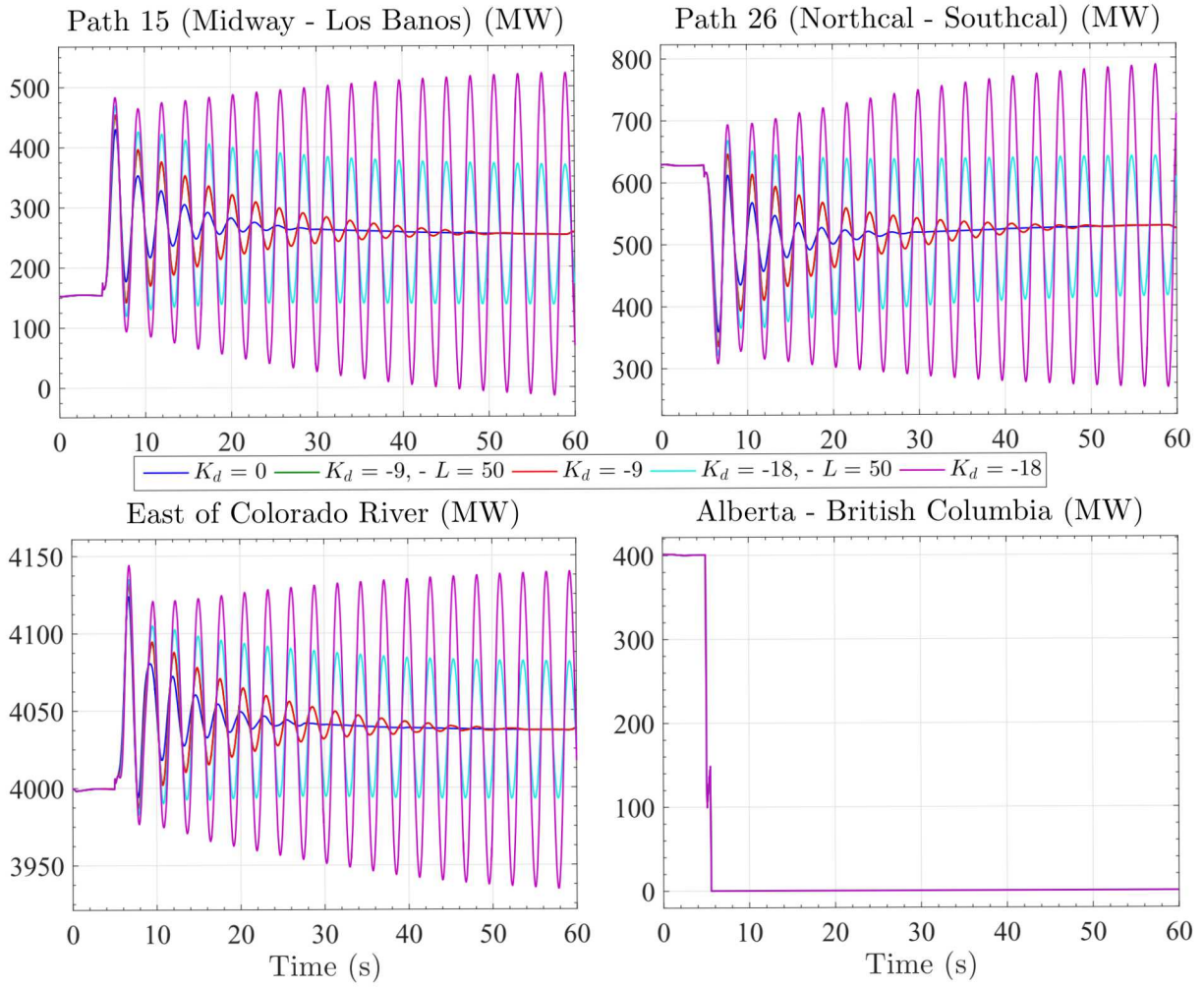


Figure 43. Active power flows. Event: BC-AB Separation

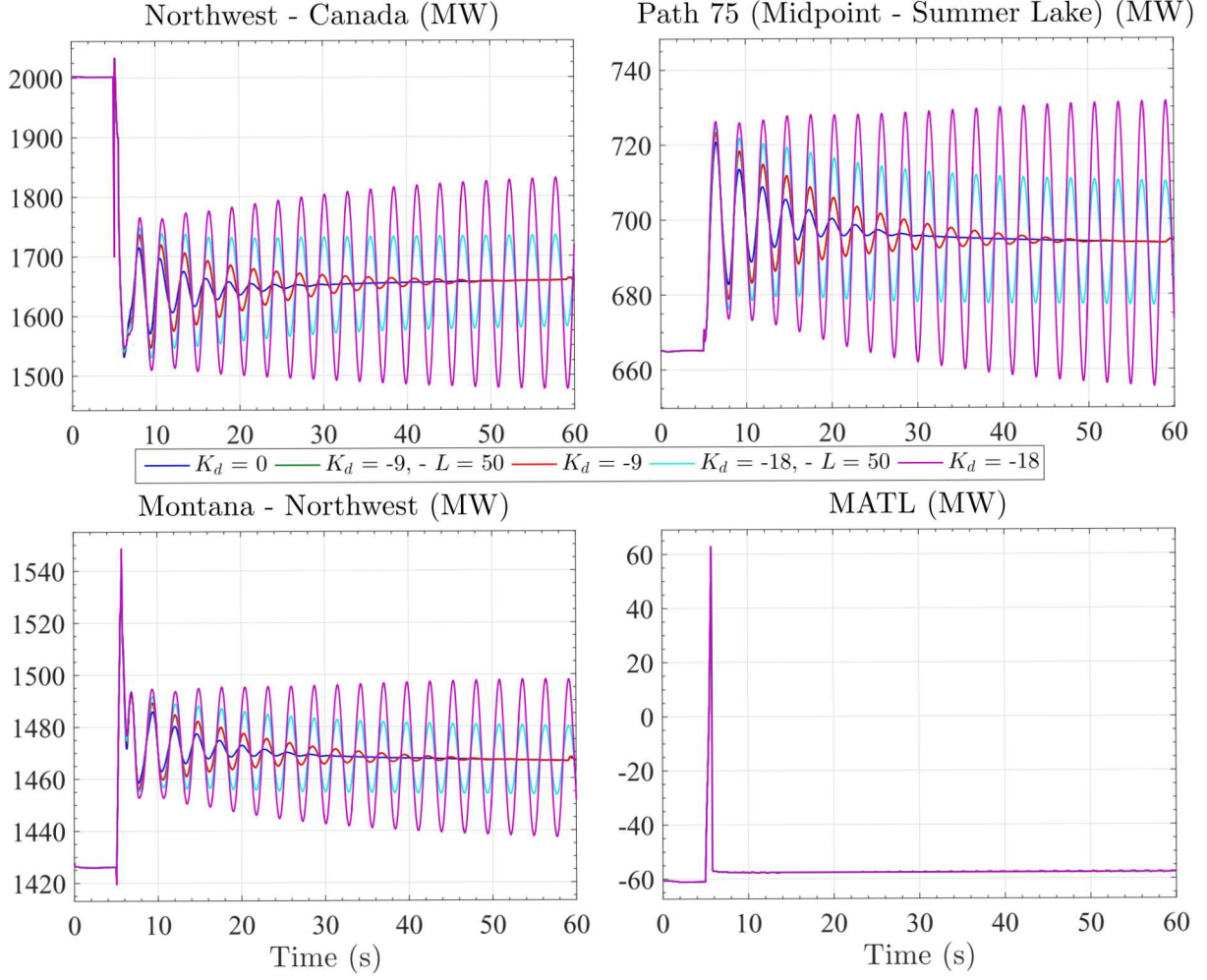


Figure 44. Active power flows. Event: BC-AB Separation

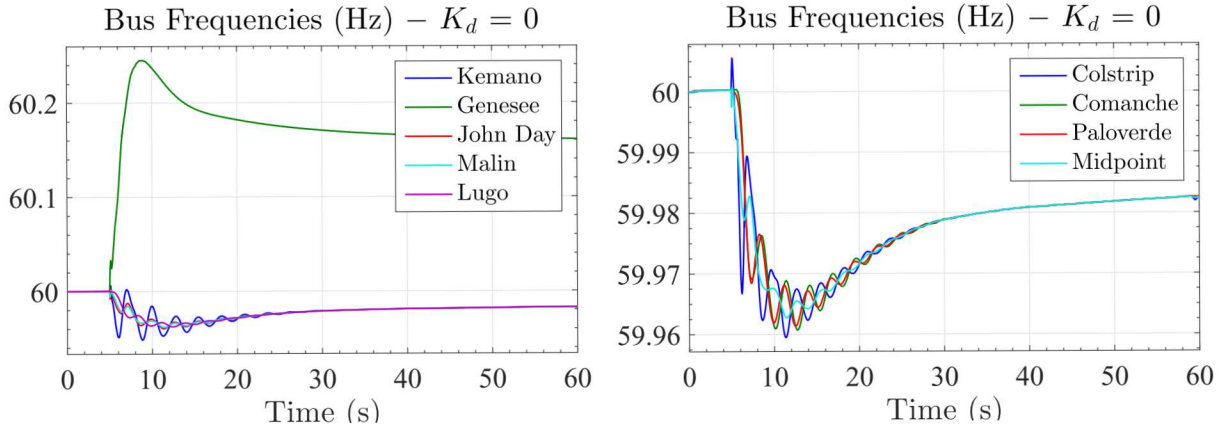


Figure 45. Bus frequencies. Event: BC-AB Separation

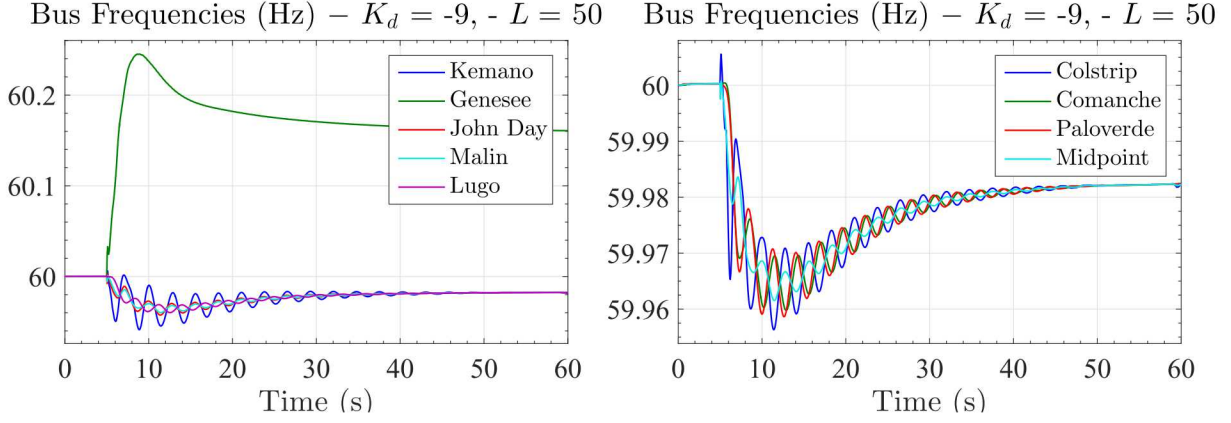


Figure 46. Bus frequencies. Event: BC-AB Separation

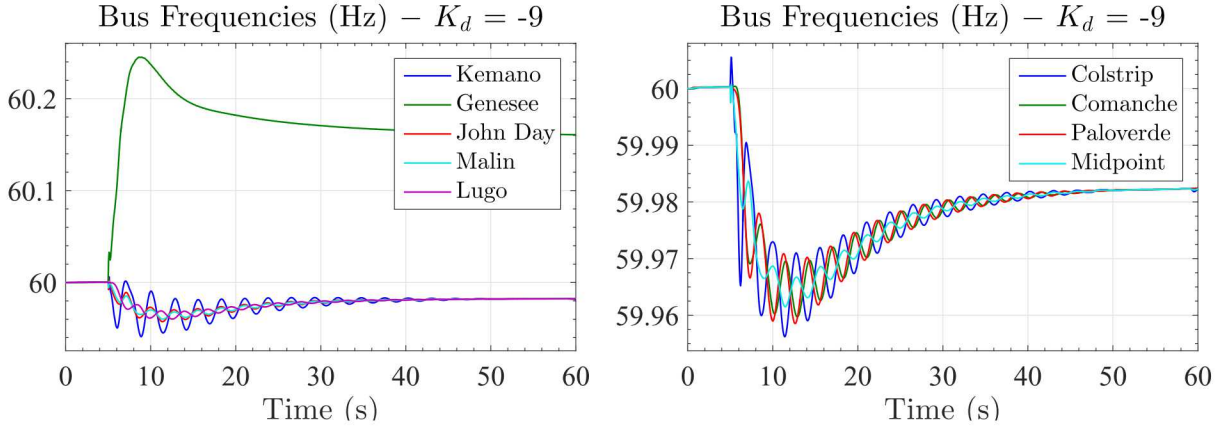


Figure 47. Bus frequencies. Event: BC-AB Separation

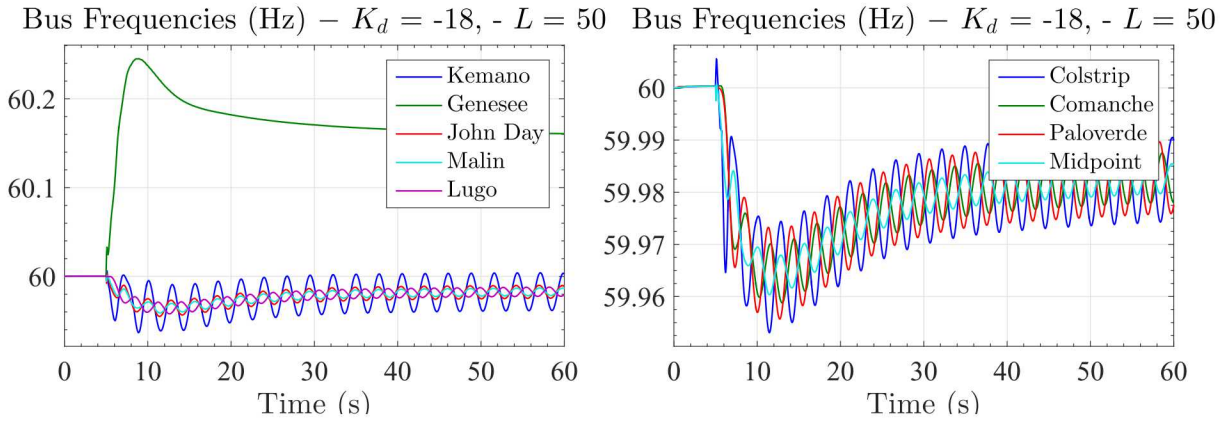


Figure 48. Bus frequencies. Event: BC-AB Separation

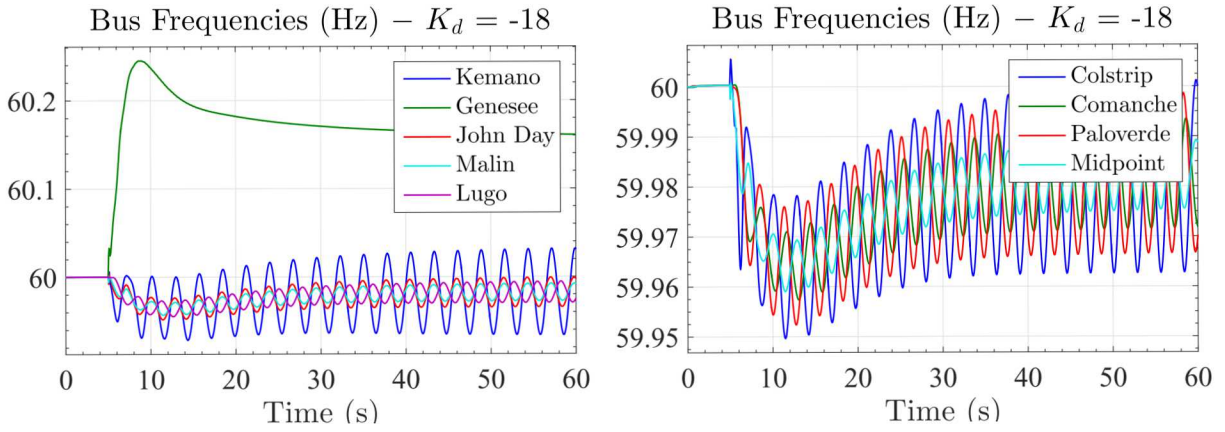


Figure 49. Bus frequencies. Event: BC-AB Separation

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

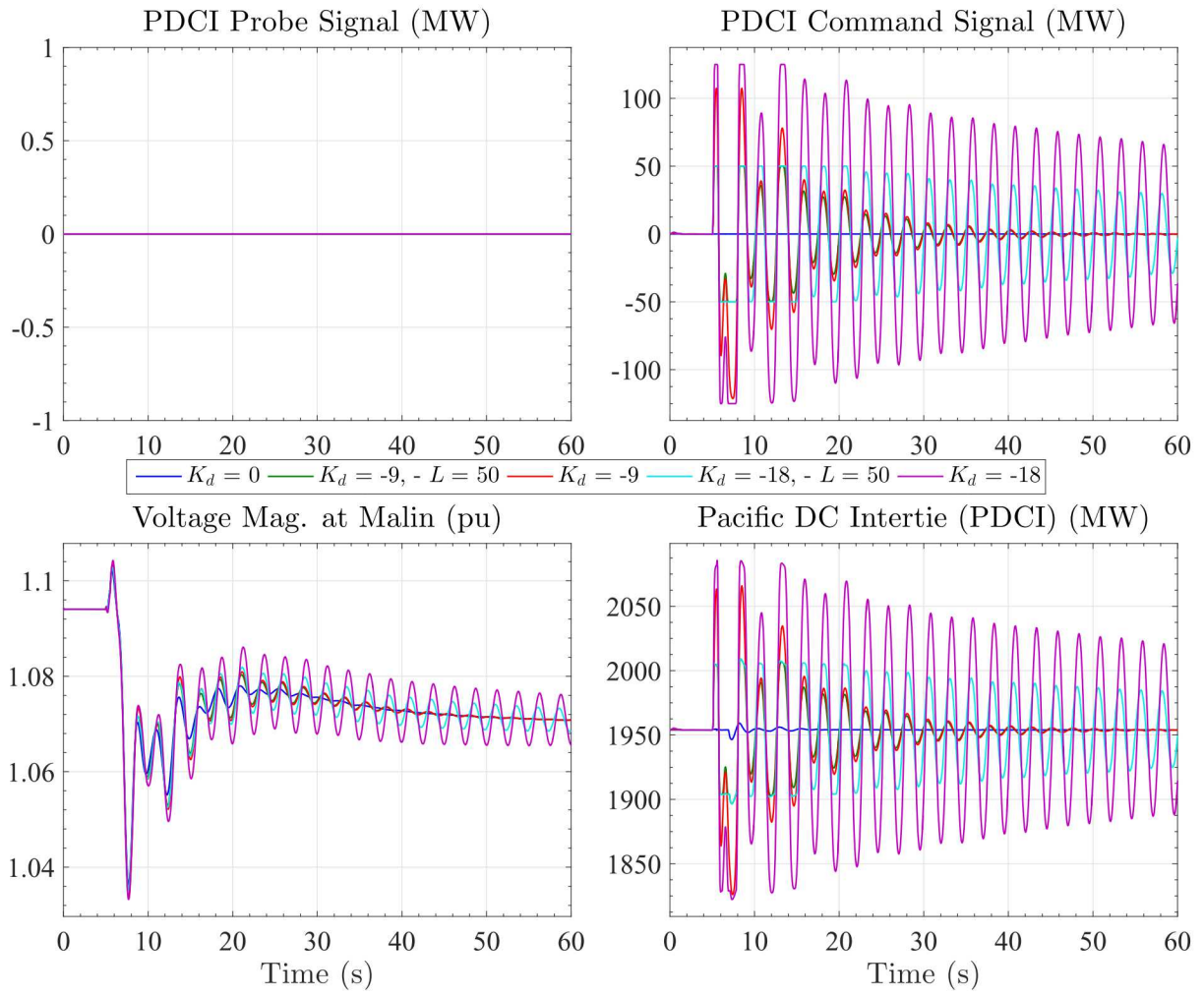


Figure 50. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + 2PV

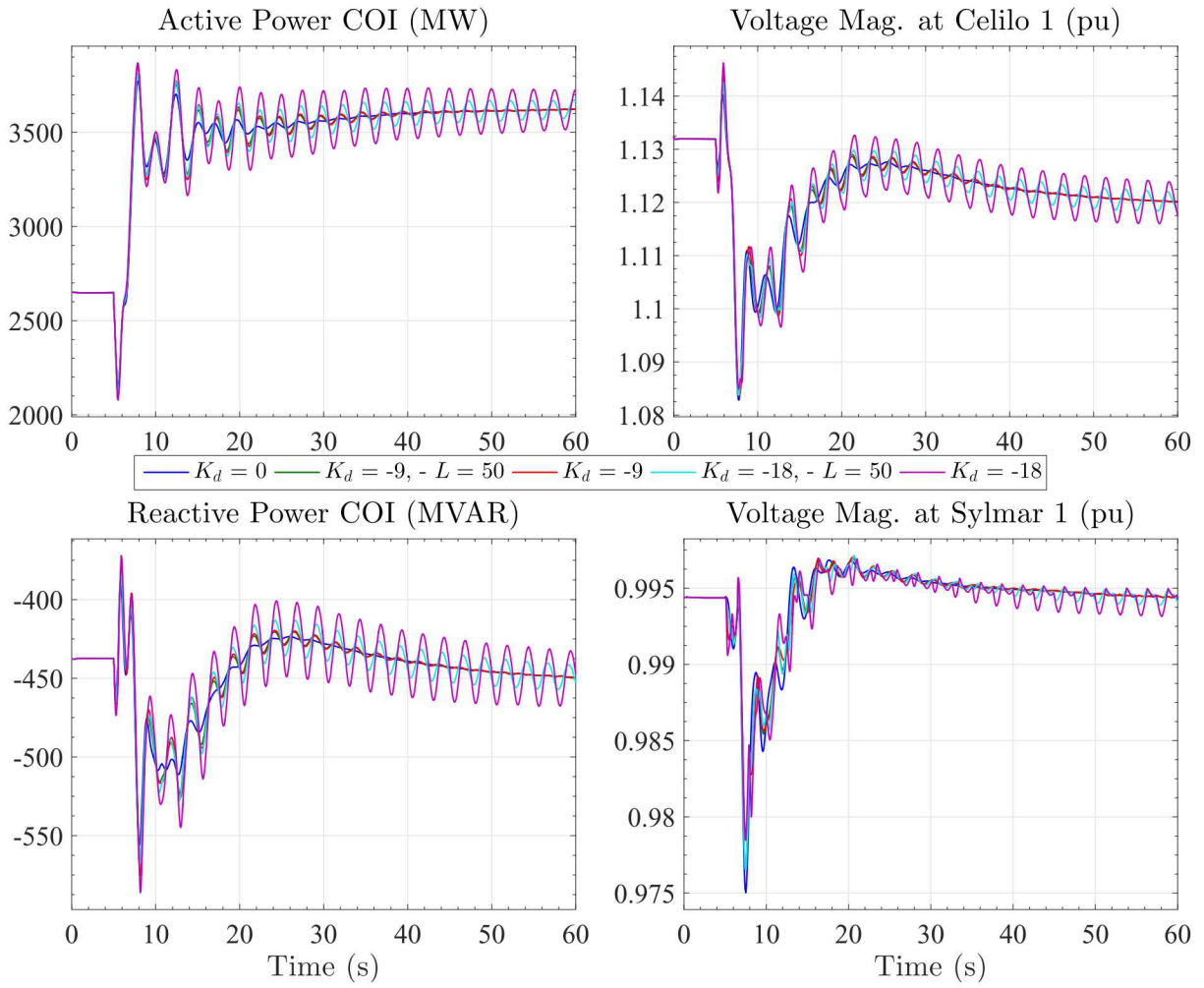


Figure 51. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + 2PV

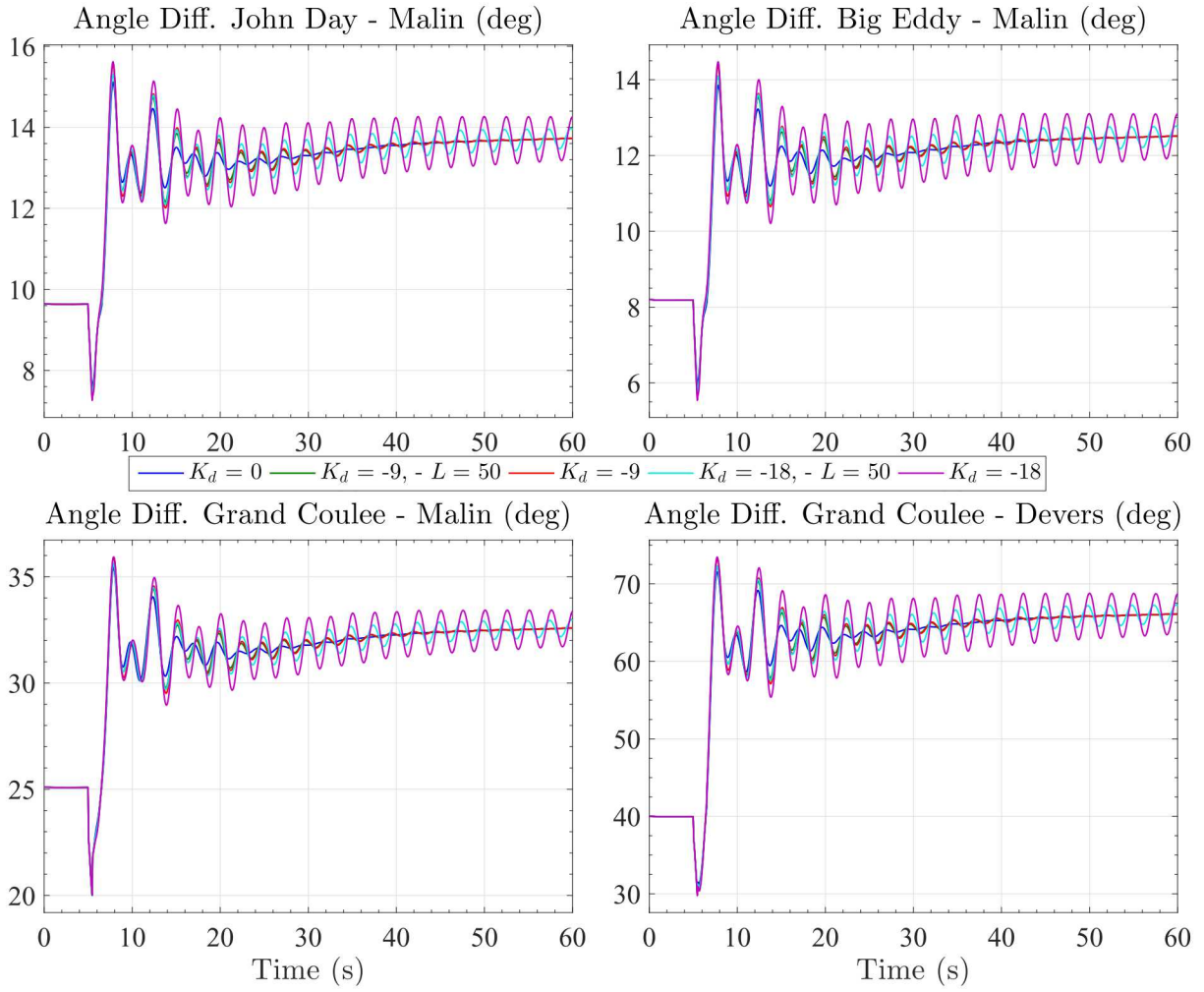


Figure 52. Angle differences. Event: CJB + 2PV

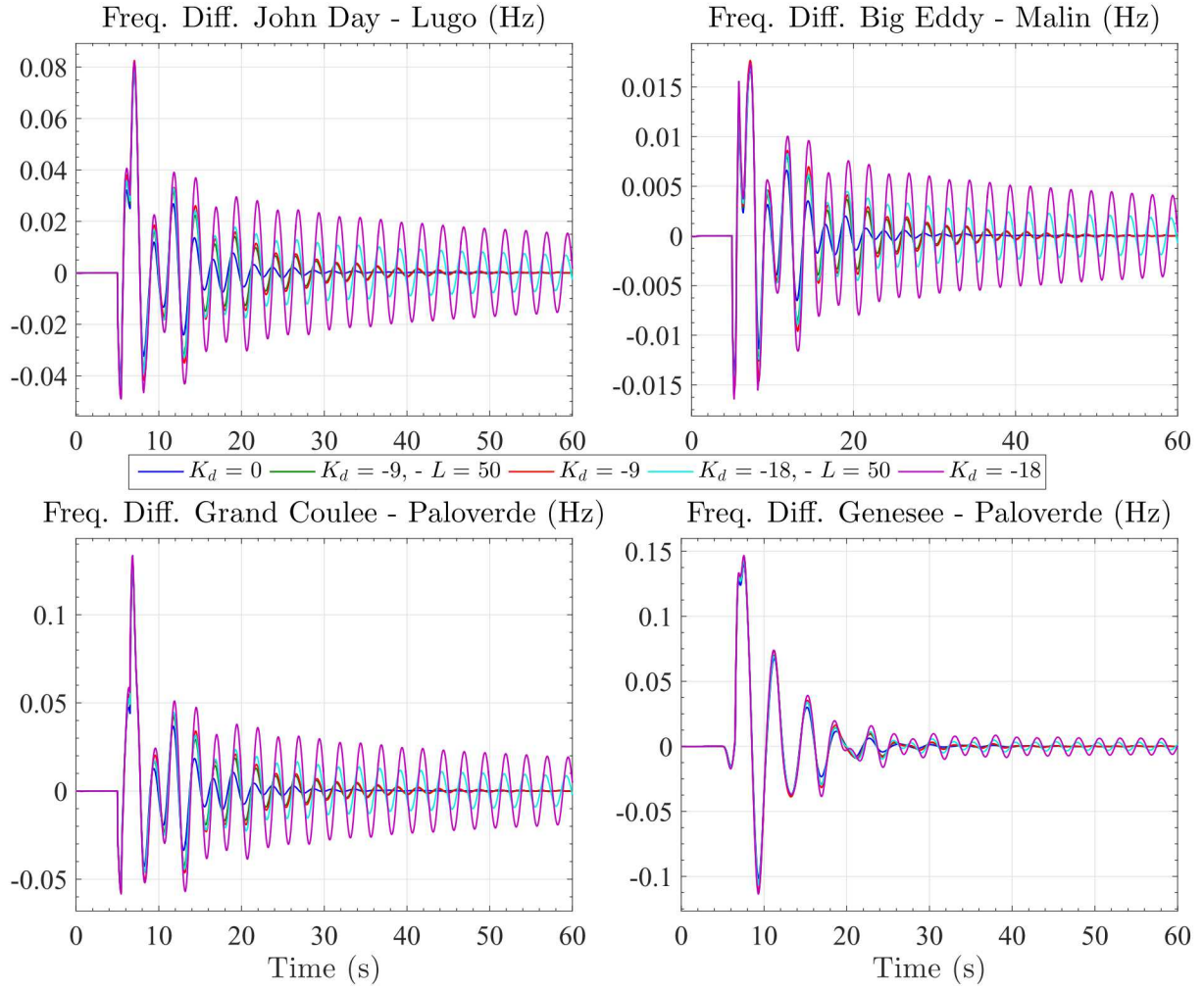


Figure 53. Frequency differences. Event: CJB + 2PV

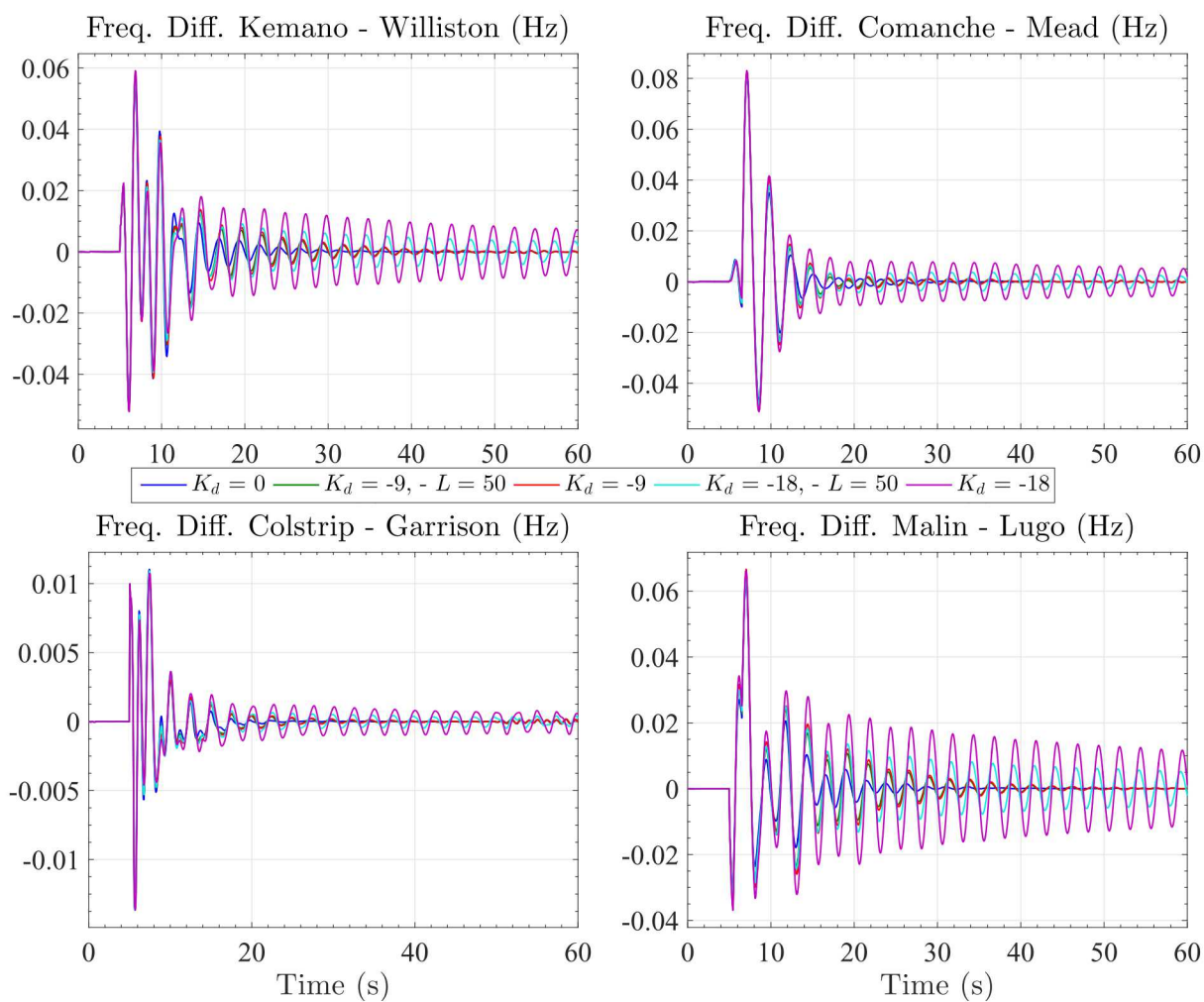


Figure 54. Frequency differences. Event: CJB + 2PV

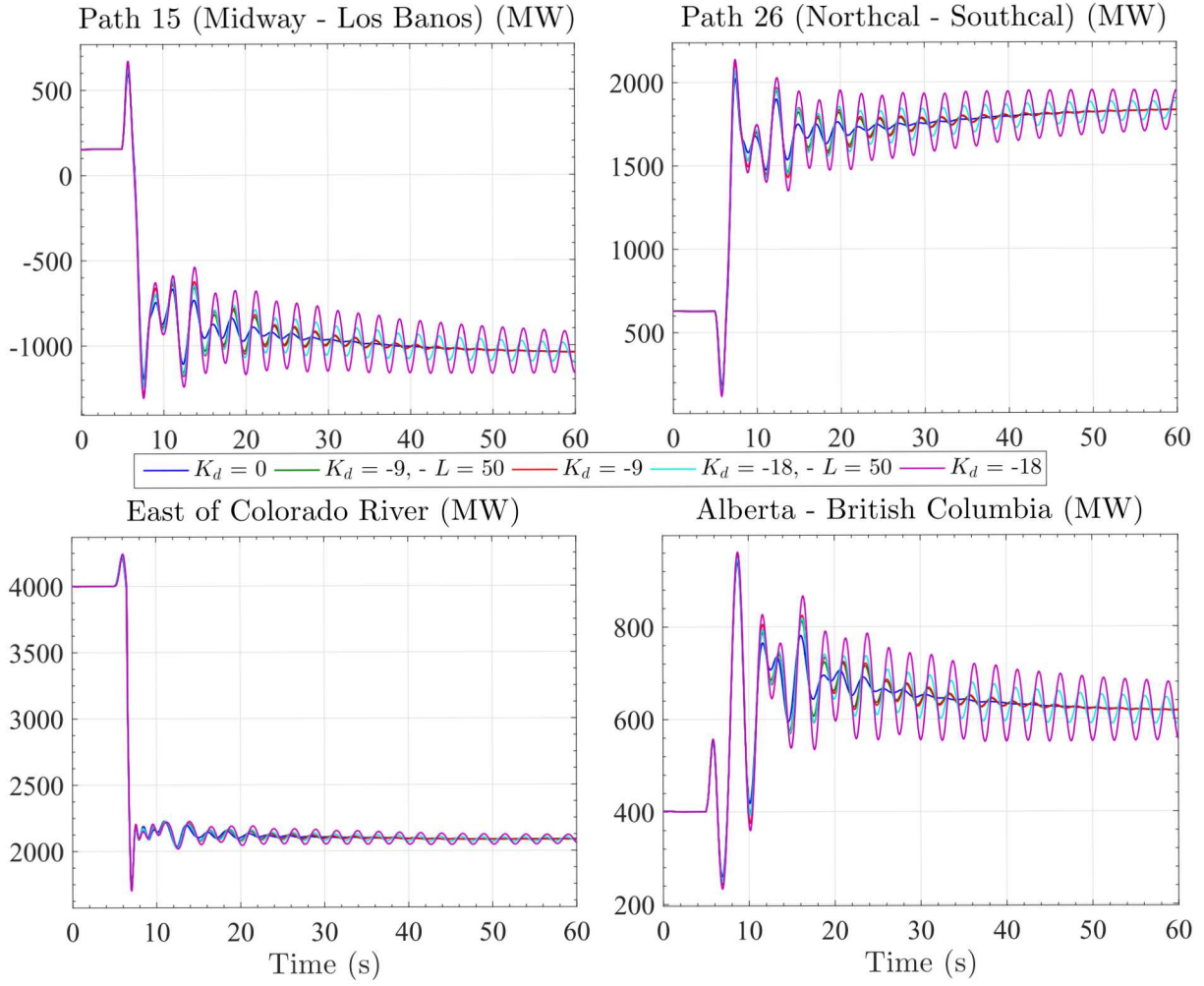


Figure 55. Active power flows. Event: CJB + 2PV

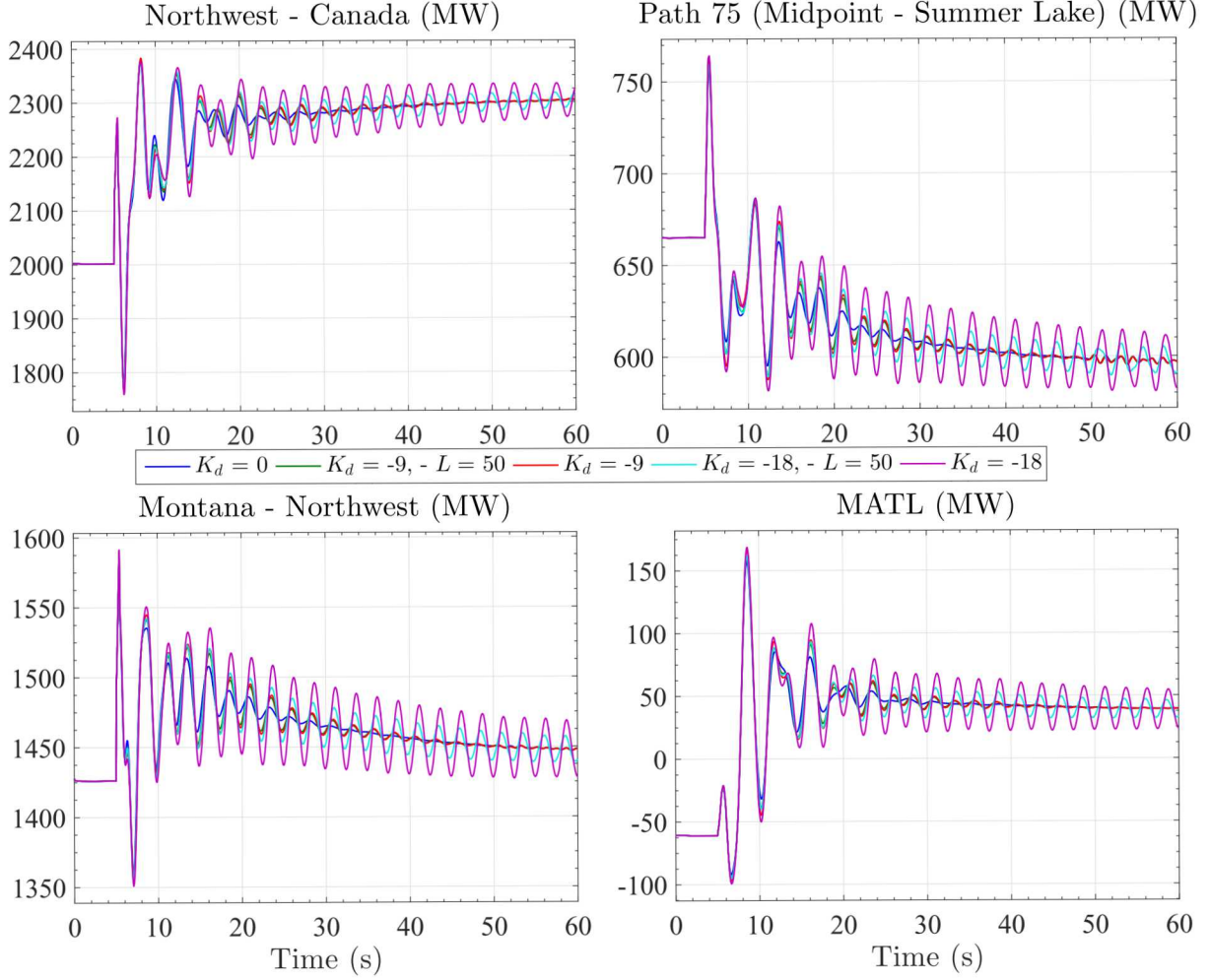


Figure 56. Active power flows. Event: CJB + 2PV

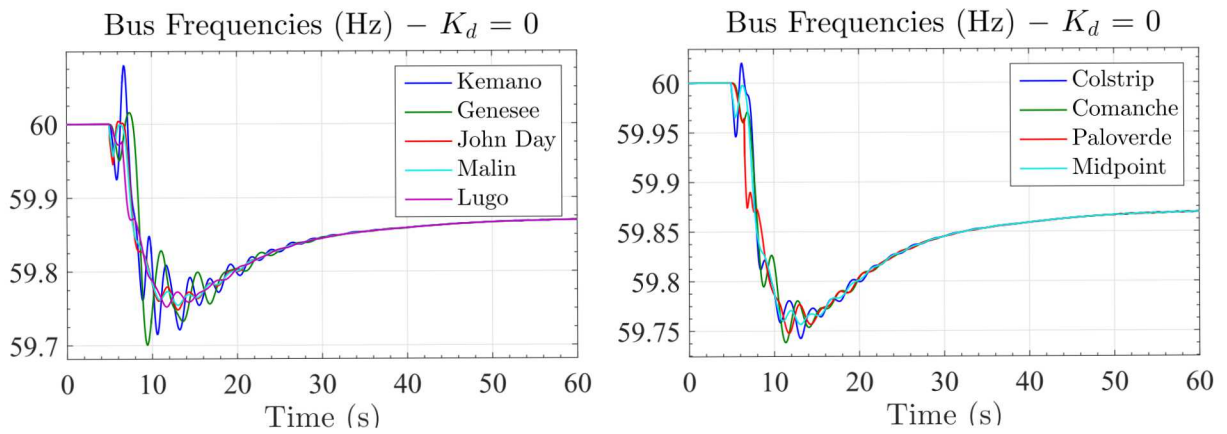


Figure 57. Bus frequencies. Event: CJB + 2PV

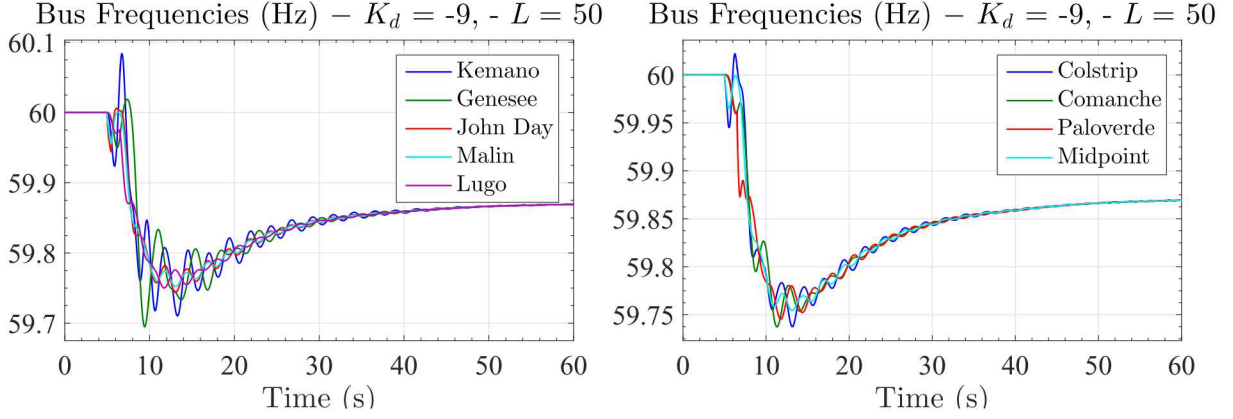


Figure 58. Bus frequencies. Event: CJB + 2PV

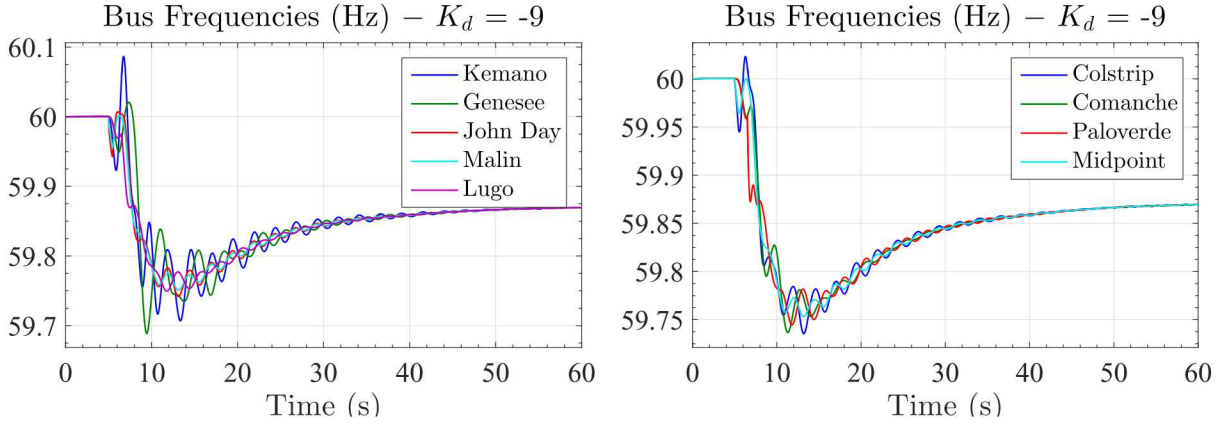


Figure 59. Bus frequencies. Event: CJB + 2PV

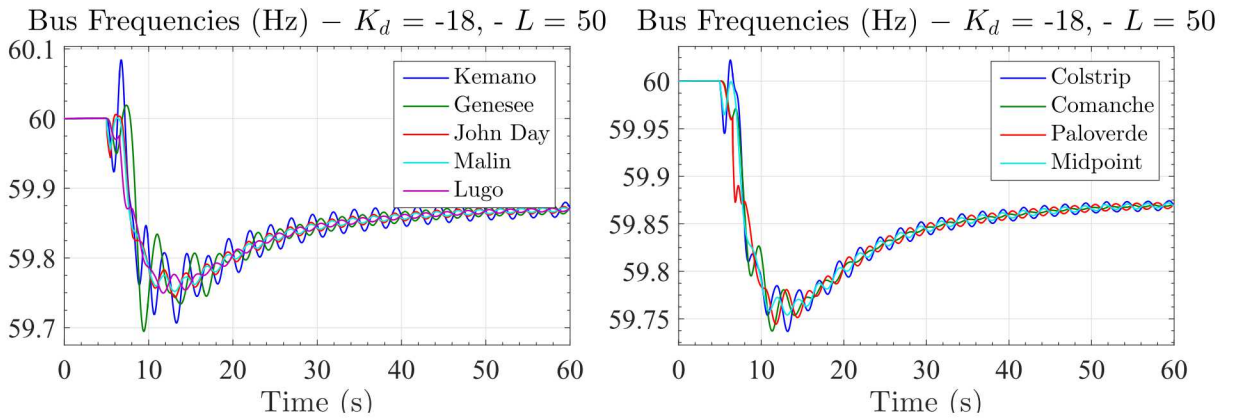


Figure 60. Bus frequencies. Event: CJB + 2PV

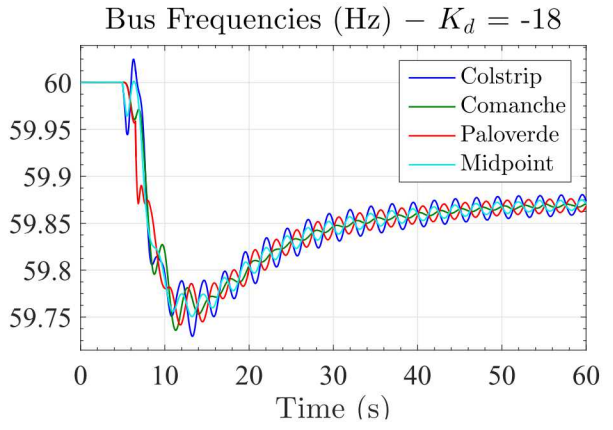
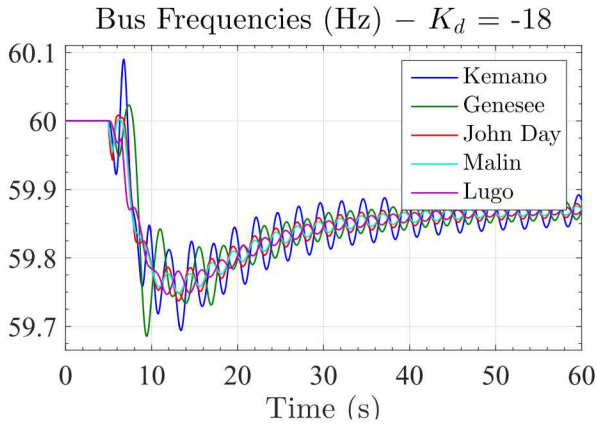


Figure 61. Bus frequencies. Event: CJB + 2PV

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

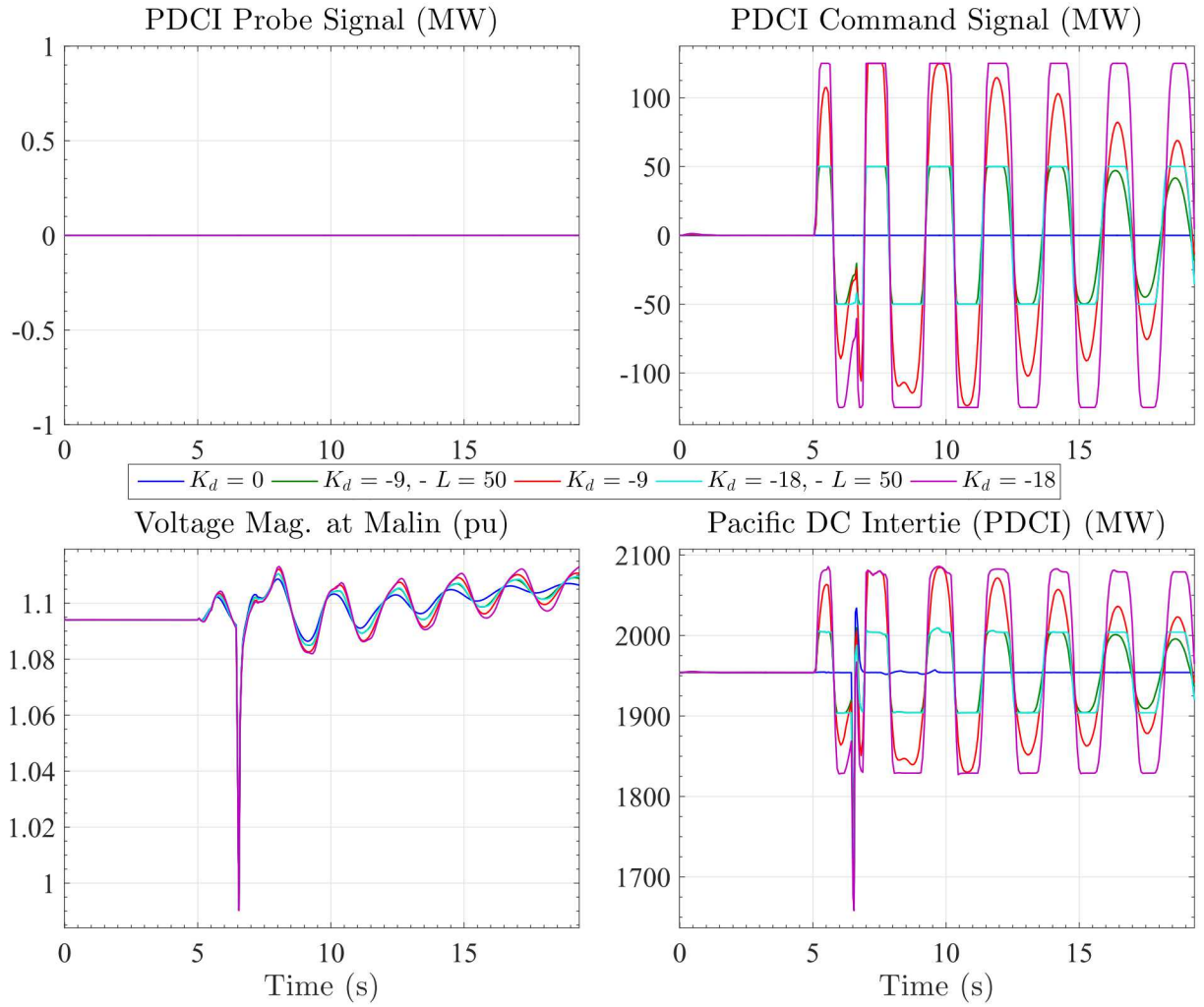


Figure 62. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCUS Separation

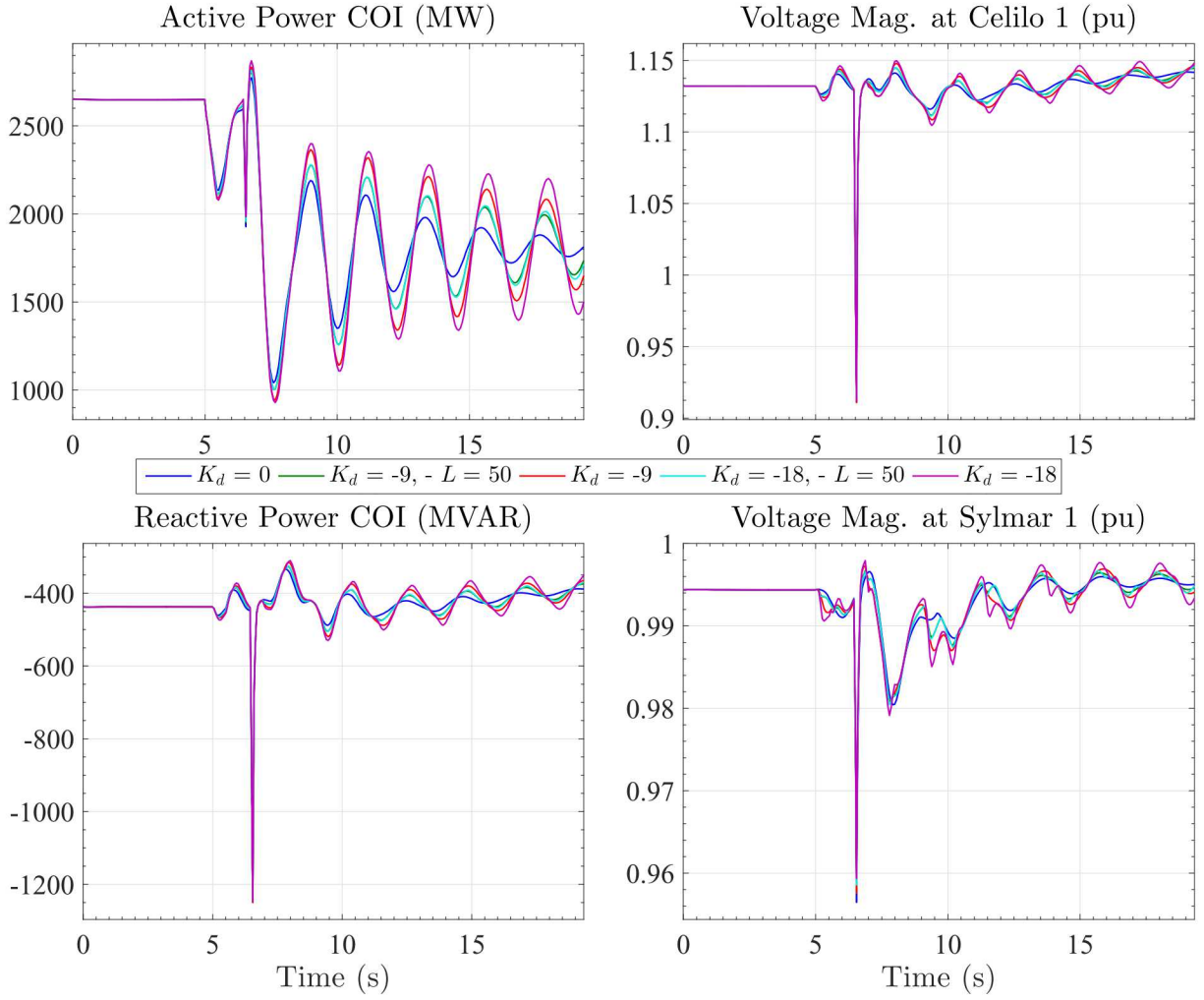


Figure 63. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCUS Separation

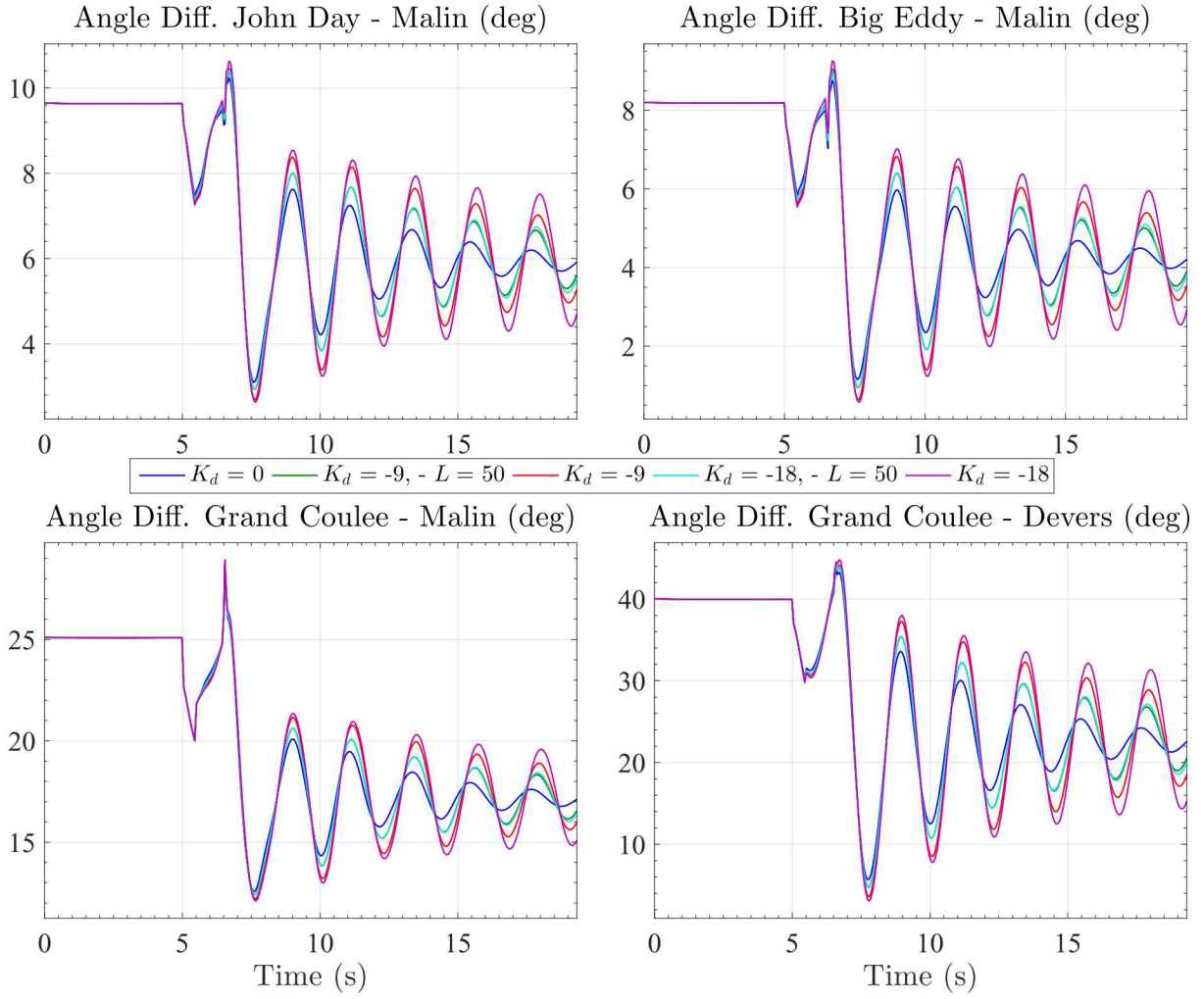


Figure 64. Angle differences. Event: CJB + BCUS Separation

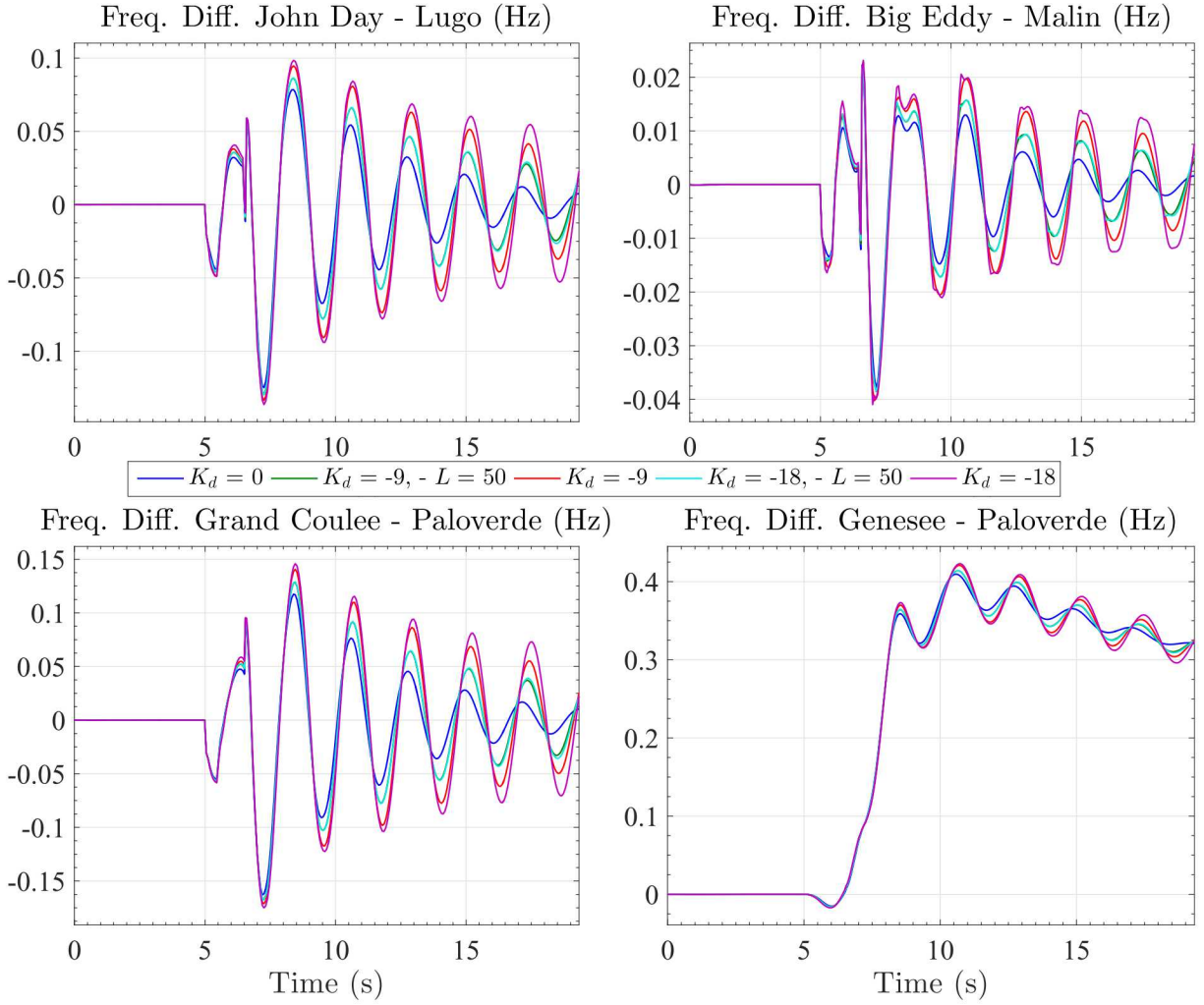


Figure 65. Frequency differences. Event: CJB + BCUS Separation

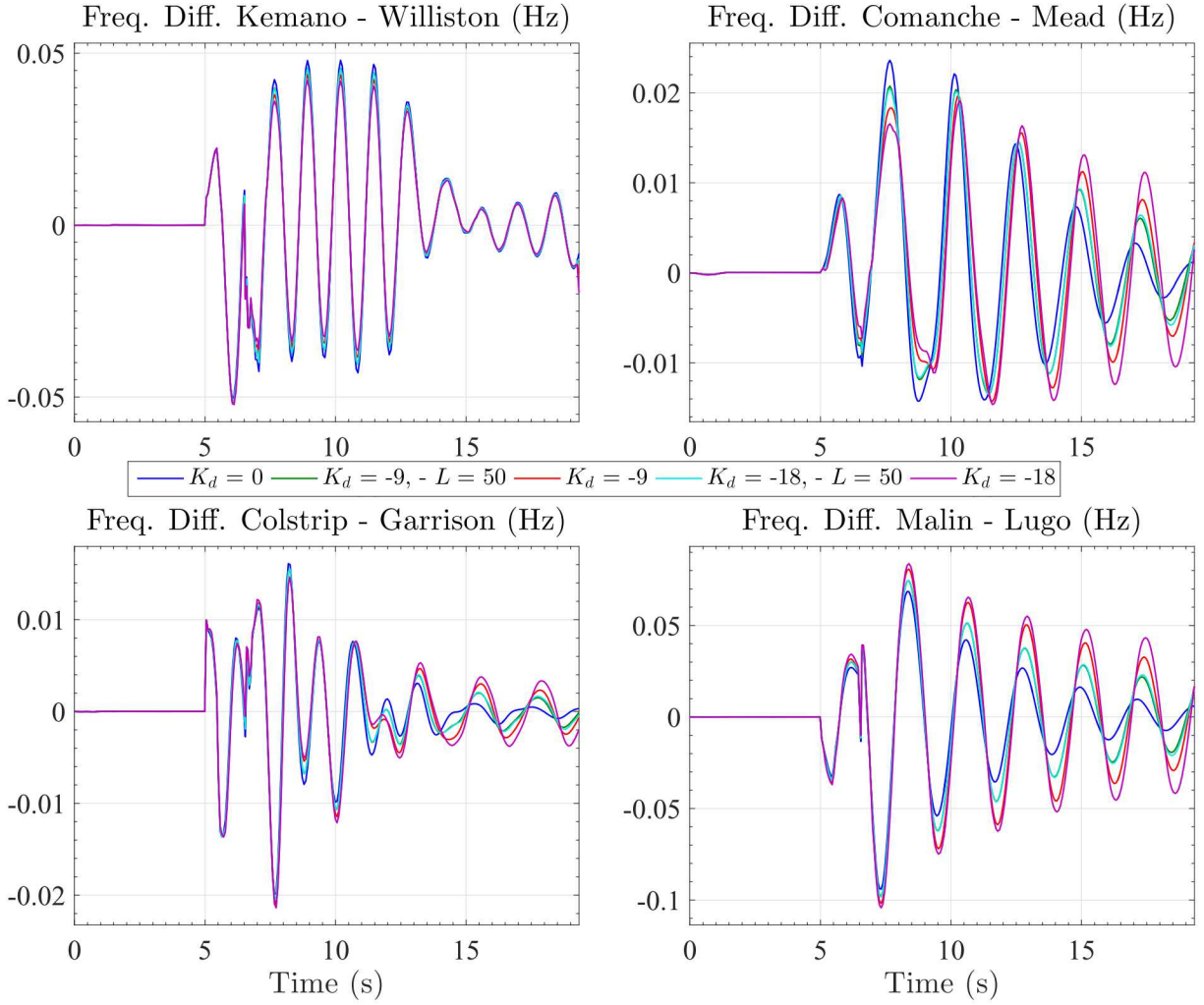


Figure 66. Frequency differences. Event: CJB + BCUS Separation

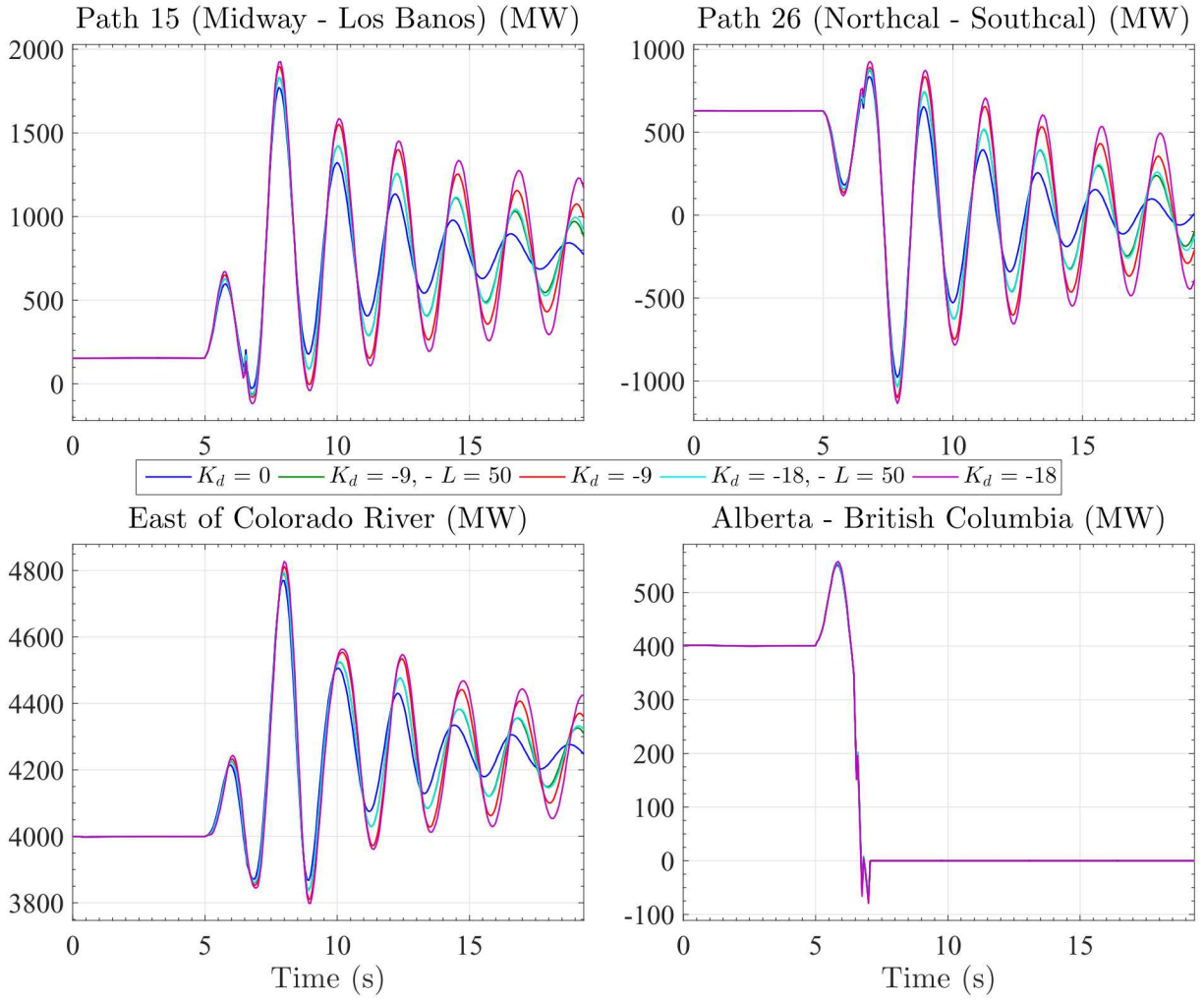


Figure 67. Active power flows. Event: CJB + BCUS Separation

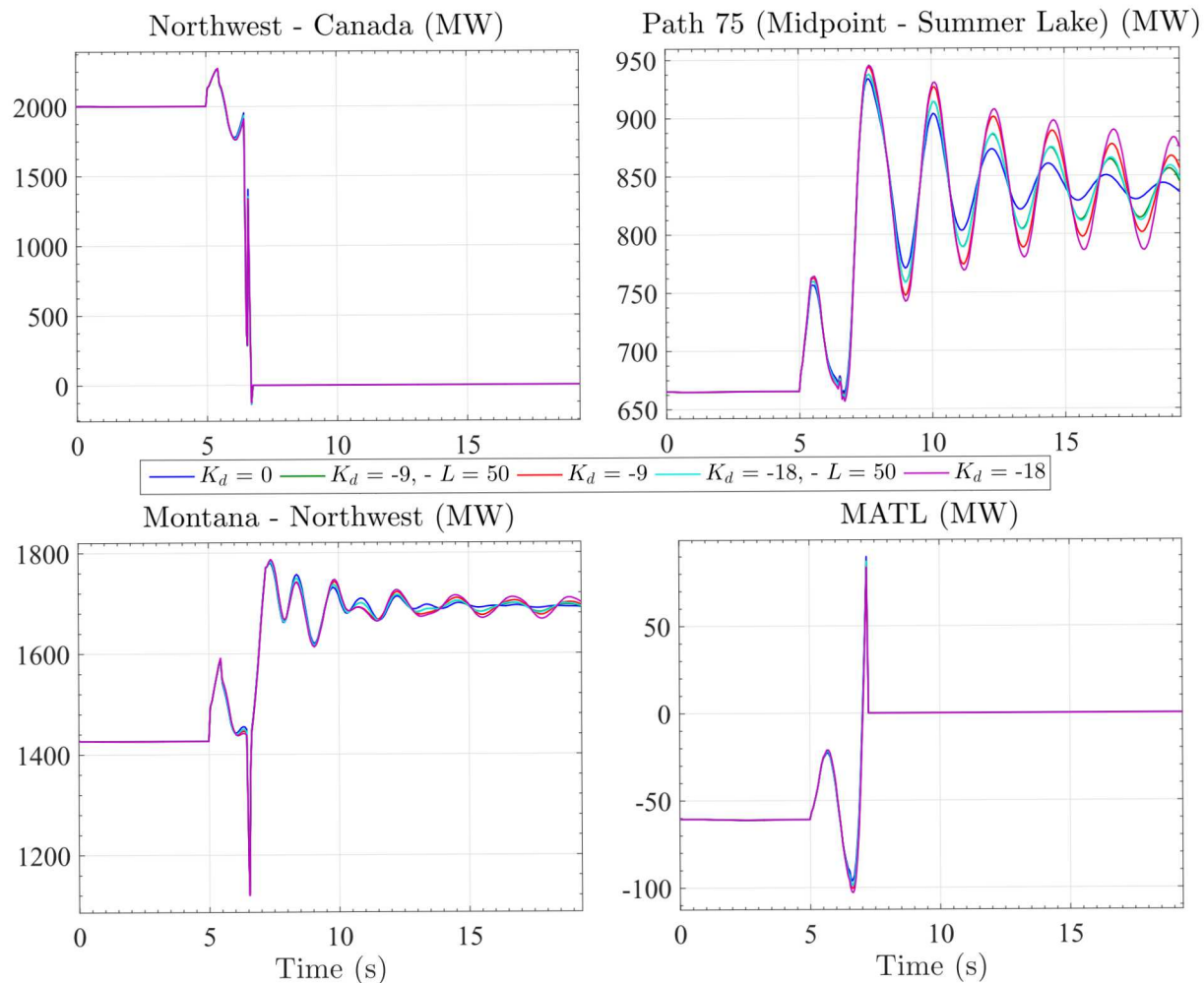


Figure 68. Active power flows. Event: CJB + BCUS Separation

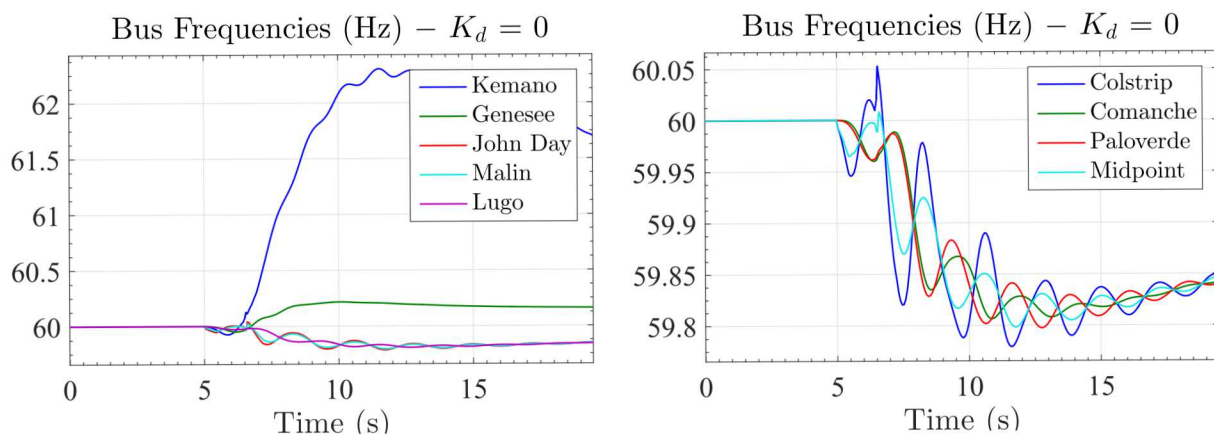


Figure 69. Bus frequencies. Event: CJB + BCUS Separation

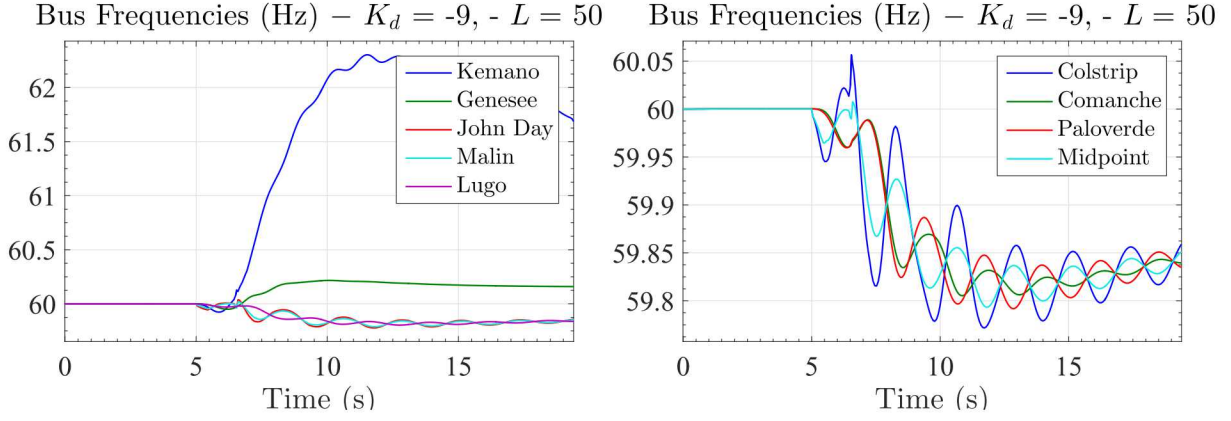


Figure 70. Bus frequencies. Event: CJB + BCUS Separation

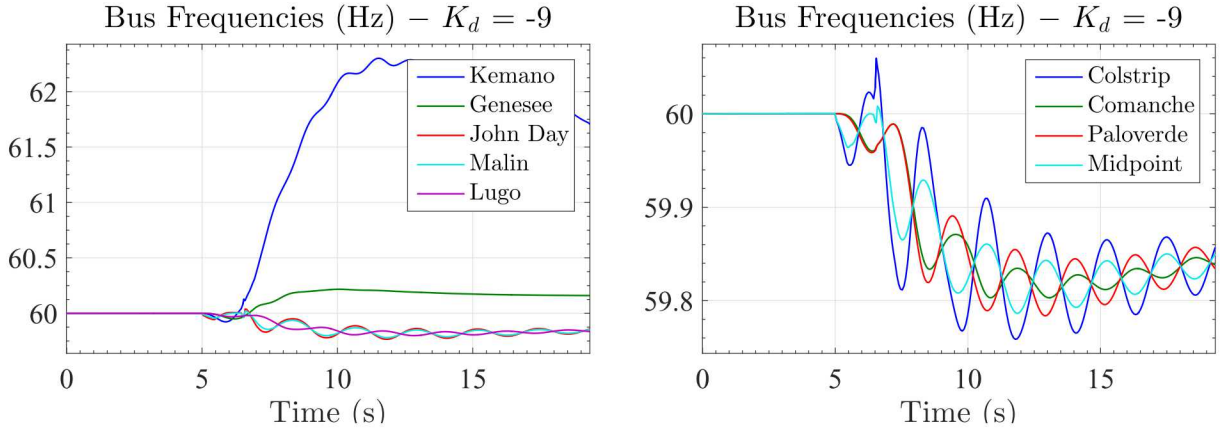


Figure 71. Bus frequencies. Event: CJB + BCUS Separation

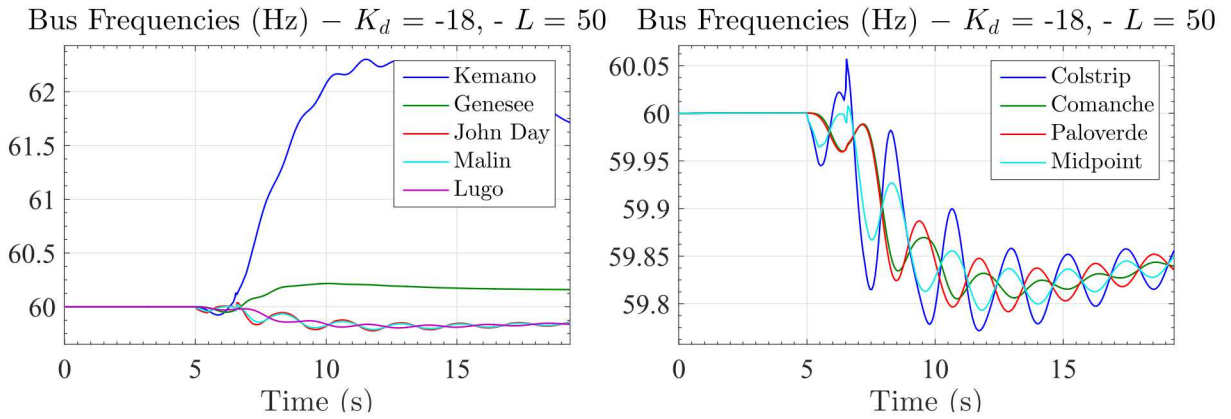


Figure 72. Bus frequencies. Event: CJB + BCUS Separation

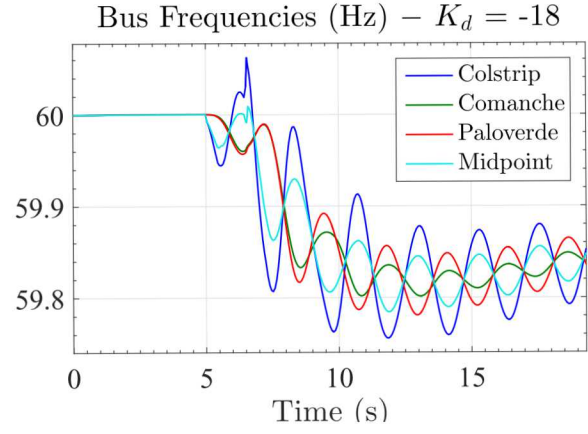
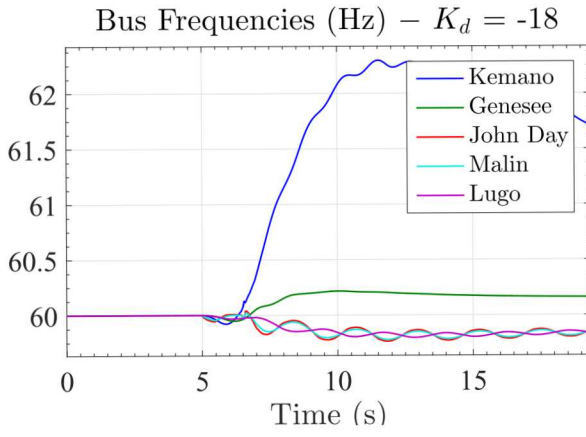


Figure 73. Bus frequencies. Event: CJB + BCUS Separation

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

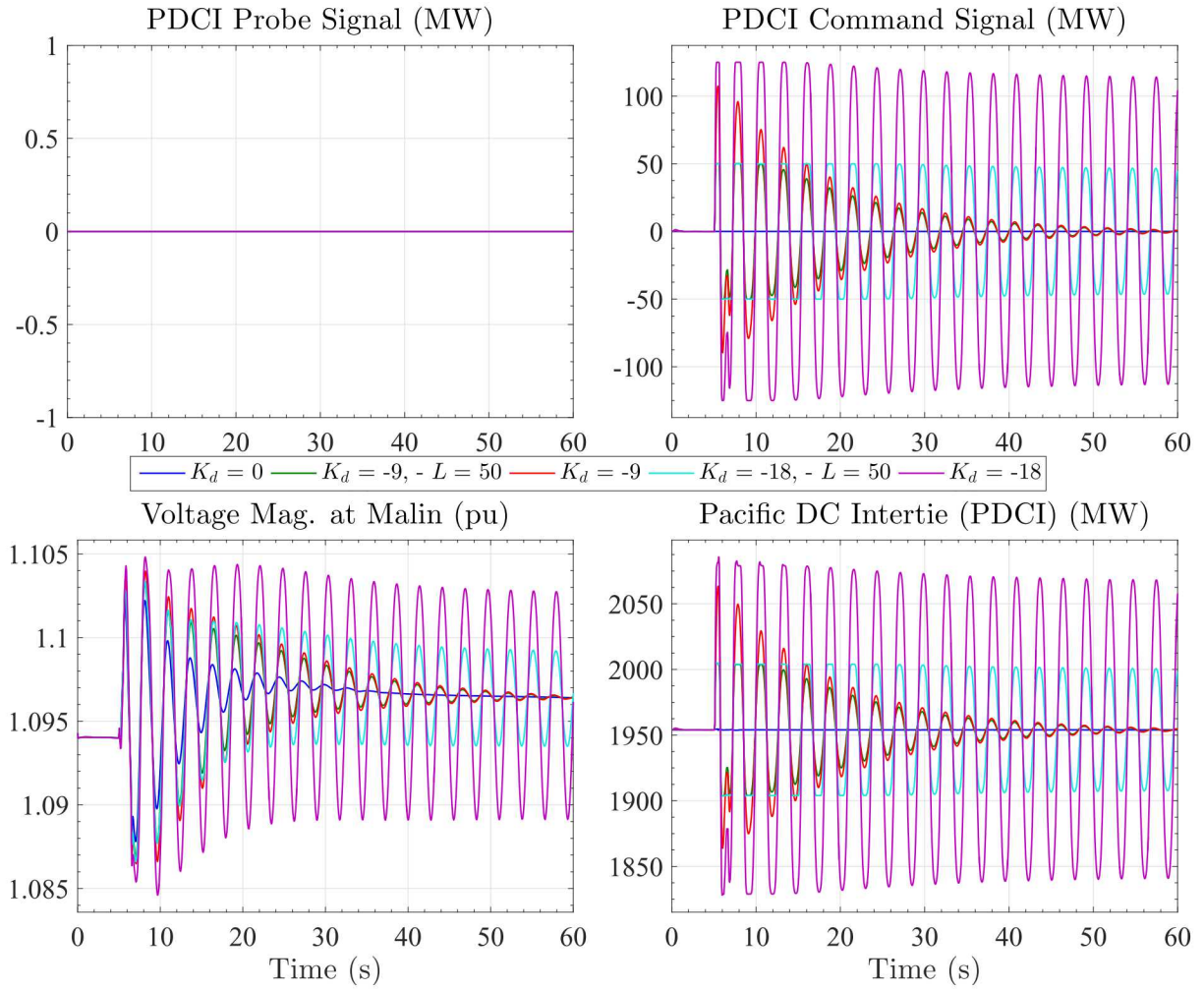


Figure 74. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCAB Separation

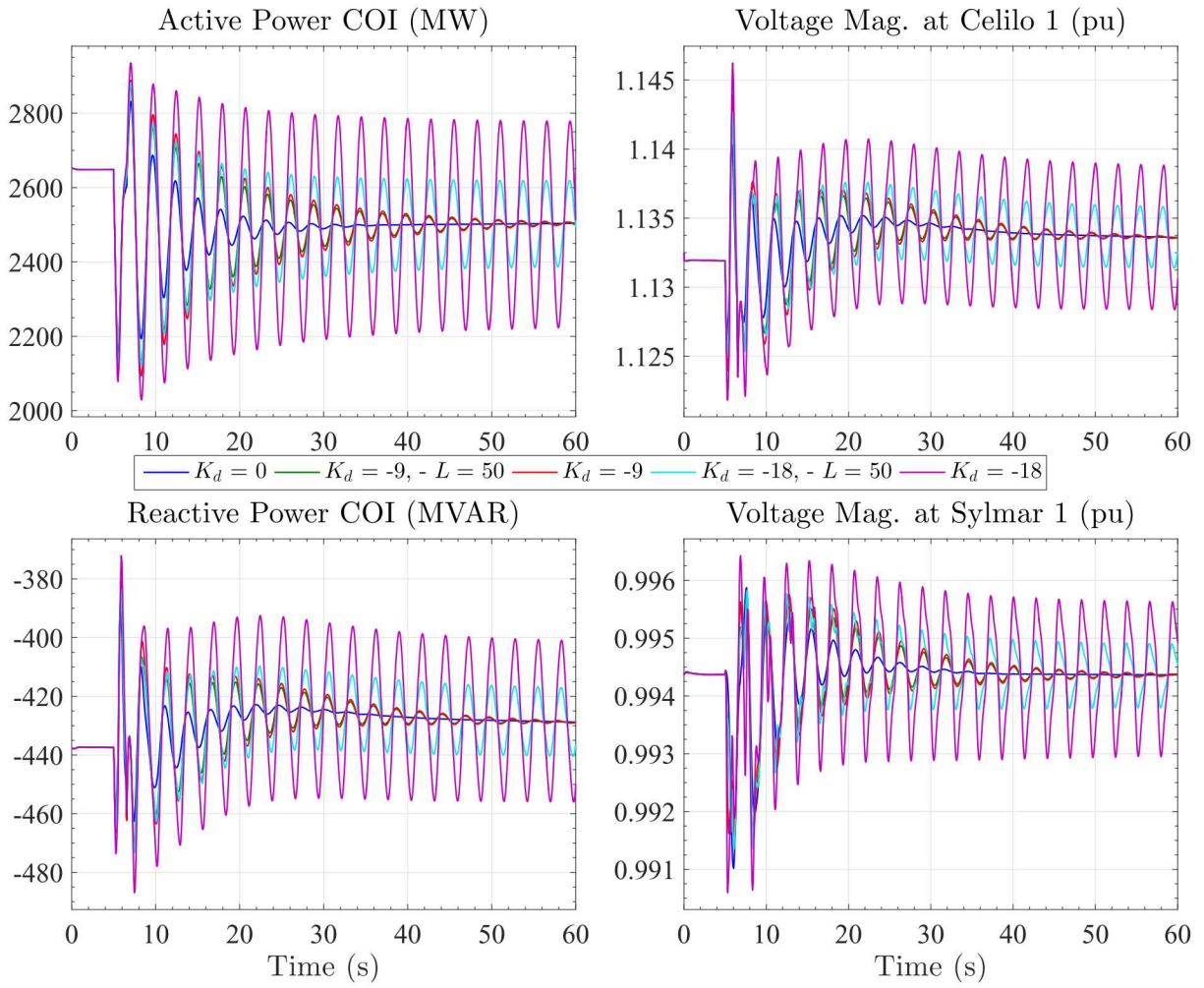


Figure 75. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCAB Separation

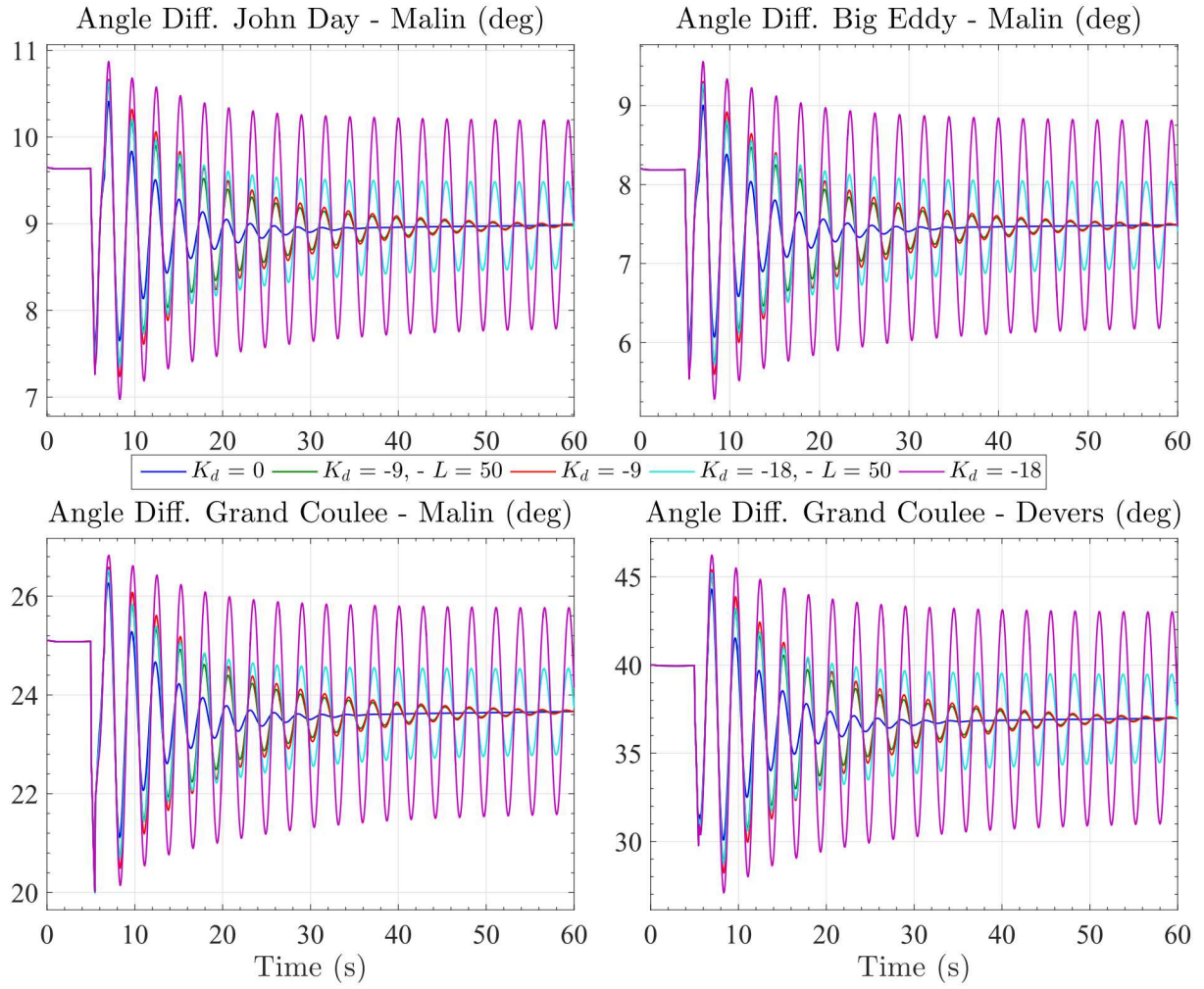


Figure 76. Angle differences. Event: CJB + BCAB Separation

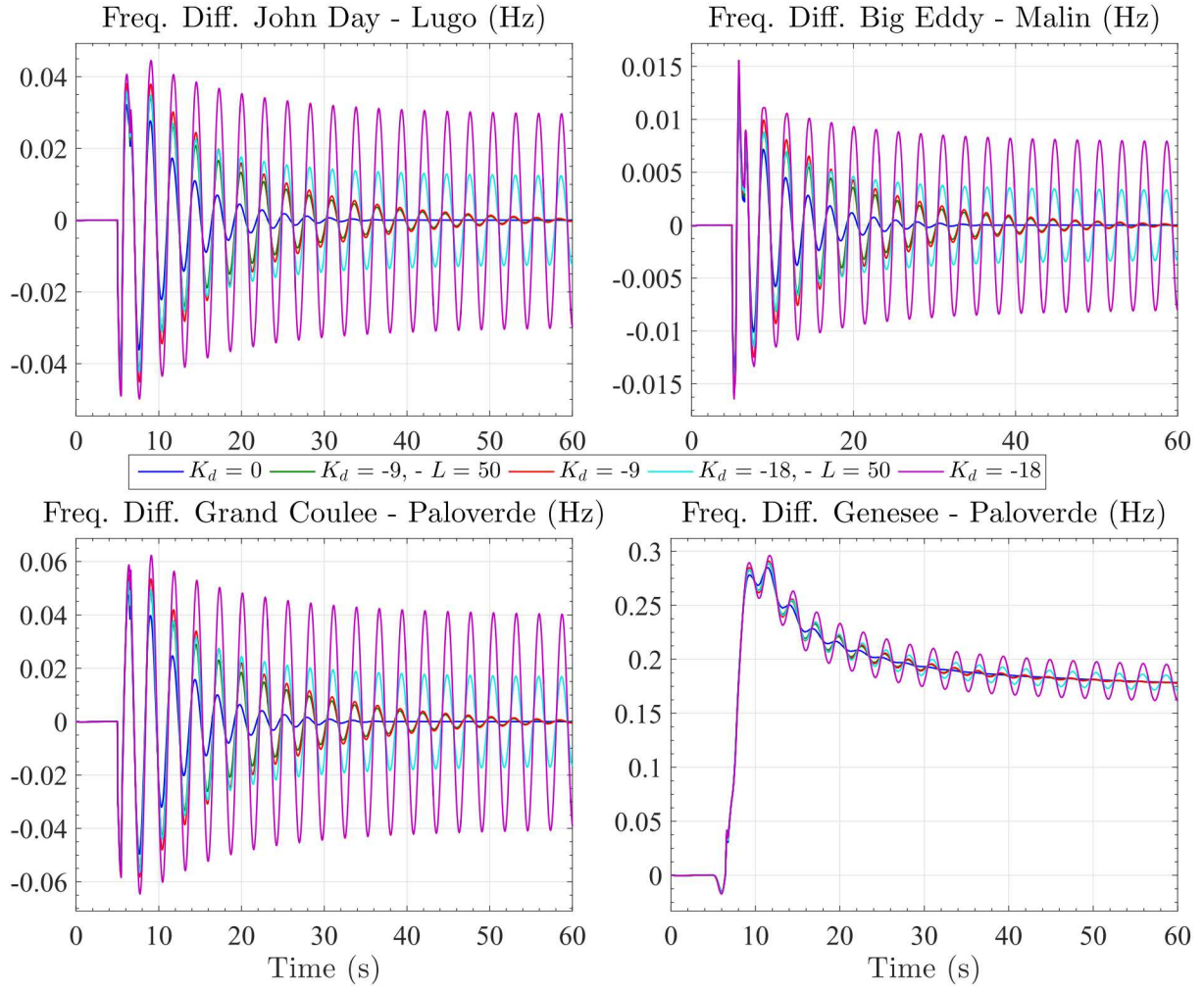


Figure 77. Frequency differences. Event: CJB + BCAB Separation

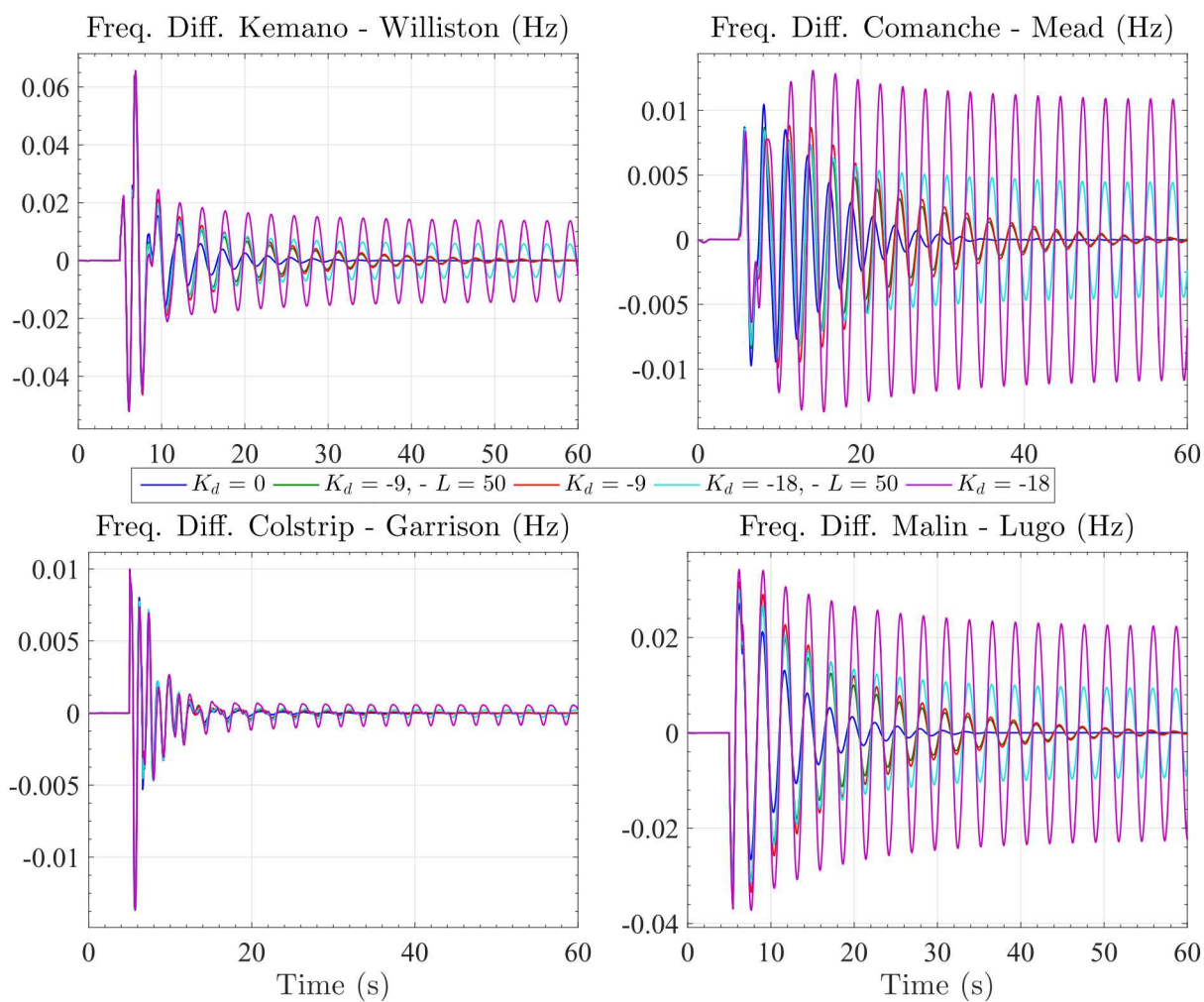


Figure 78. Frequency differences. Event: CJB + BCAB Separation

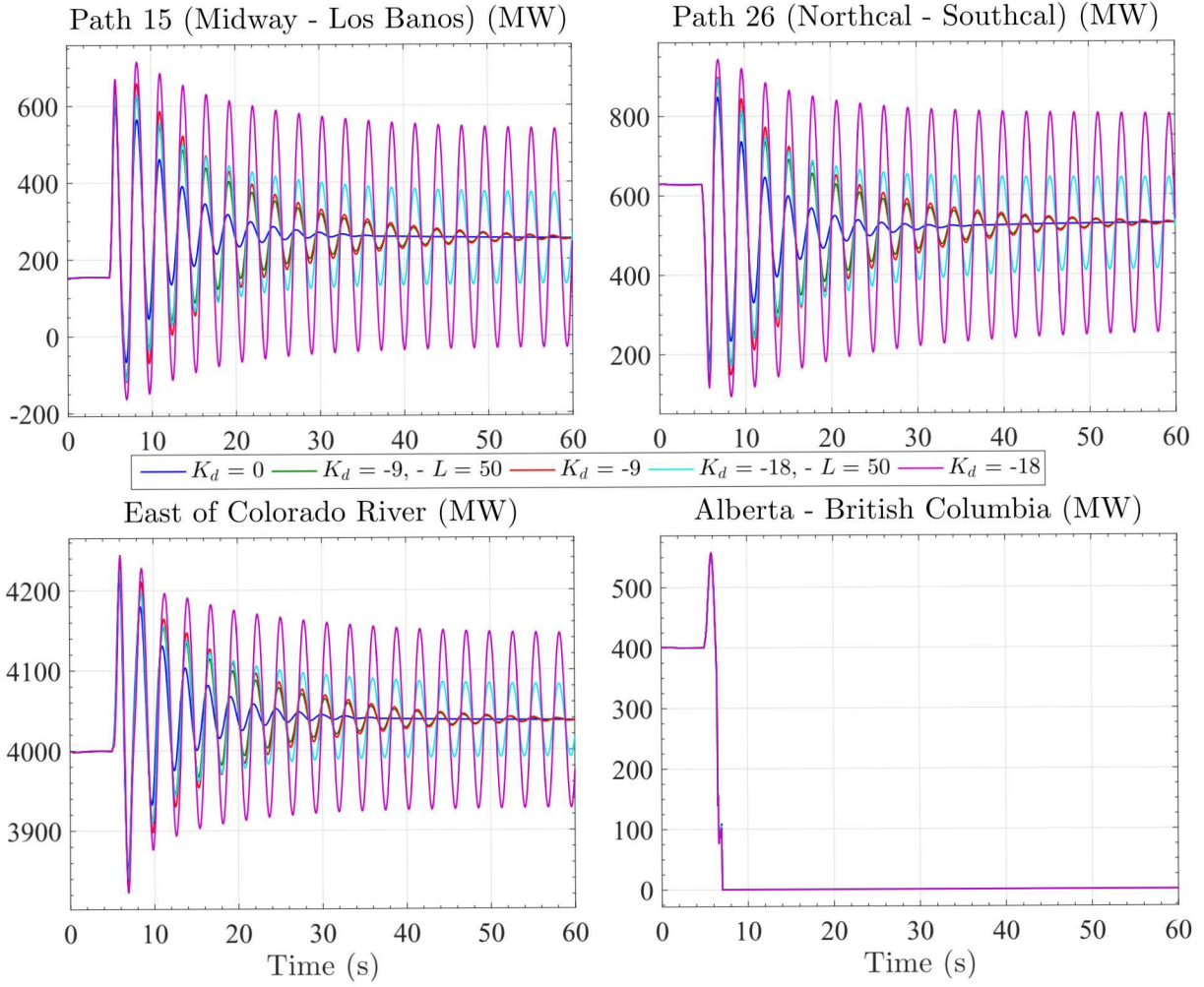


Figure 79. Active power flows. Event: CJB + BCAB Separation

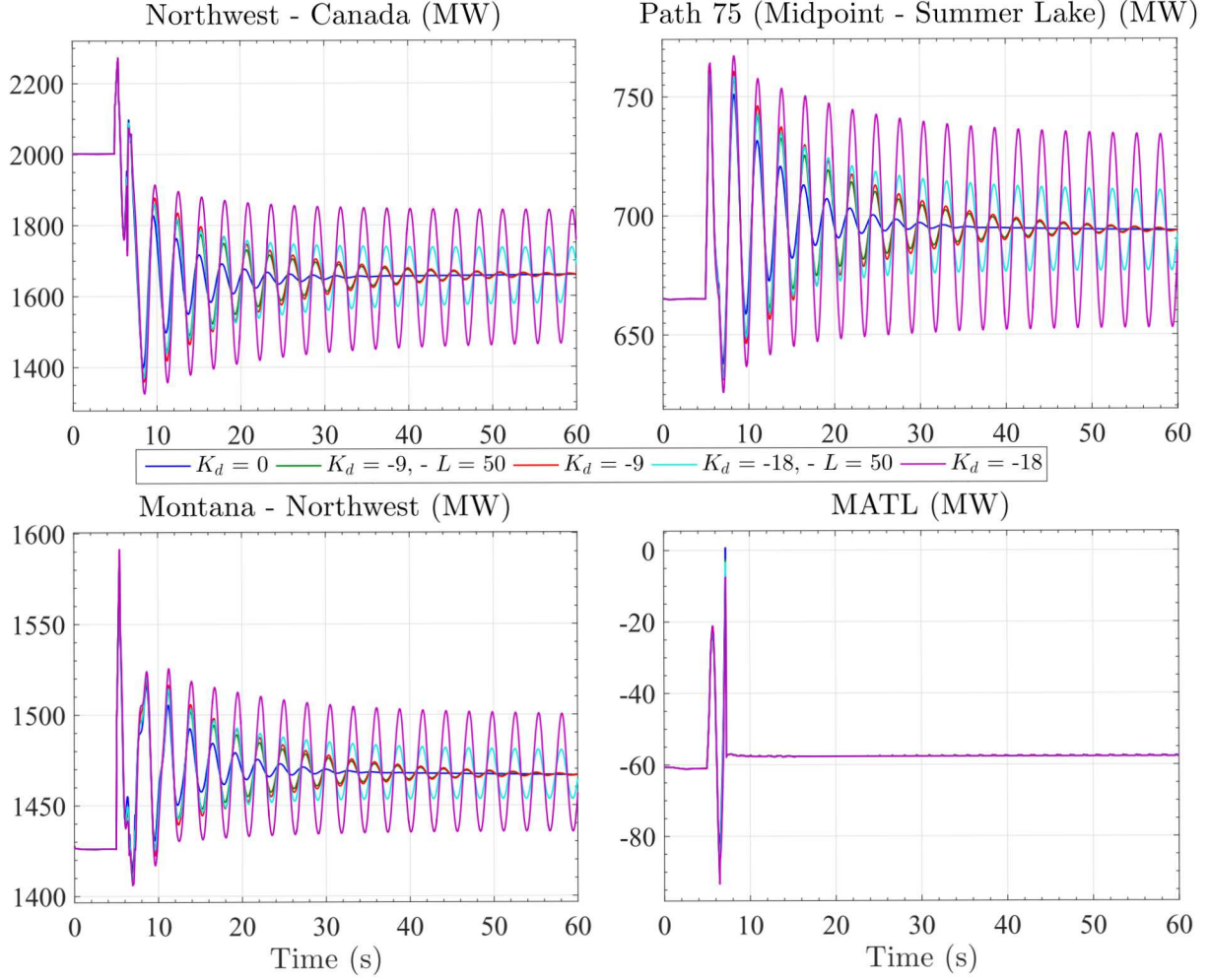


Figure 80. Active power flows. Event: CJB + BCAB Separation

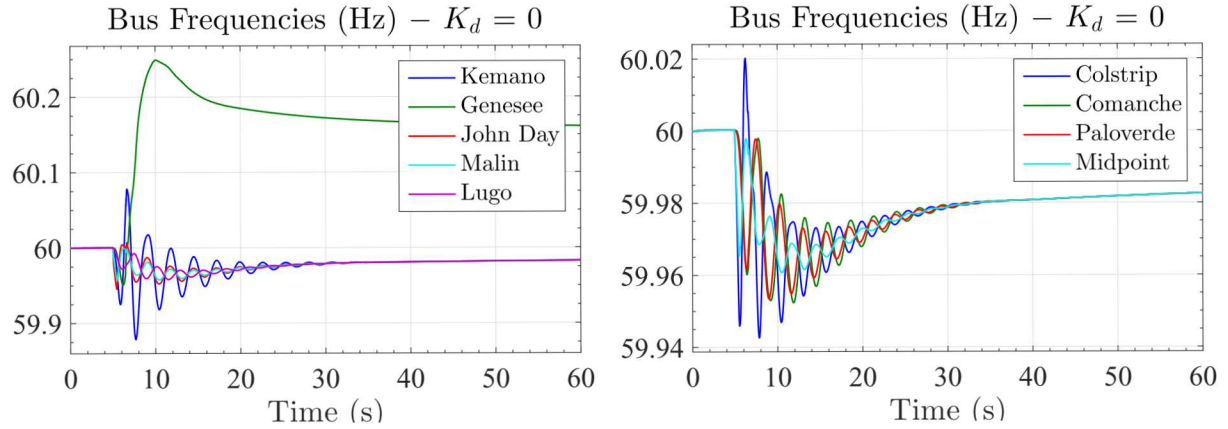


Figure 81. Bus frequencies. Event: CJB + BCAB Separation

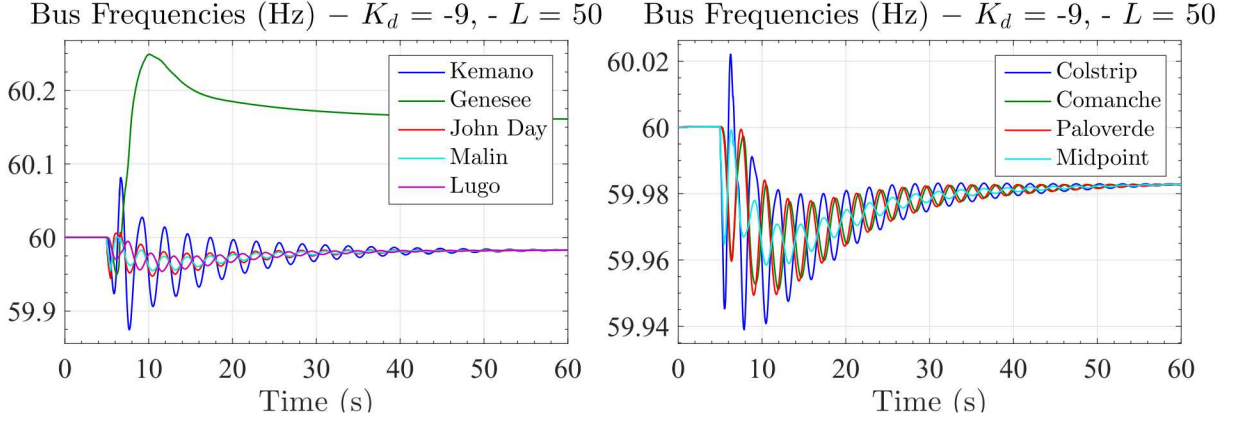


Figure 82. Bus frequencies. Event: CJB + BCAB Separation

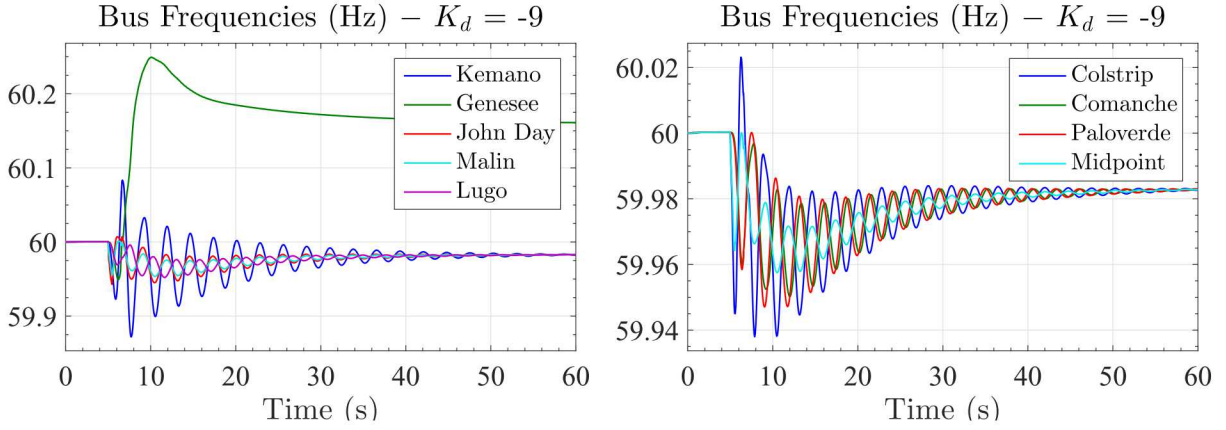


Figure 83. Bus frequencies. Event: CJB + BCAB Separation

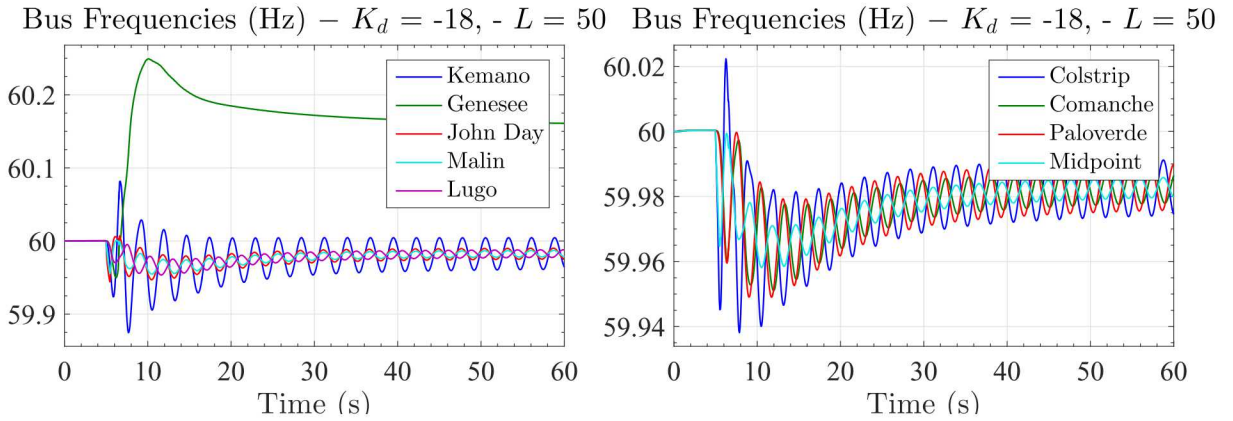


Figure 84. Bus frequencies. Event: CJB + BCAB Separation

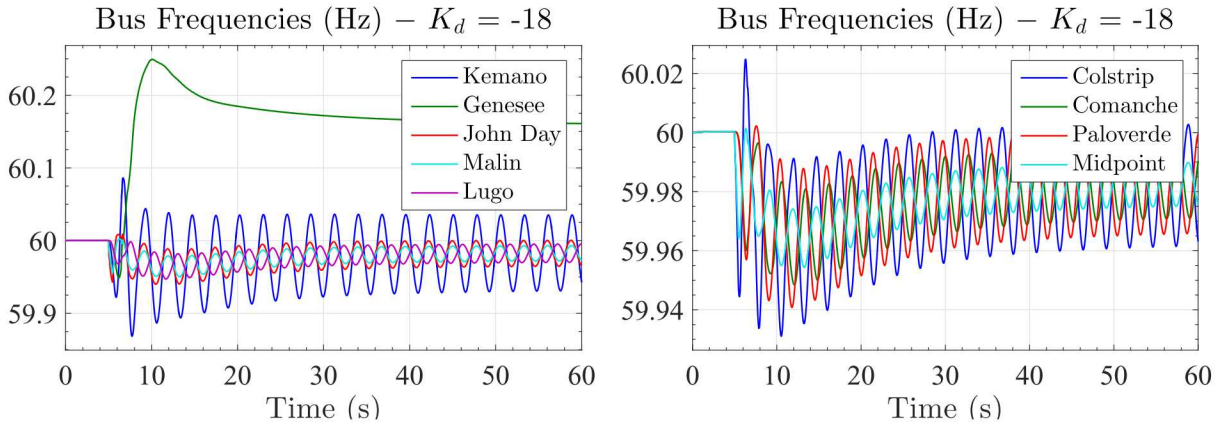


Figure 85. Bus frequencies. Event: CJB + BCAB Separation

3. CONTROLLER LIMITS (HIGHER GAINS)

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

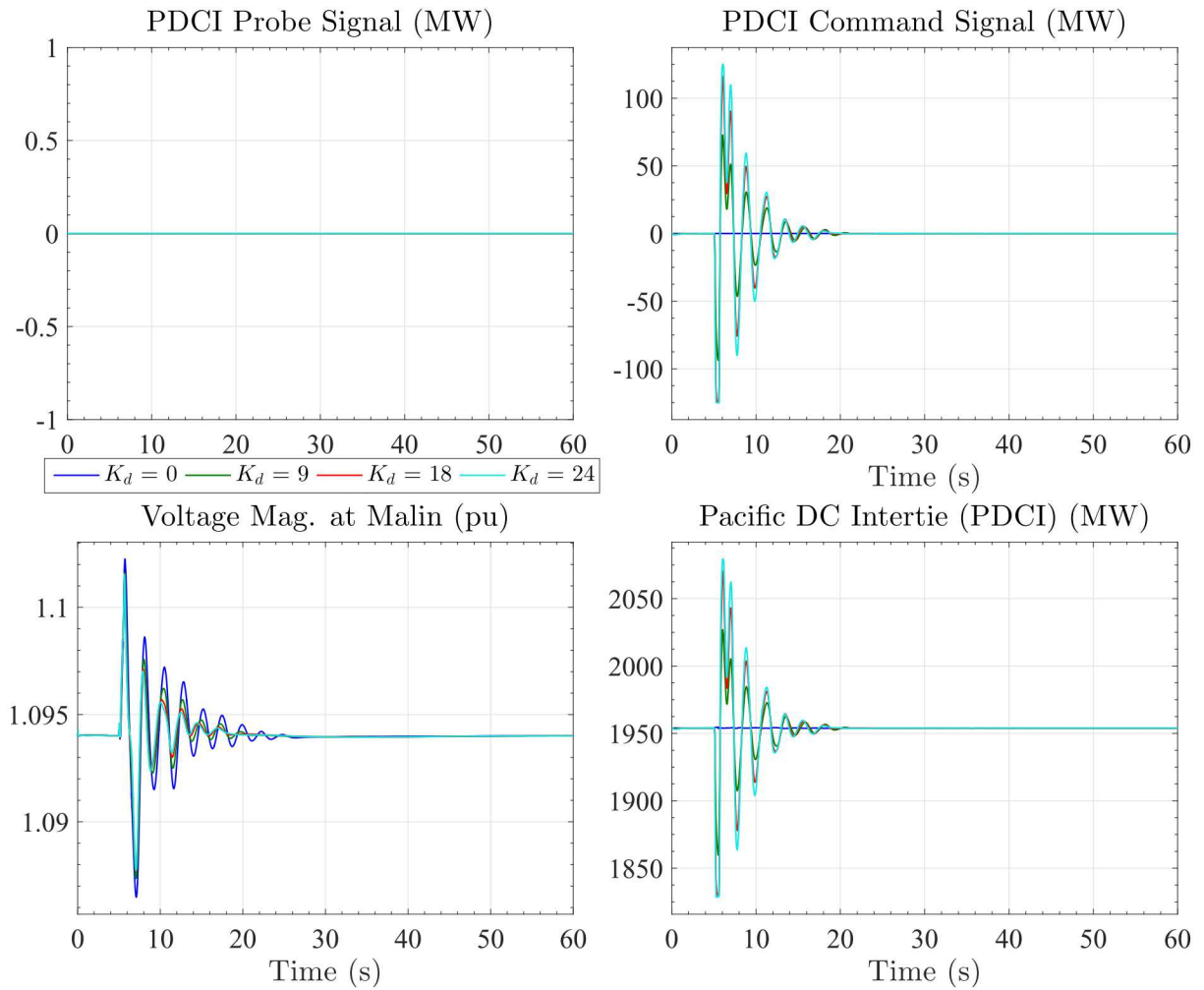


Figure 86. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joe Brake

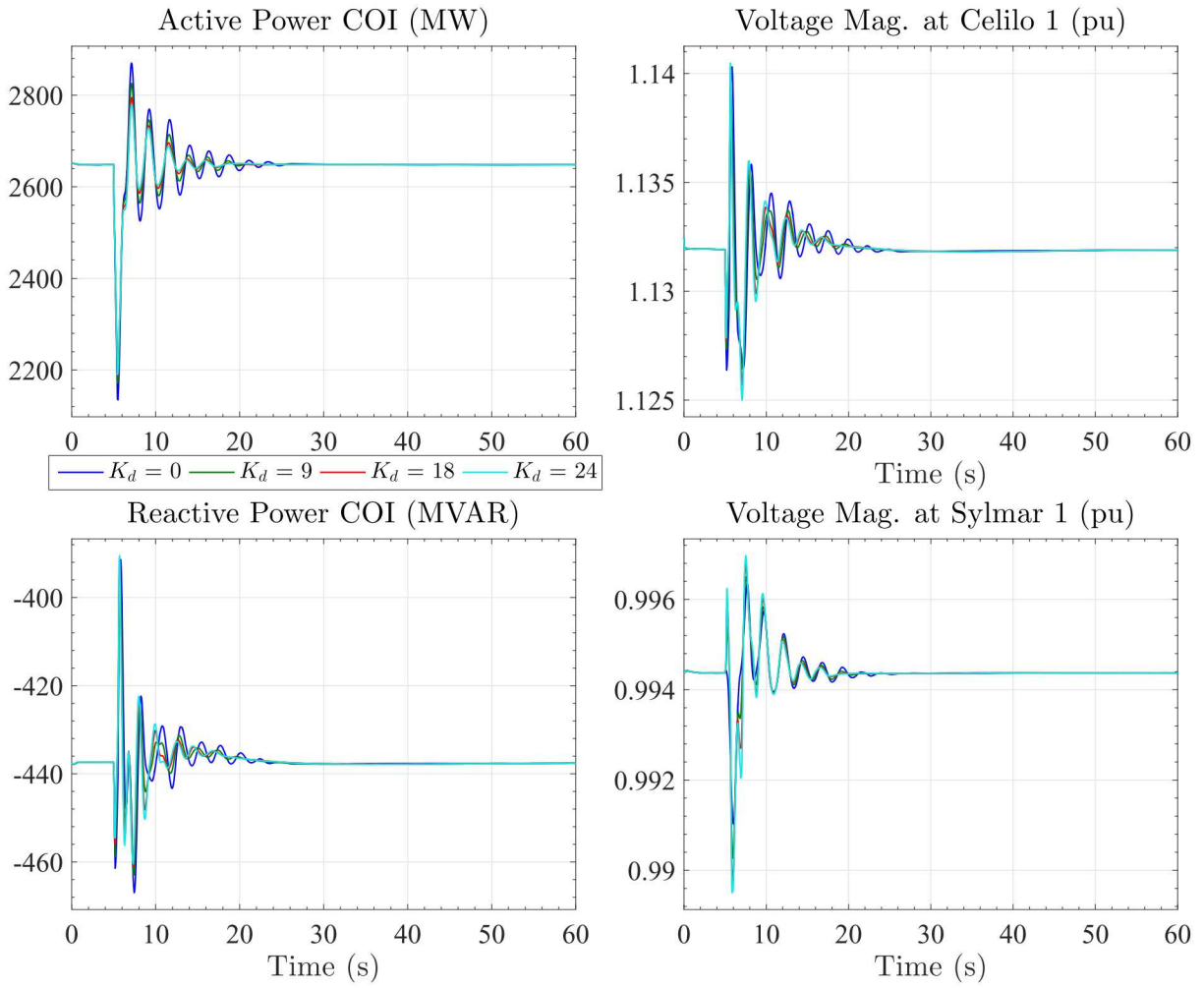


Figure 87. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joe Brake

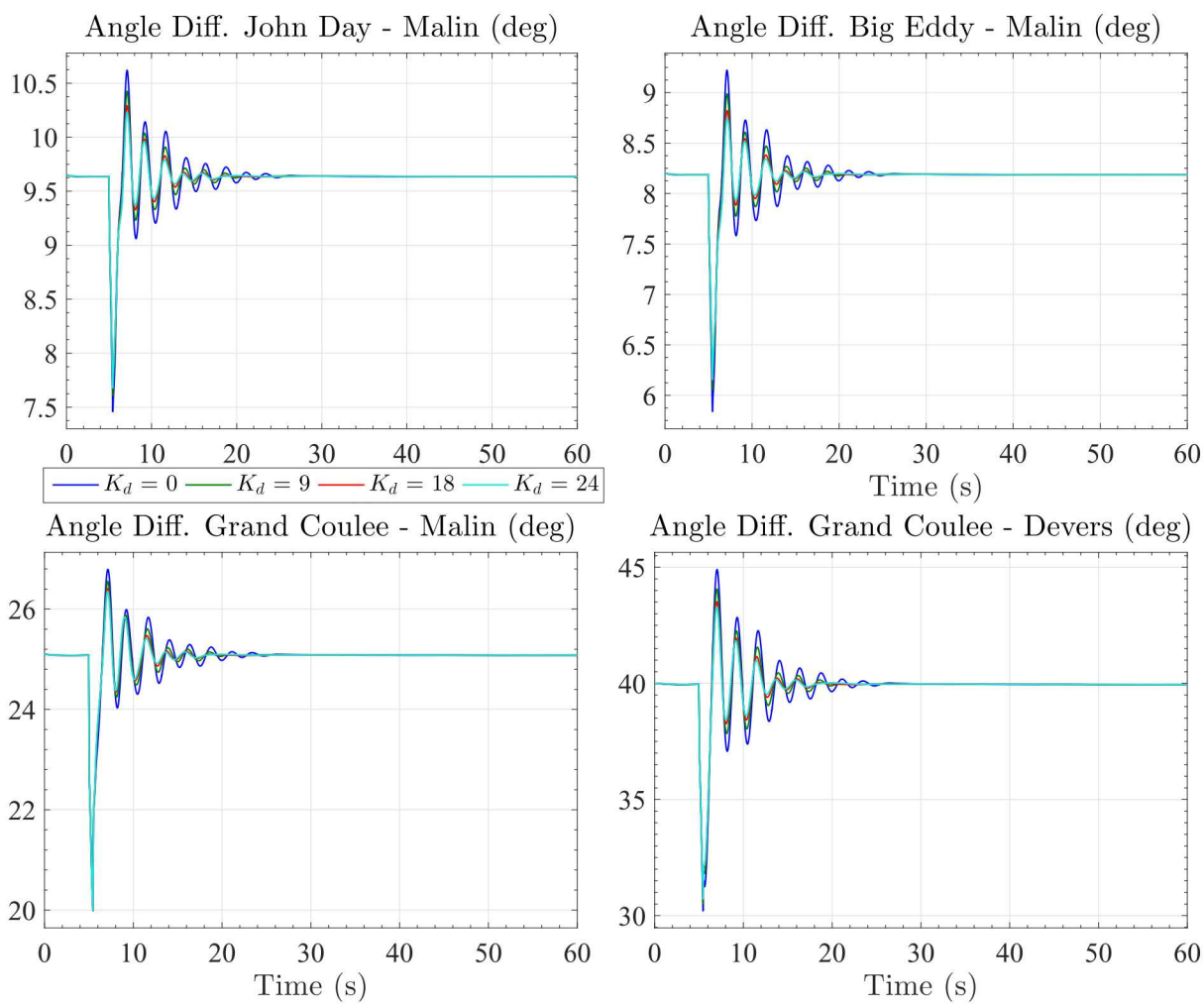


Figure 88. Angle differences. Event: Chief Joe Brake

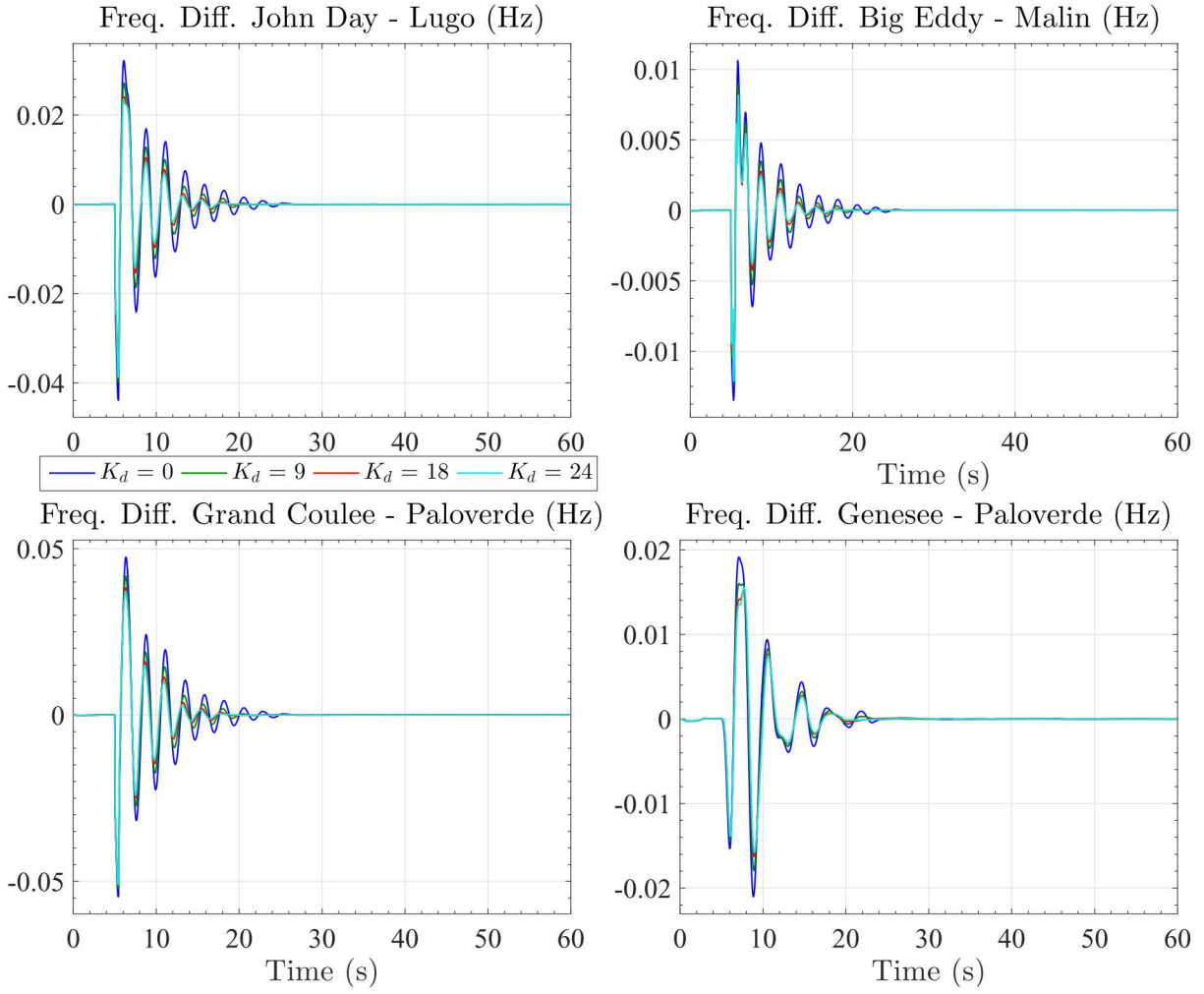


Figure 89. Frequency differences. Event: Chief Joe Brake

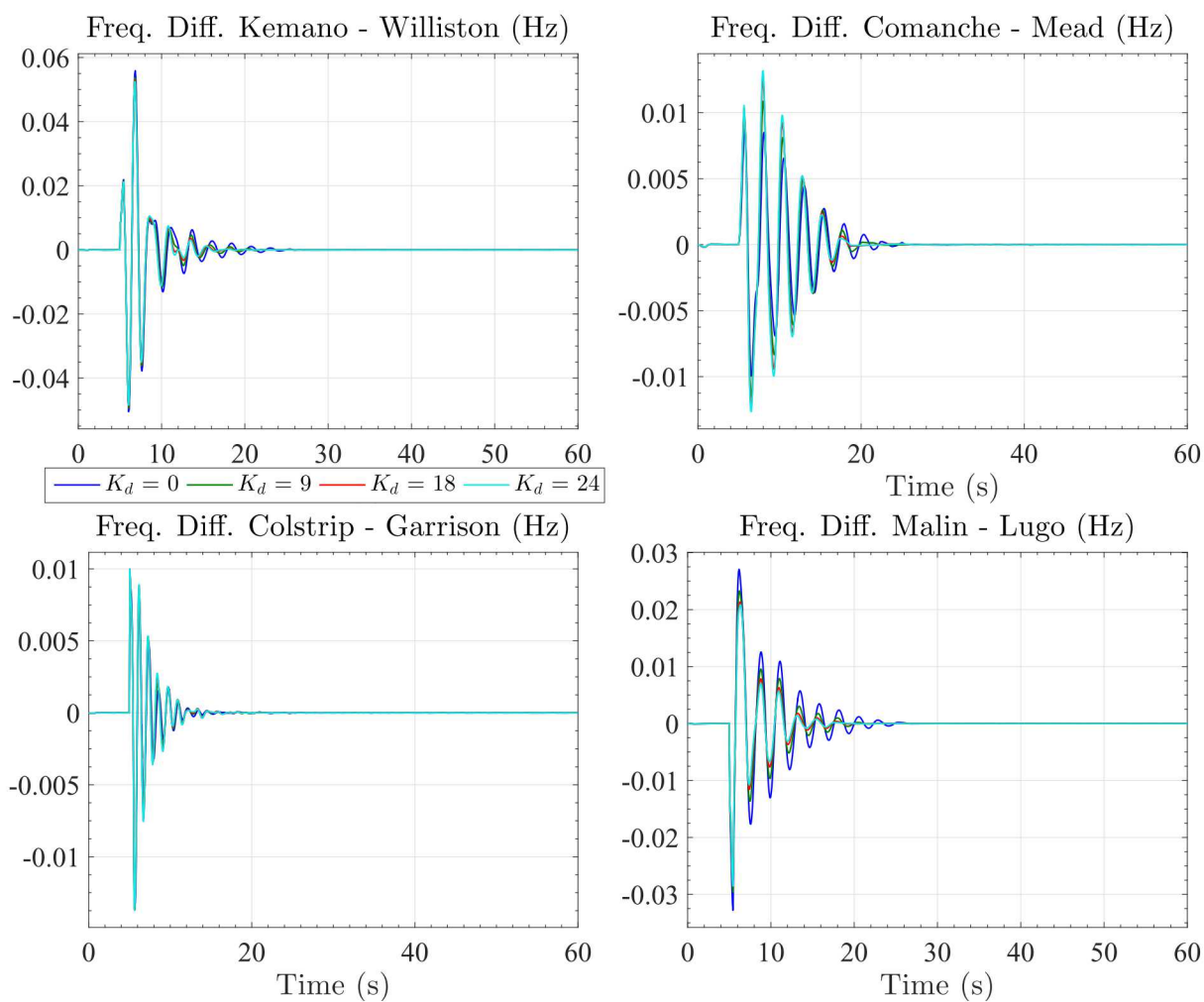


Figure 90. Frequency differences. Event: Chief Joe Brake

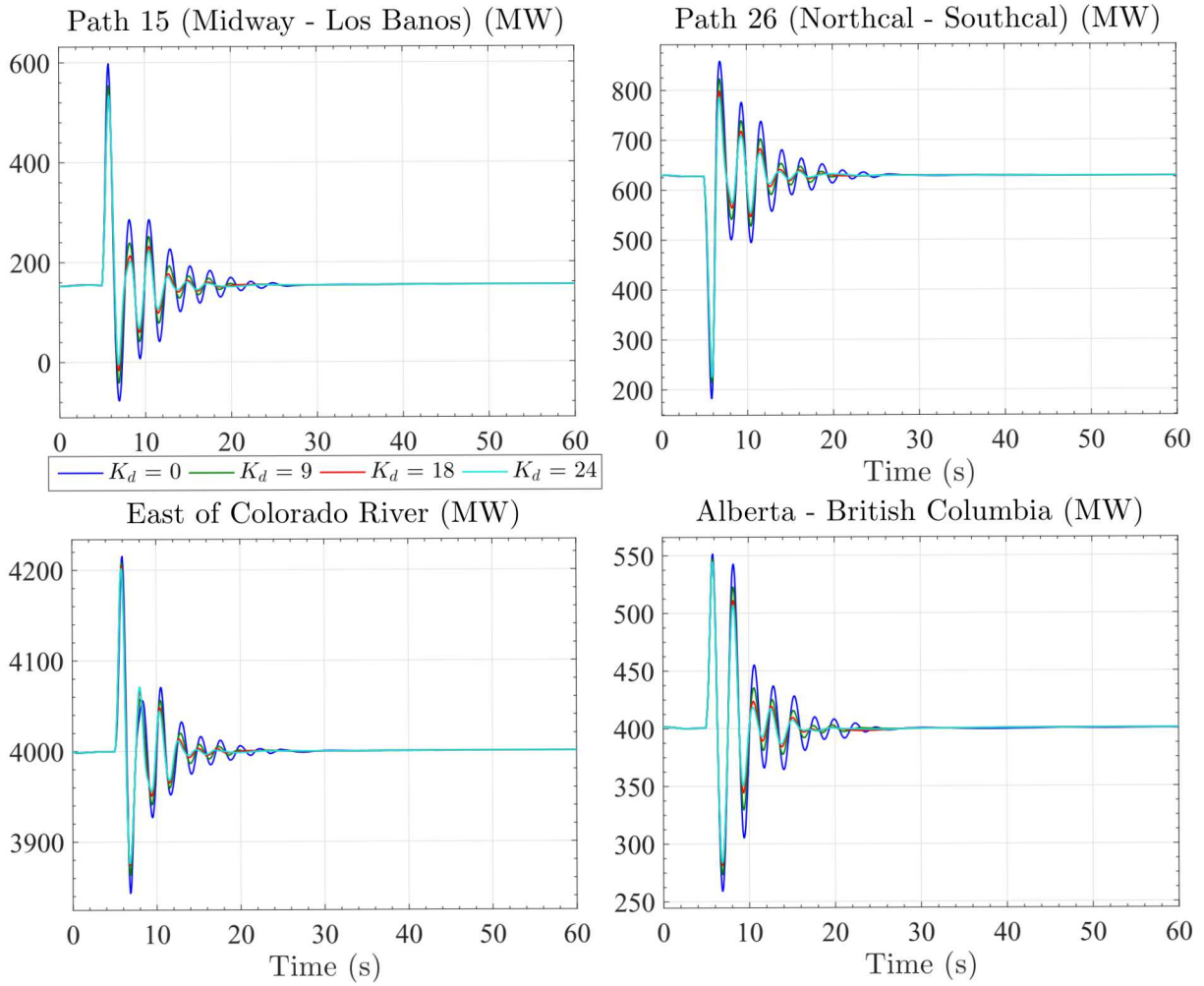


Figure 91. Active power flows. Event: Chief Joe Brake

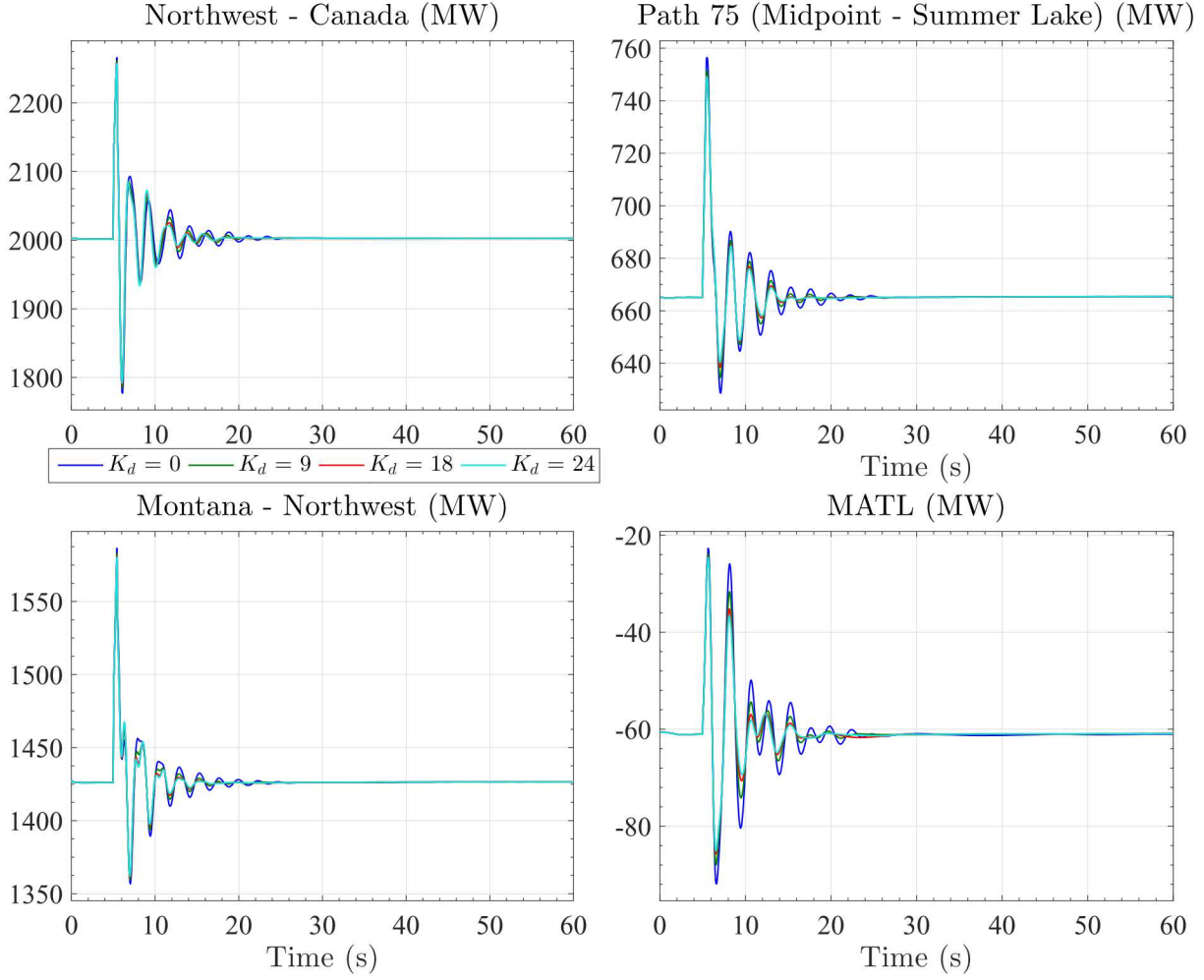


Figure 92. Active power flows. Event: Chief Joe Brake

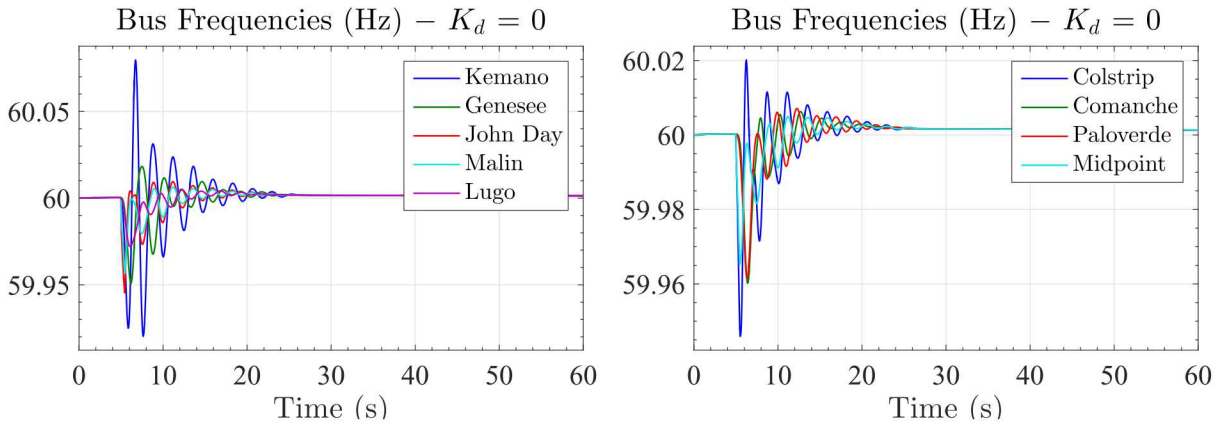


Figure 93. Bus frequencies. Event: Chief Joe Brake

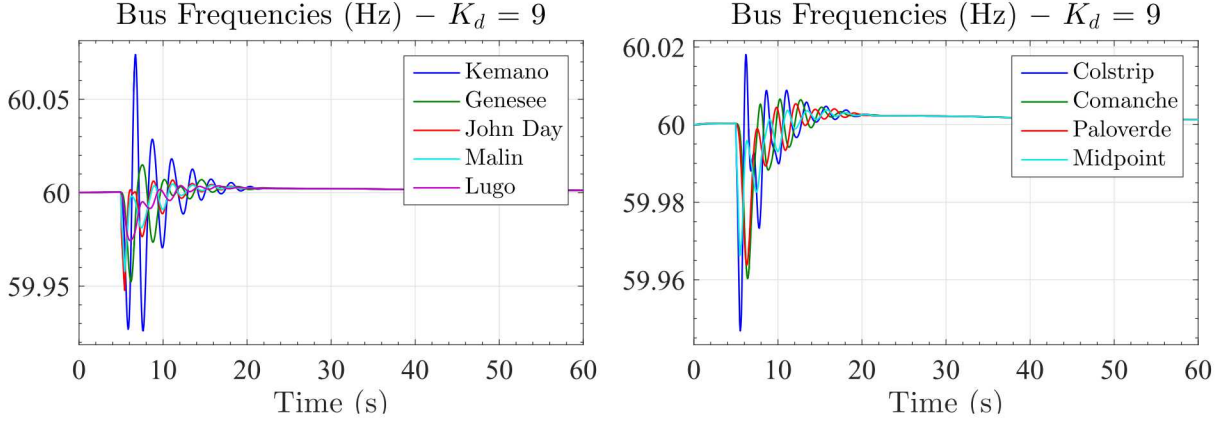


Figure 94. Bus frequencies. Event: Chief Joe Brake

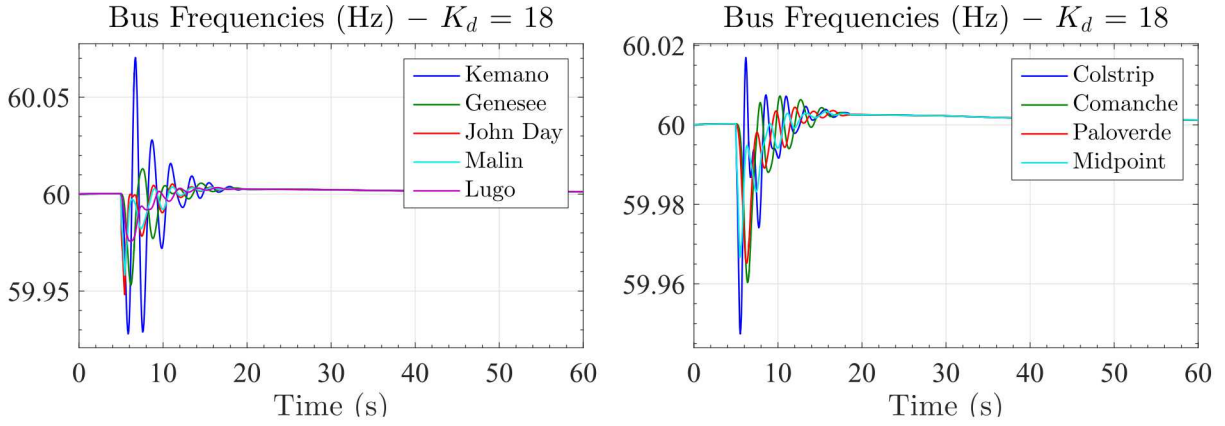


Figure 95. Bus frequencies. Event: Chief Joe Brake

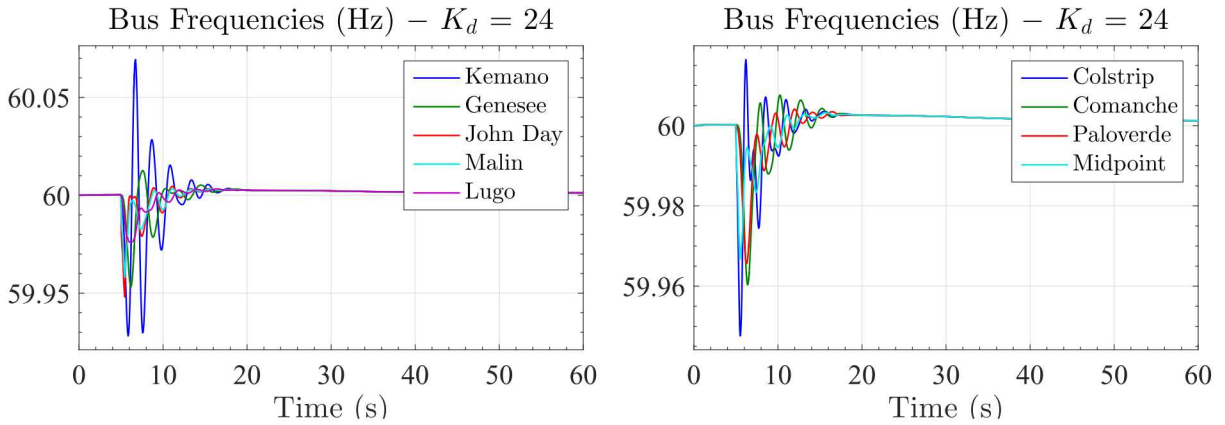


Figure 96. Bus frequencies. Event: Chief Joe Brake

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

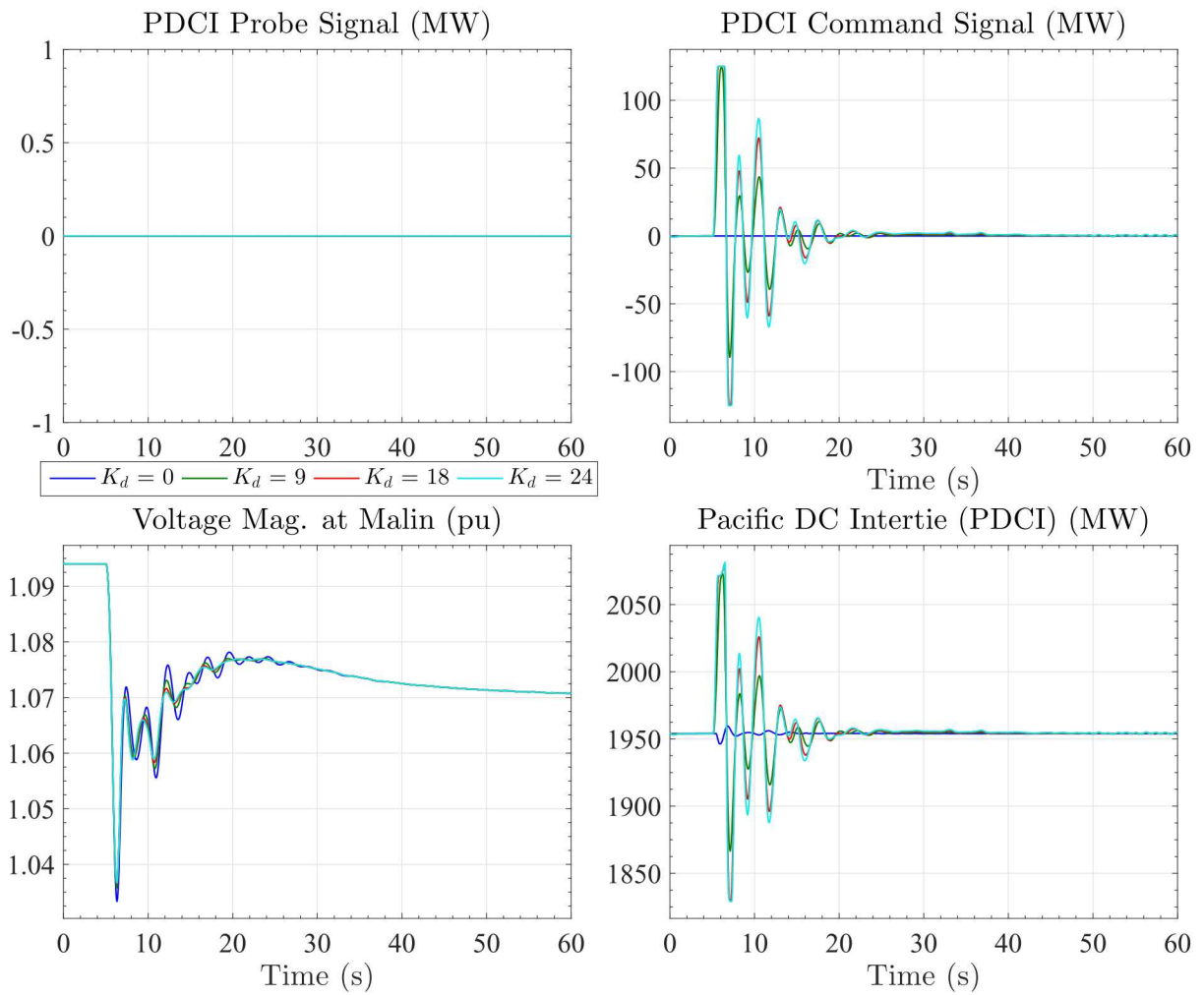


Figure 97. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Double Palo Verde Trip

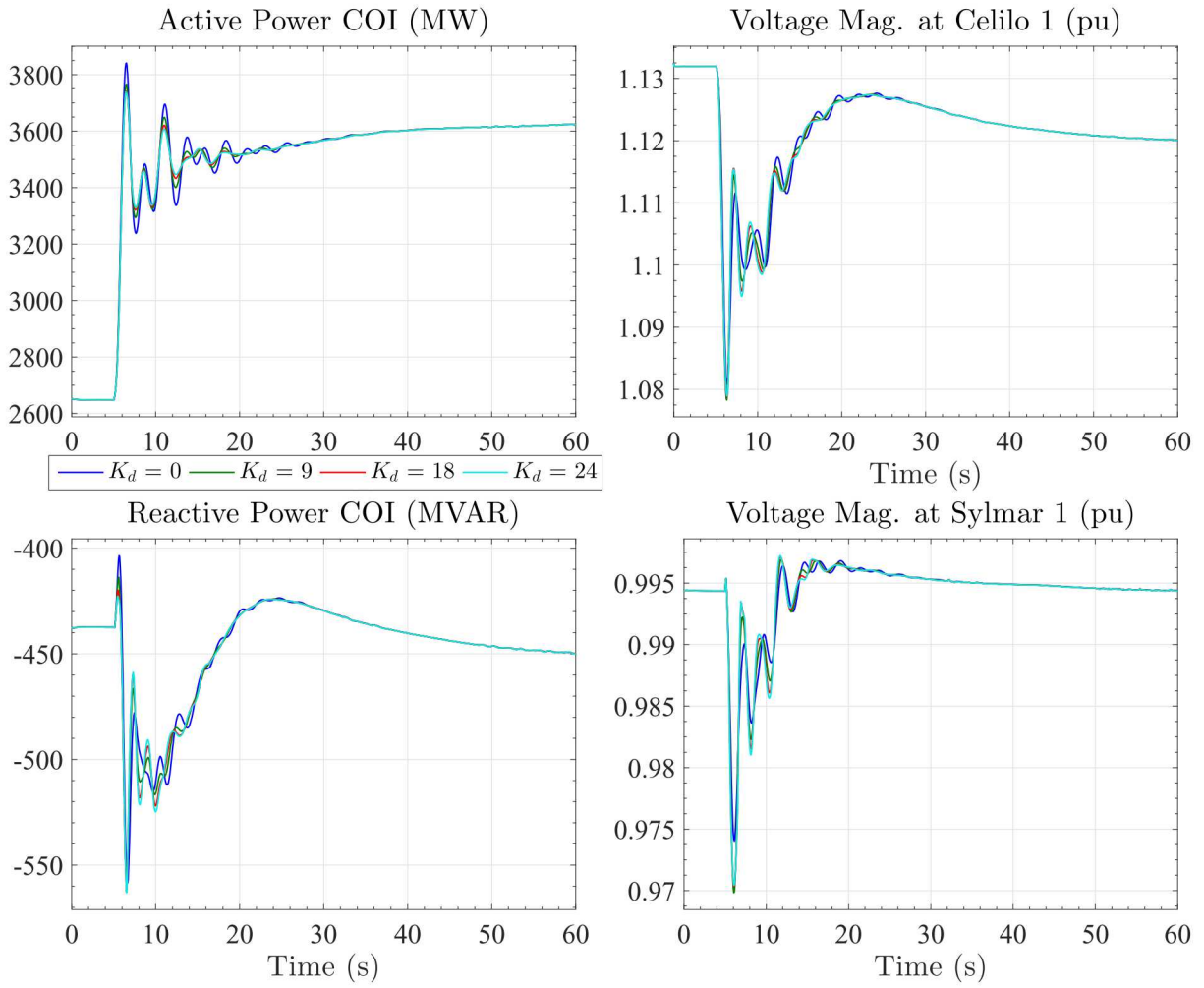


Figure 98. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Double Palo Verde Trip

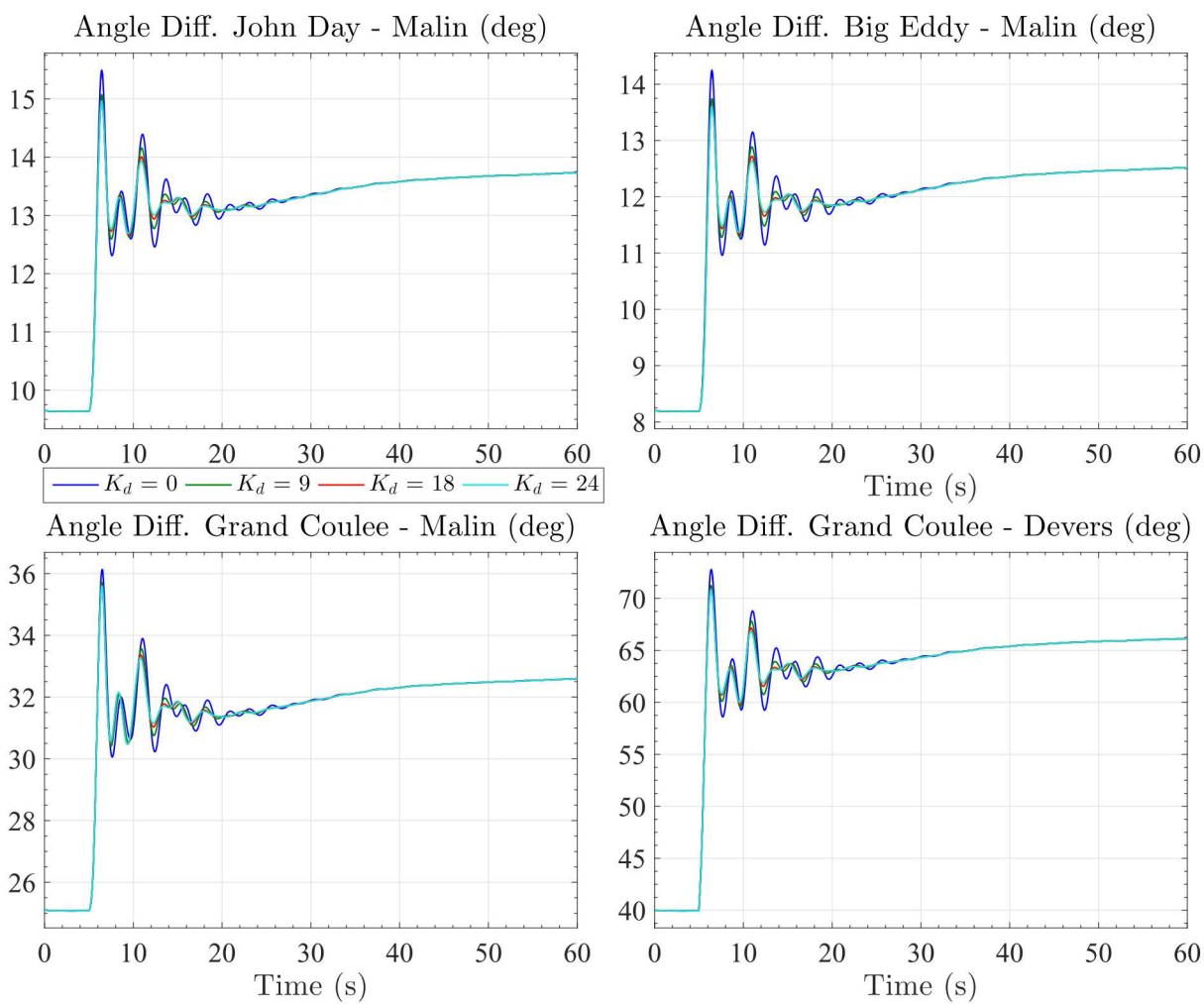


Figure 99. Angle differences. Event: Double Palo Verde Trip

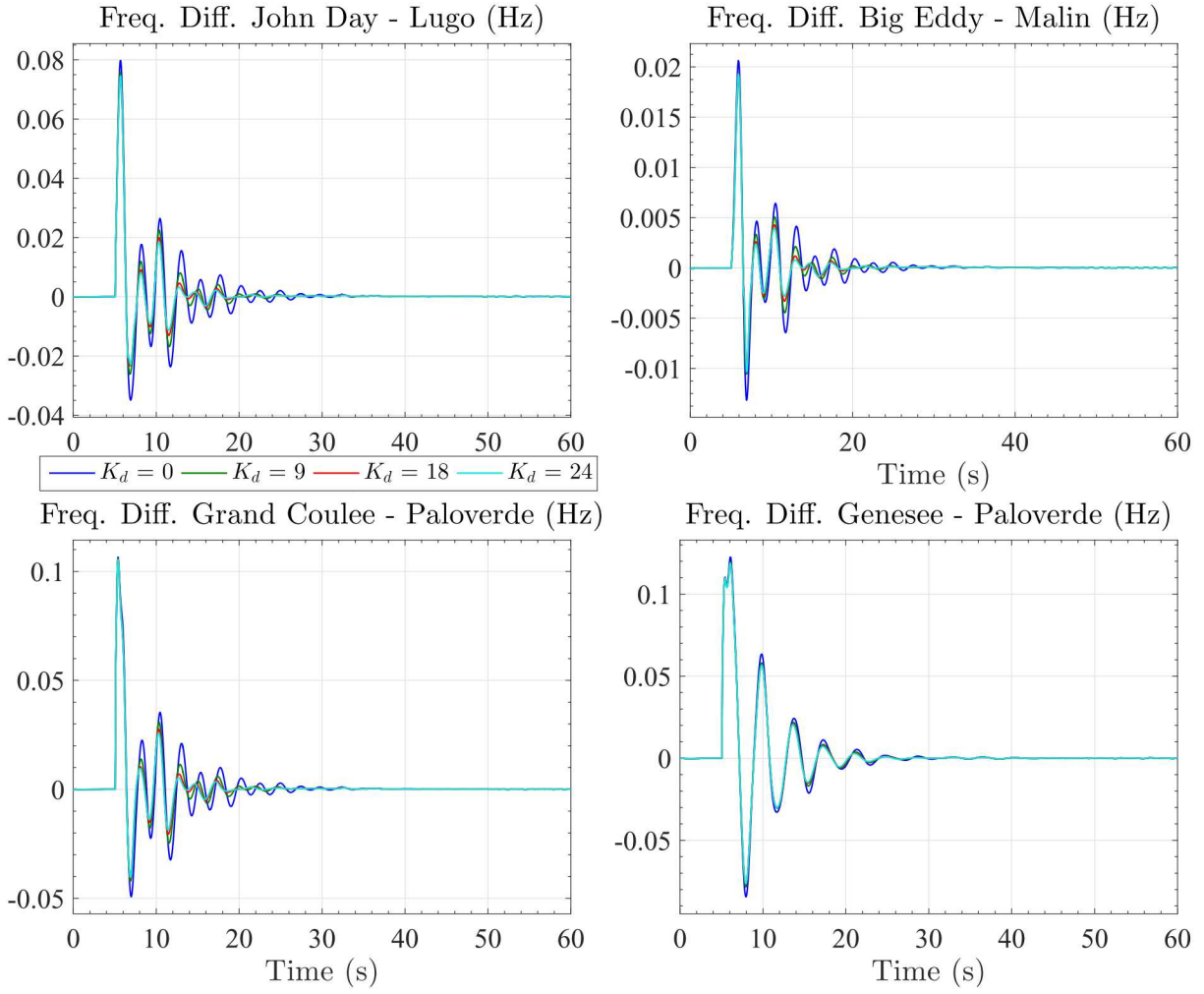


Figure 100. Frequency differences. Event: Double Palo Verde Trip

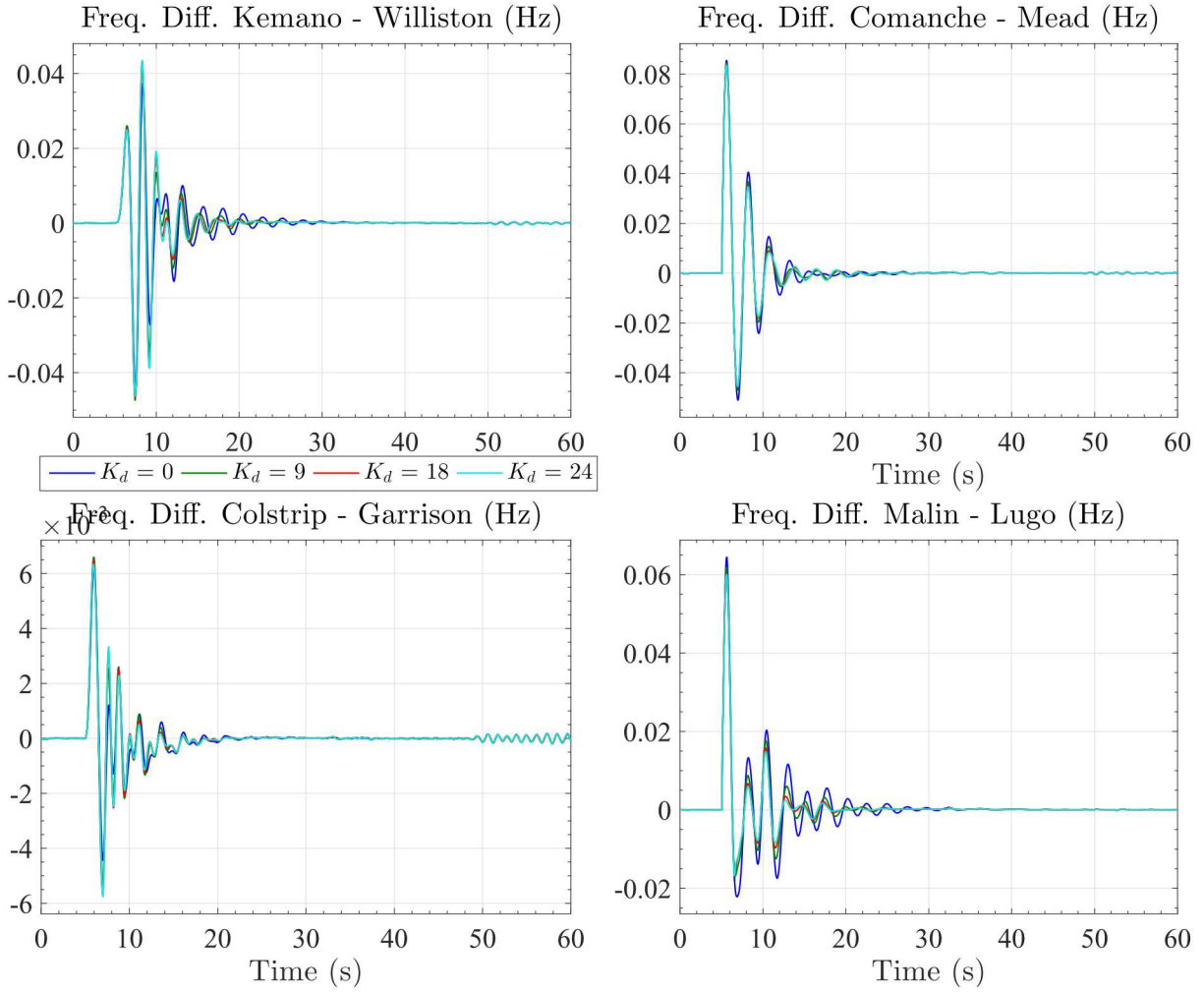


Figure 101. Frequency differences. Event: Double Palo Verde Trip

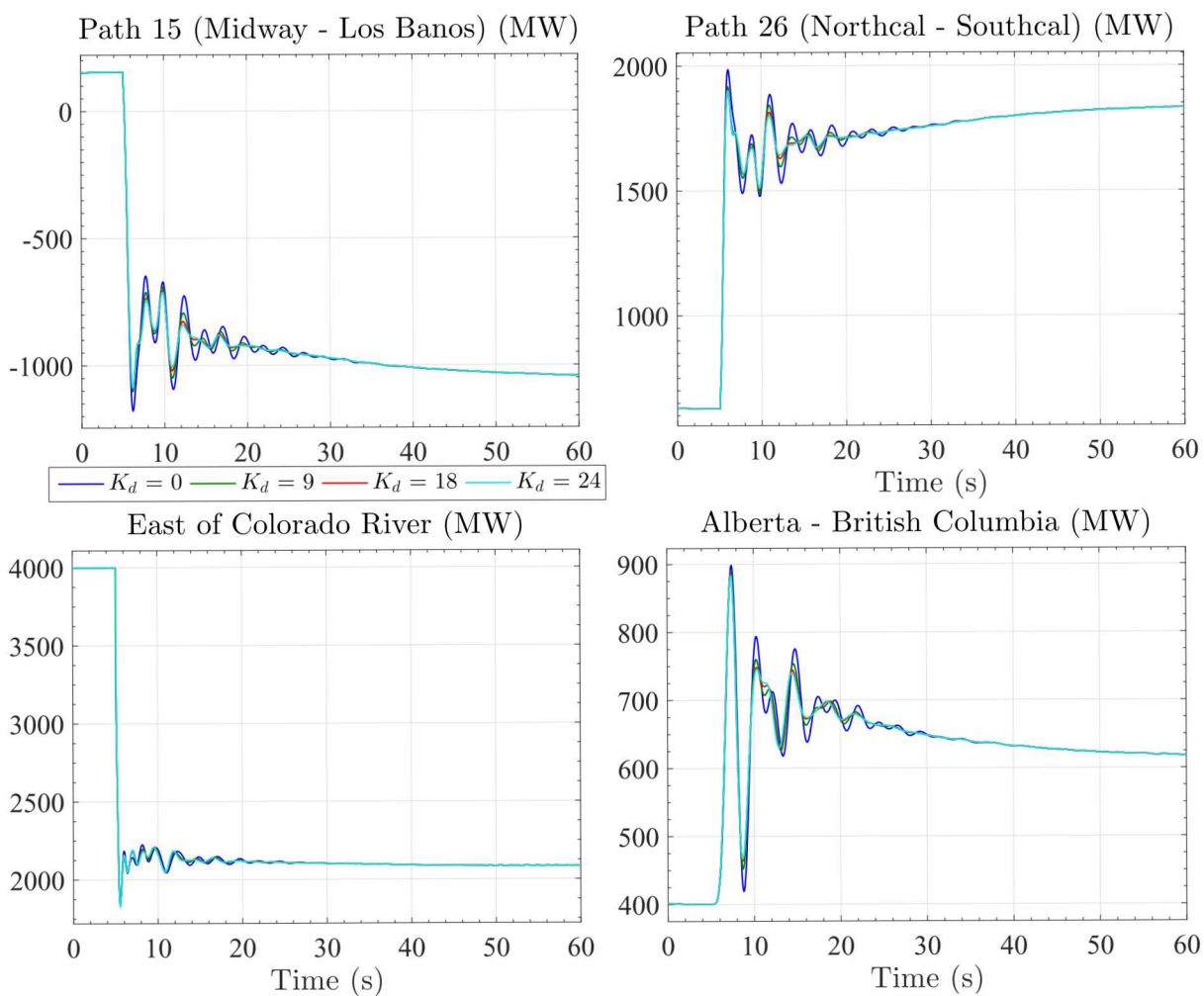


Figure 102. Active power flows. Event: Double Palo Verde Trip

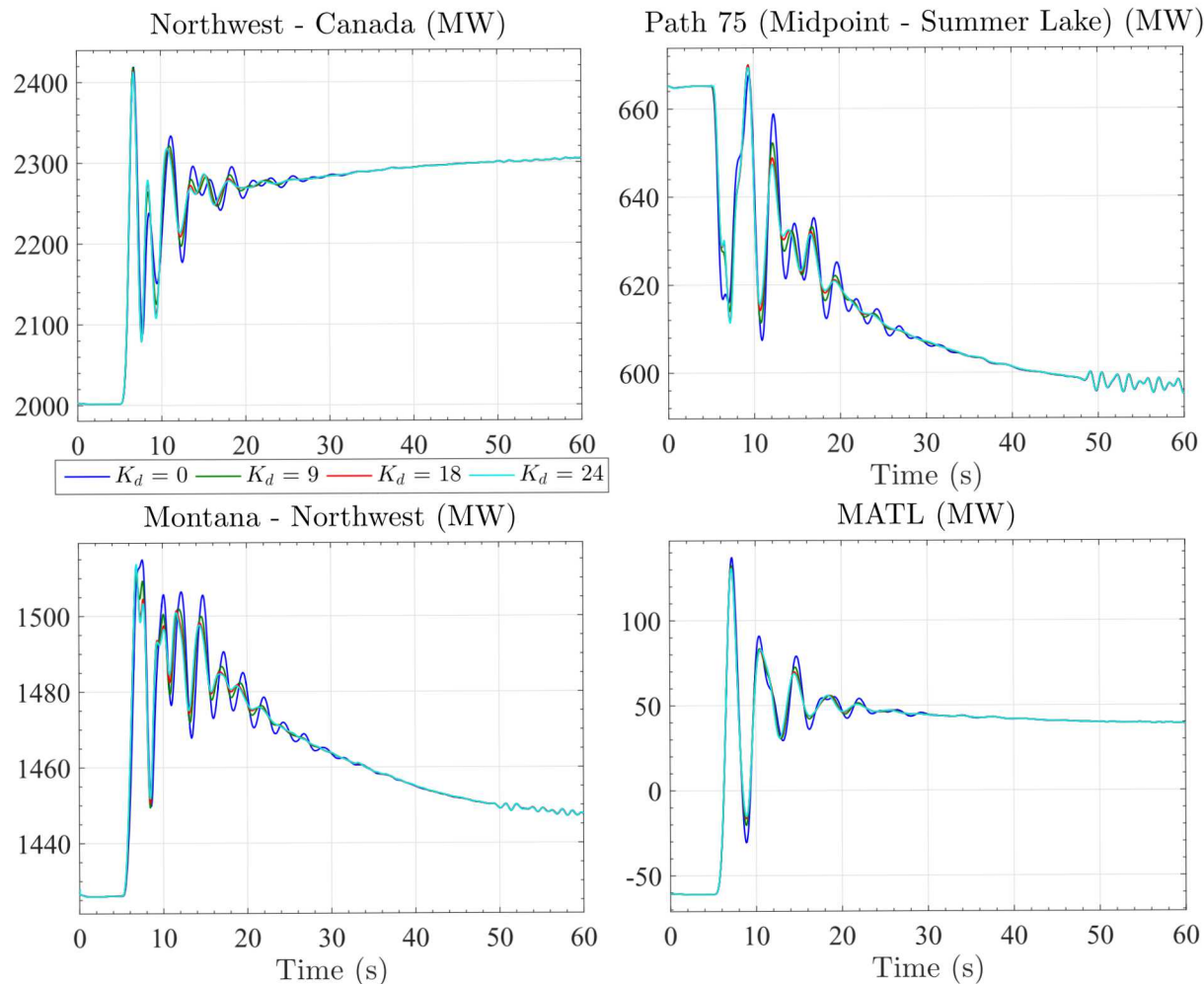


Figure 103. Active power flows. Event: Double Palo Verde Trip

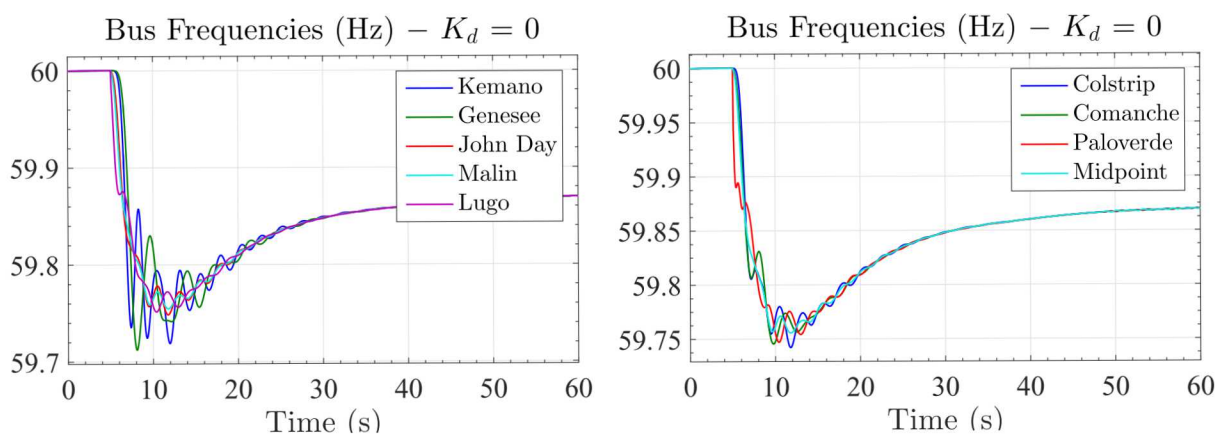


Figure 104. Bus frequencies. Event: Double Palo Verde Trip

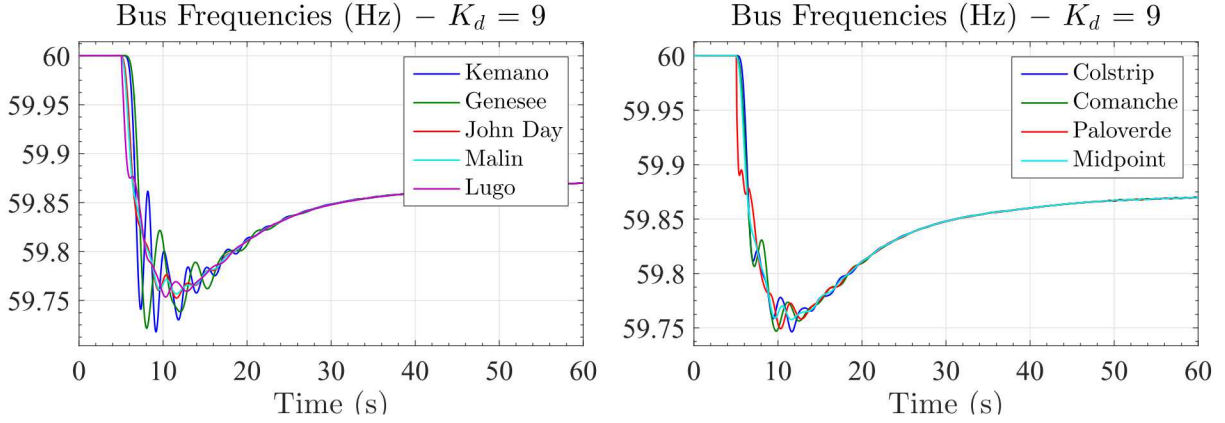


Figure 105. Bus frequencies. Event: Double Palo Verde Trip

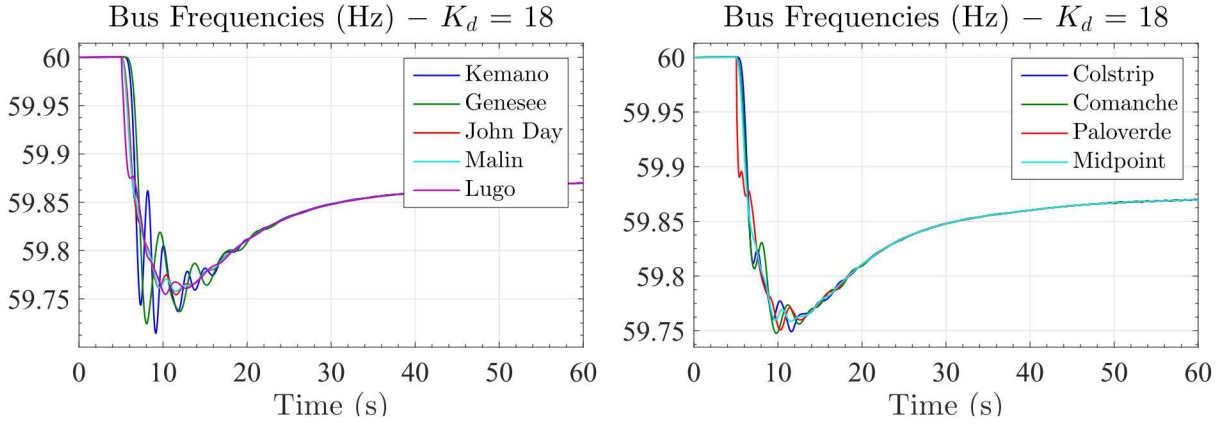


Figure 106. Bus frequencies. Event: Double Palo Verde Trip

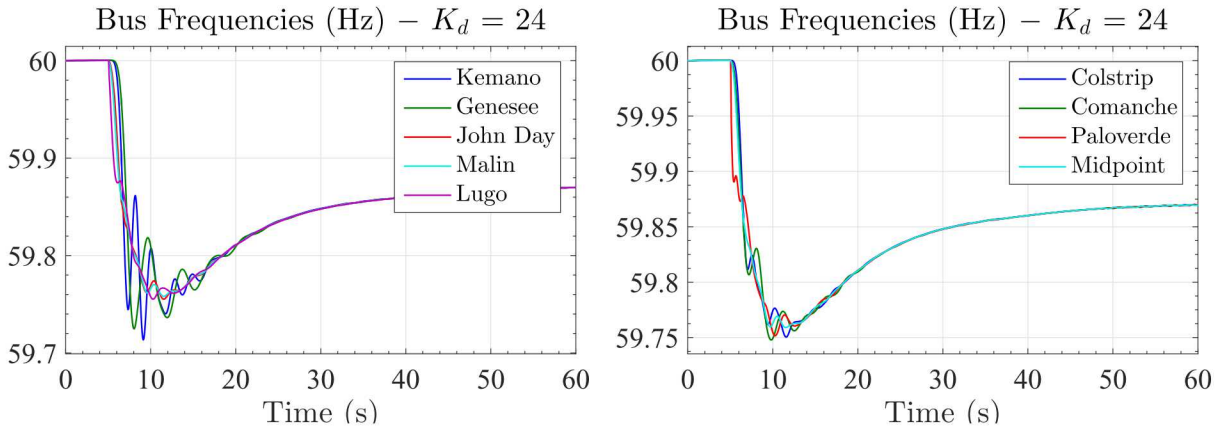


Figure 107. Bus frequencies. Event: Double Palo Verde Trip

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

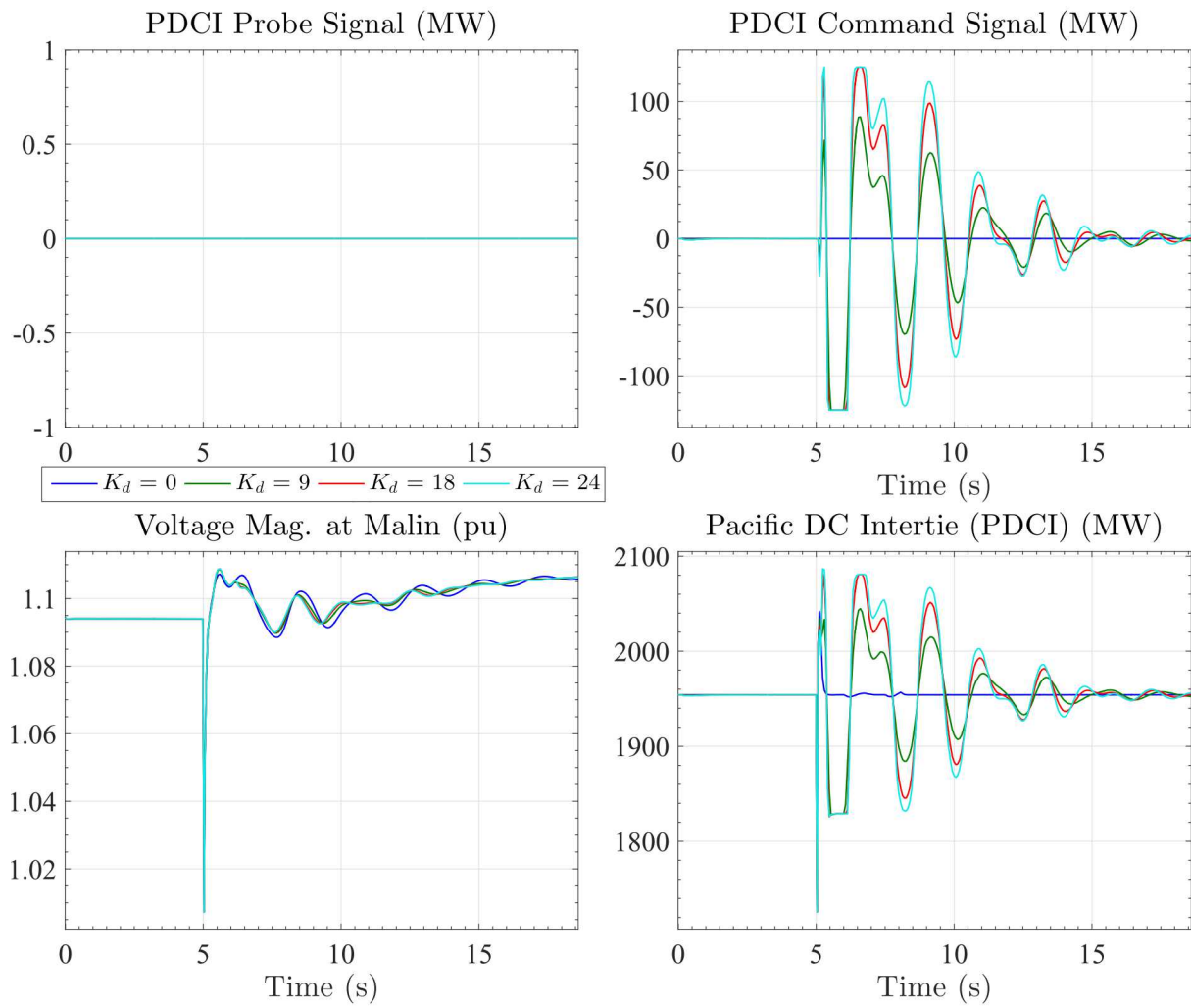


Figure 108. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-US Separation

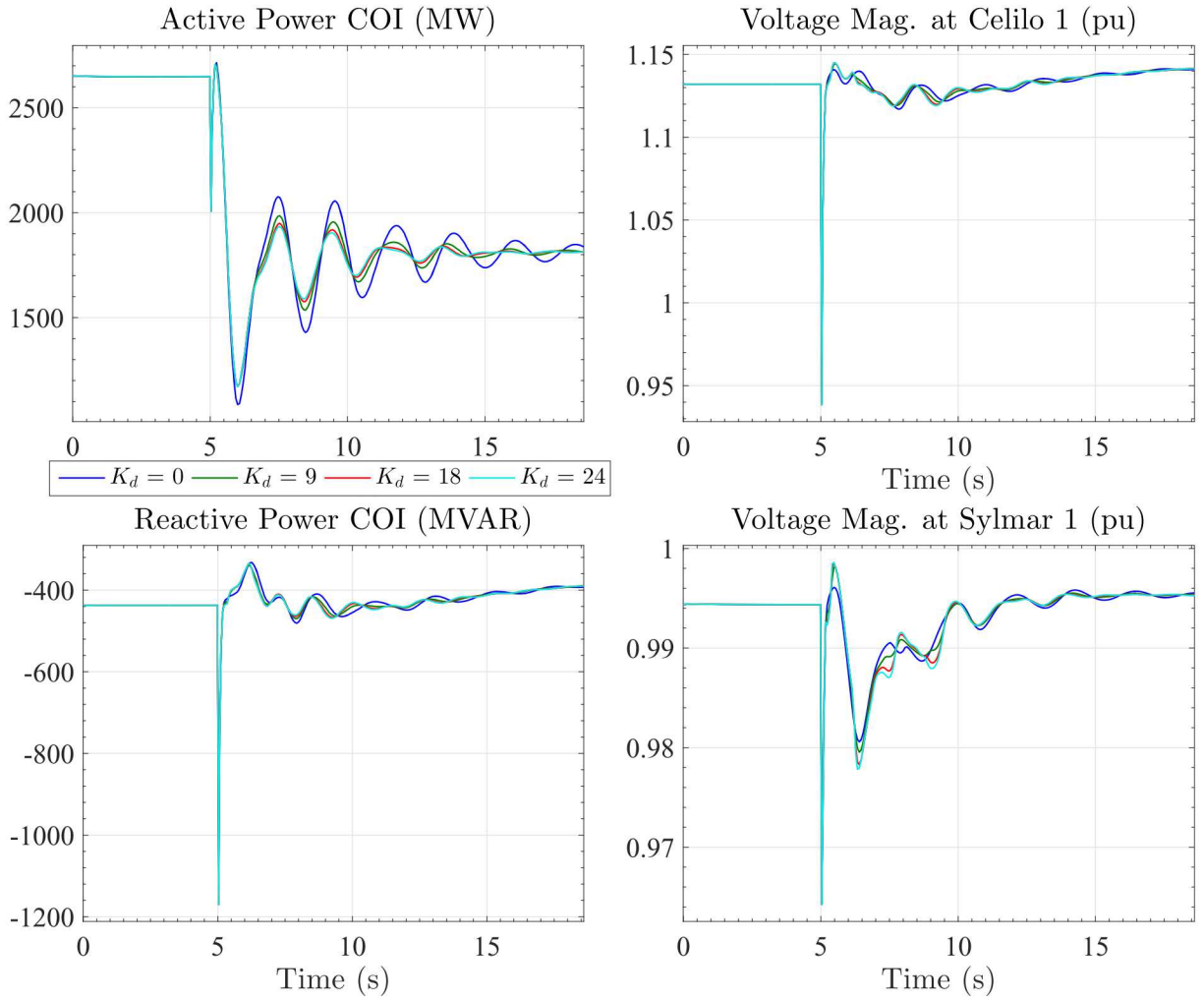


Figure 109. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-US Separation

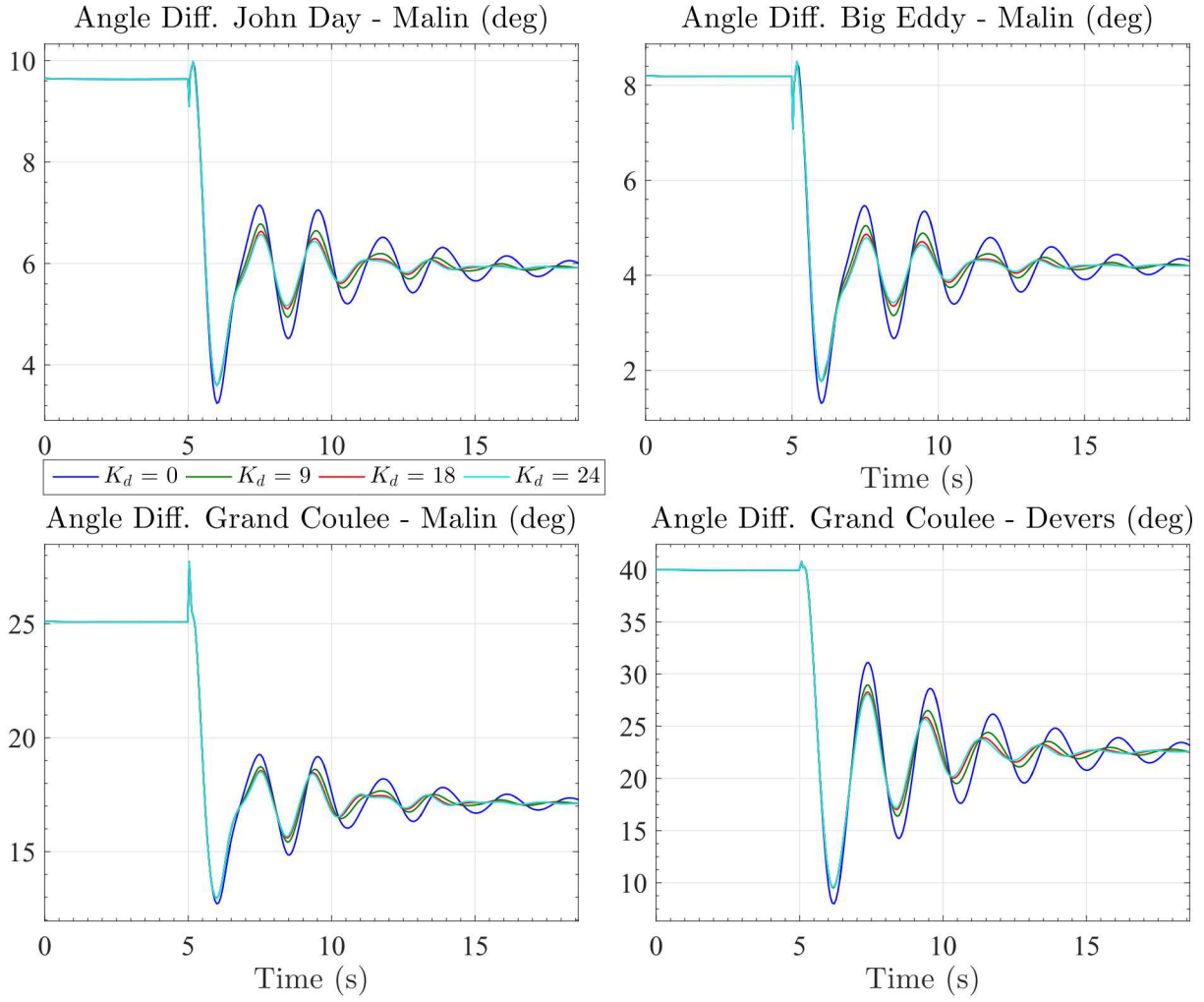


Figure 110. Angle differences. Event: BC-US Separation

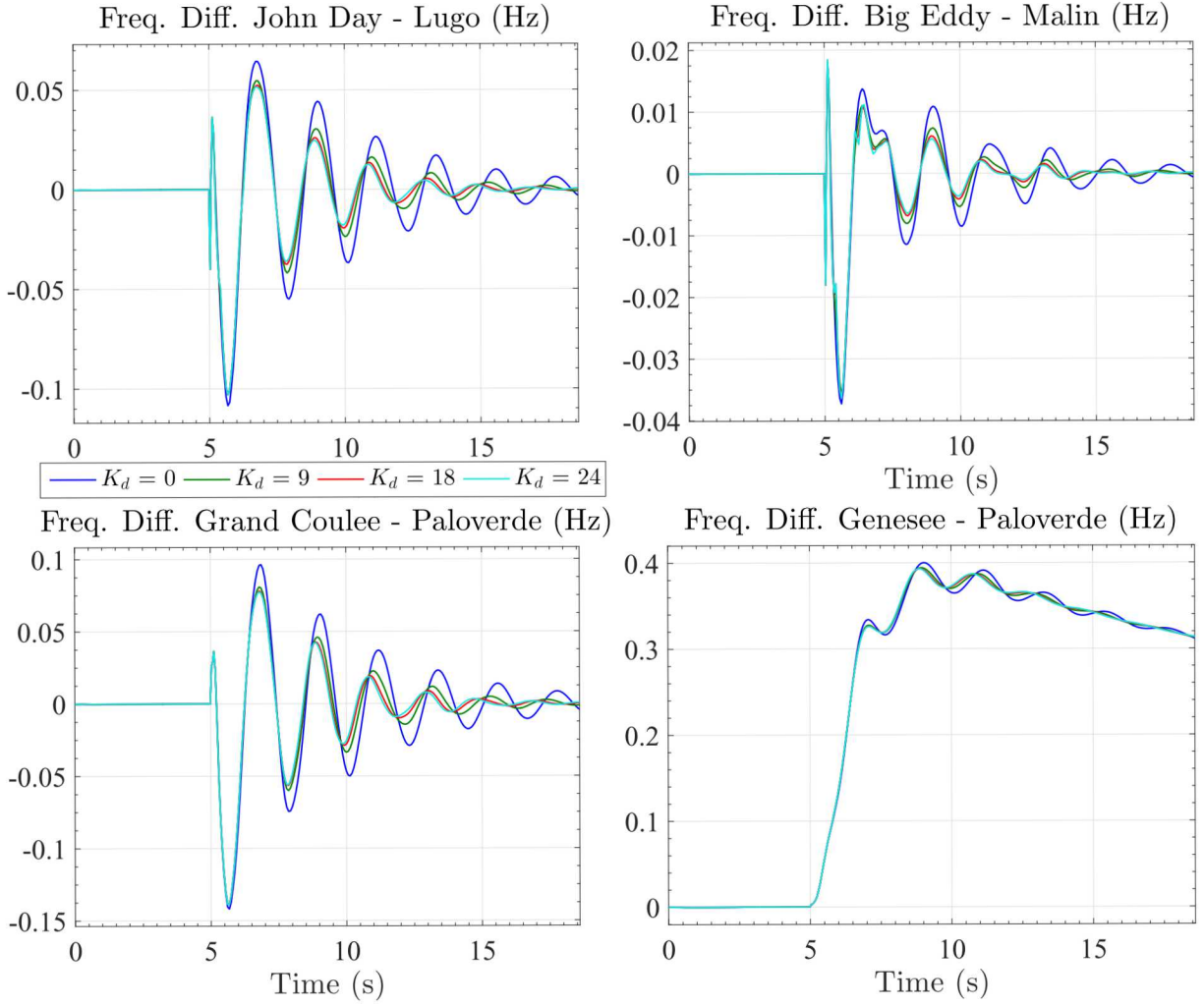


Figure 111. Frequency differences. Event: BC-US Separation

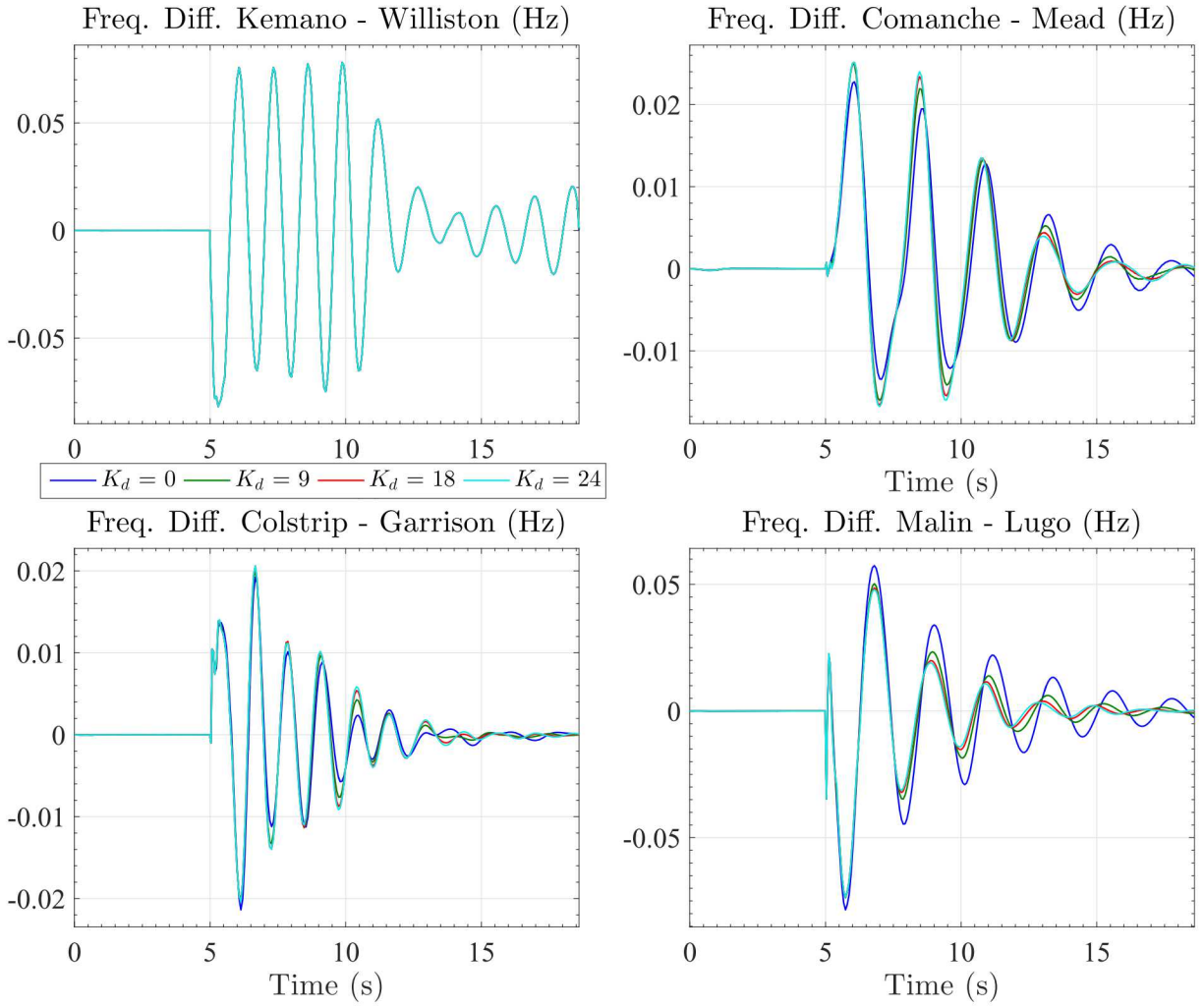


Figure 112. Frequency differences. Event: BC-US Separation

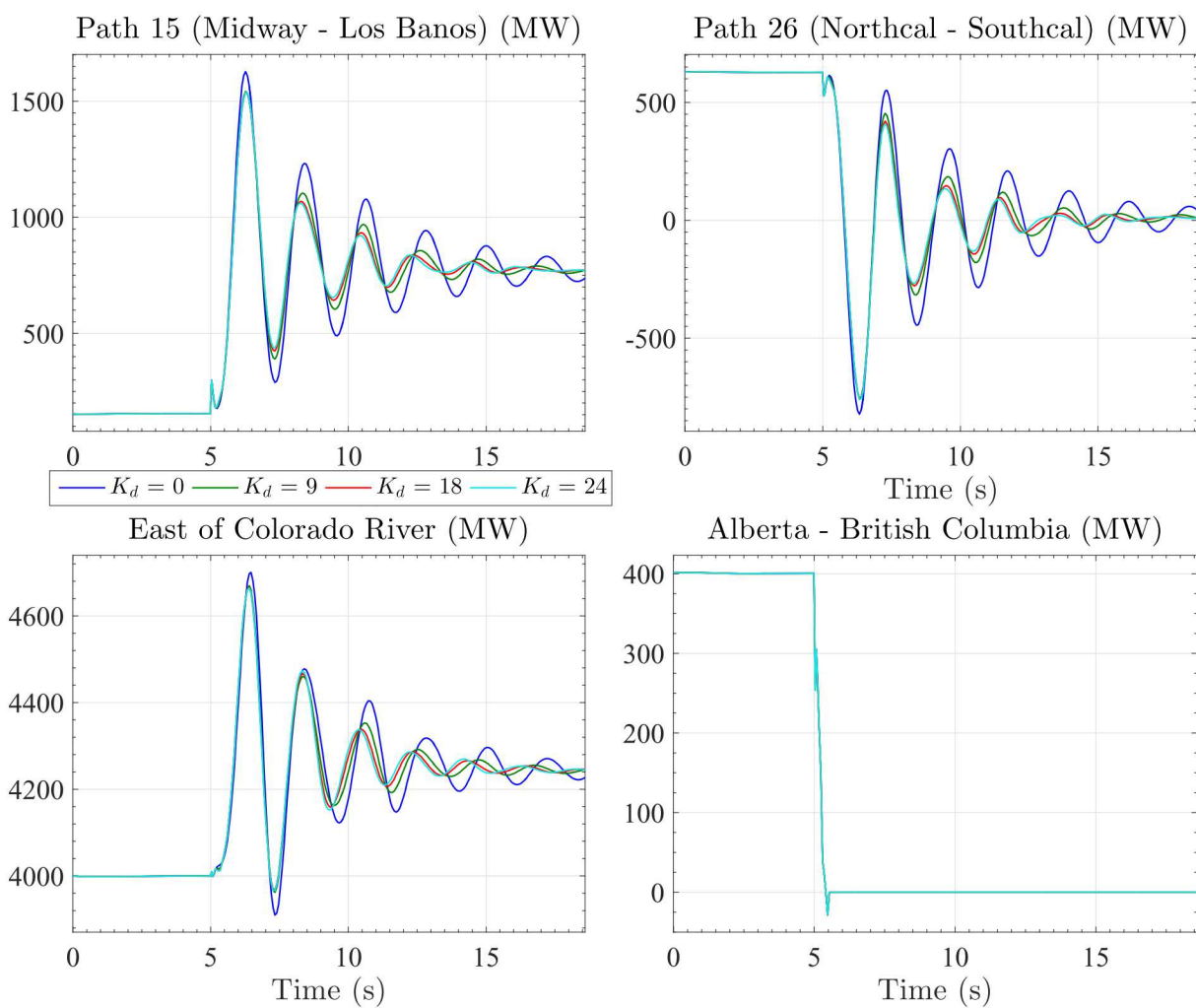


Figure 113. Active power flows. Event: BC-US Separation

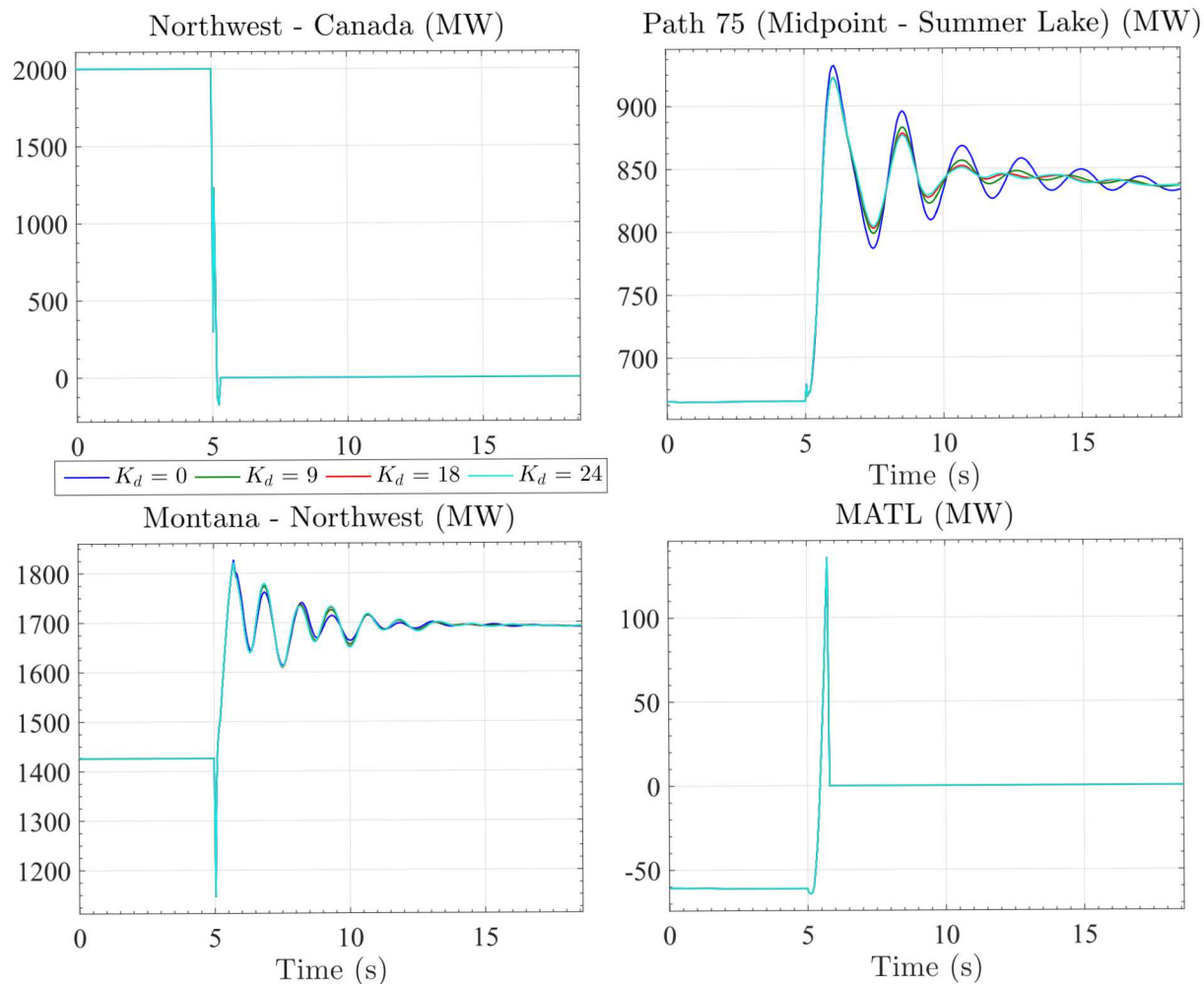


Figure 114. Active power flows. Event: BC-US Separation

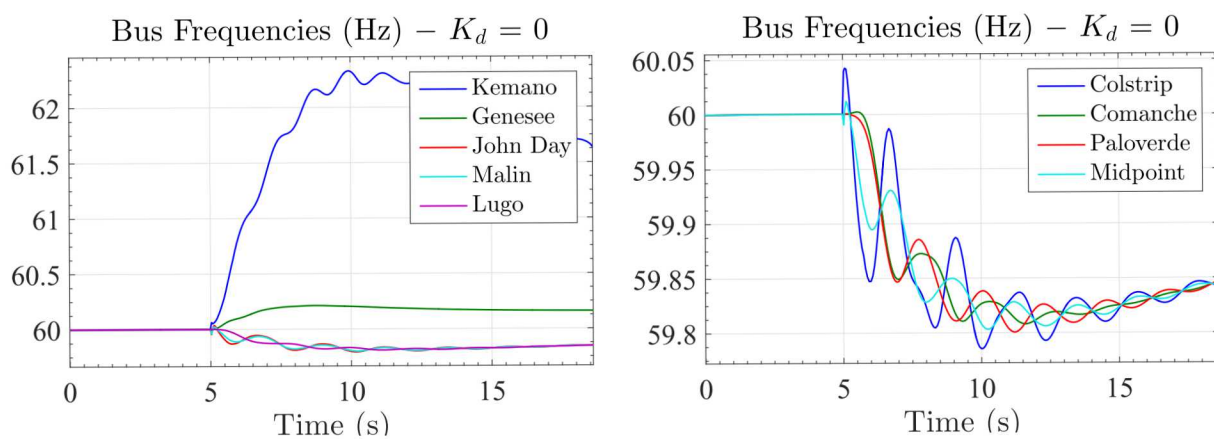


Figure 115. Bus frequencies. Event: BC-US Separation

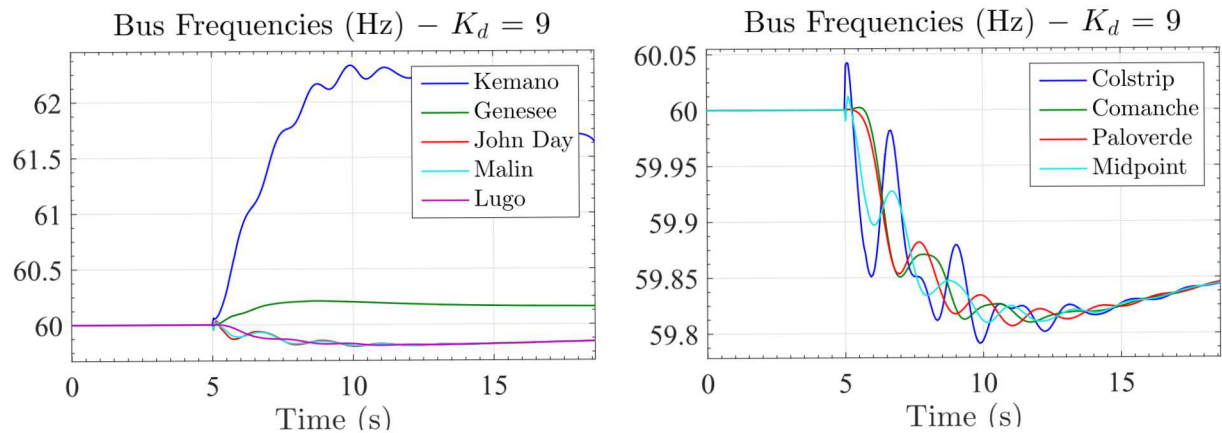


Figure 116. Bus frequencies. Event: BC-US Separation

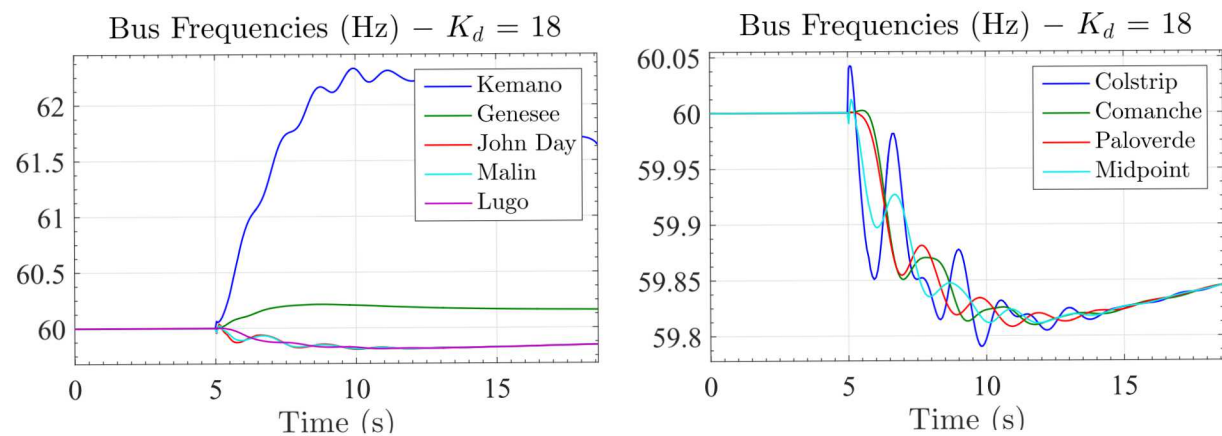


Figure 117. Bus frequencies. Event: BC-US Separation

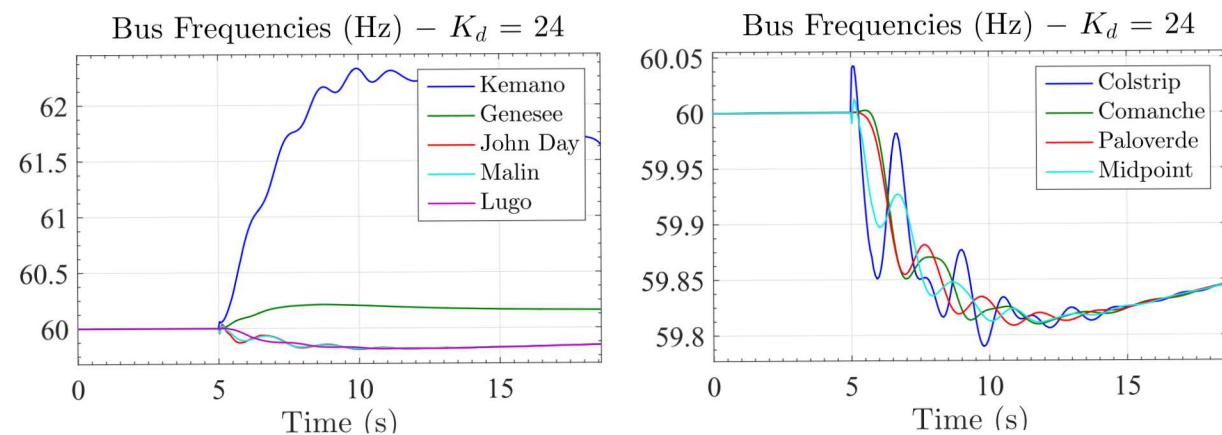


Figure 118. Bus frequencies. Event: BC-US Separation

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

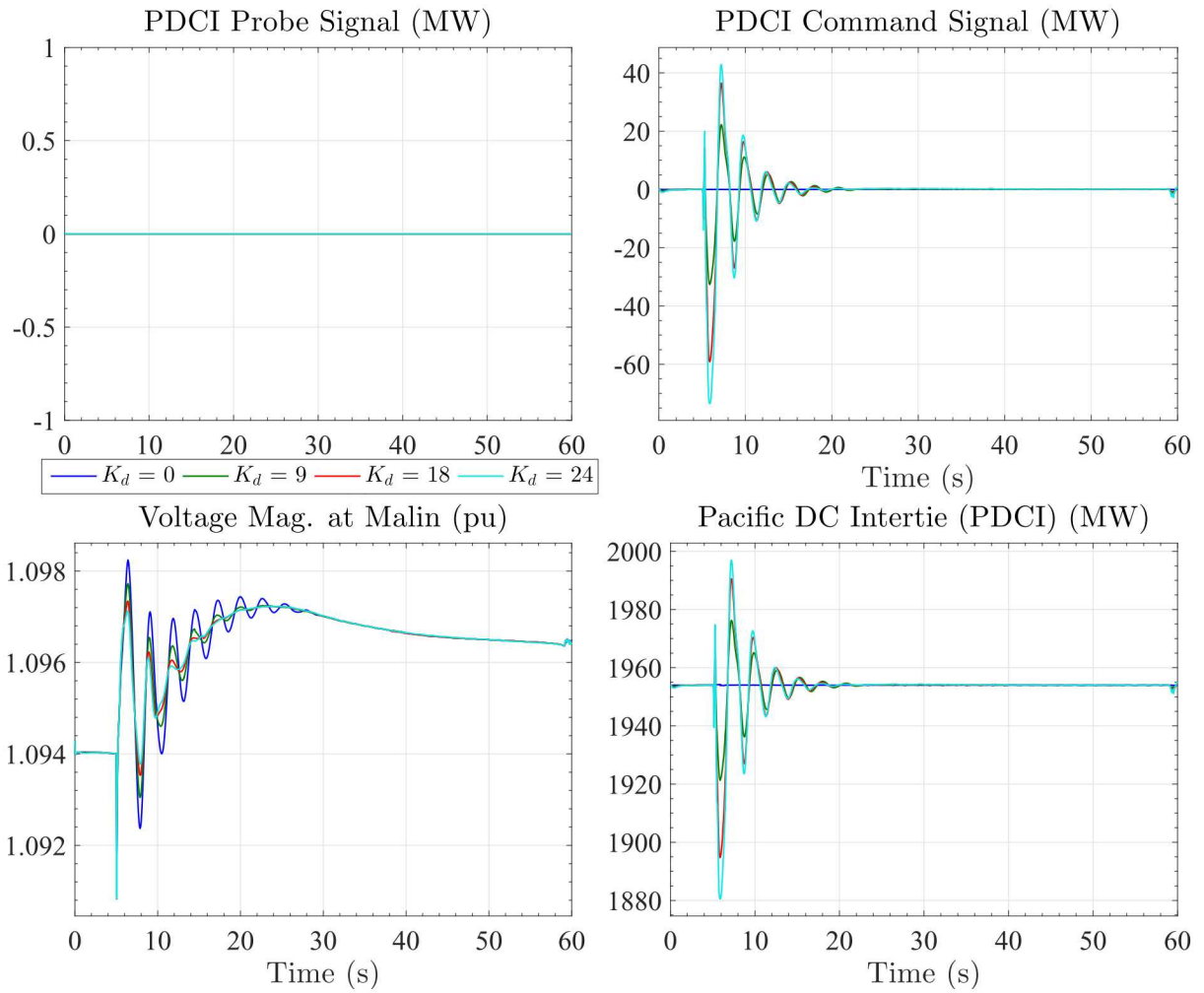


Figure 119. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: BC-AB Separation

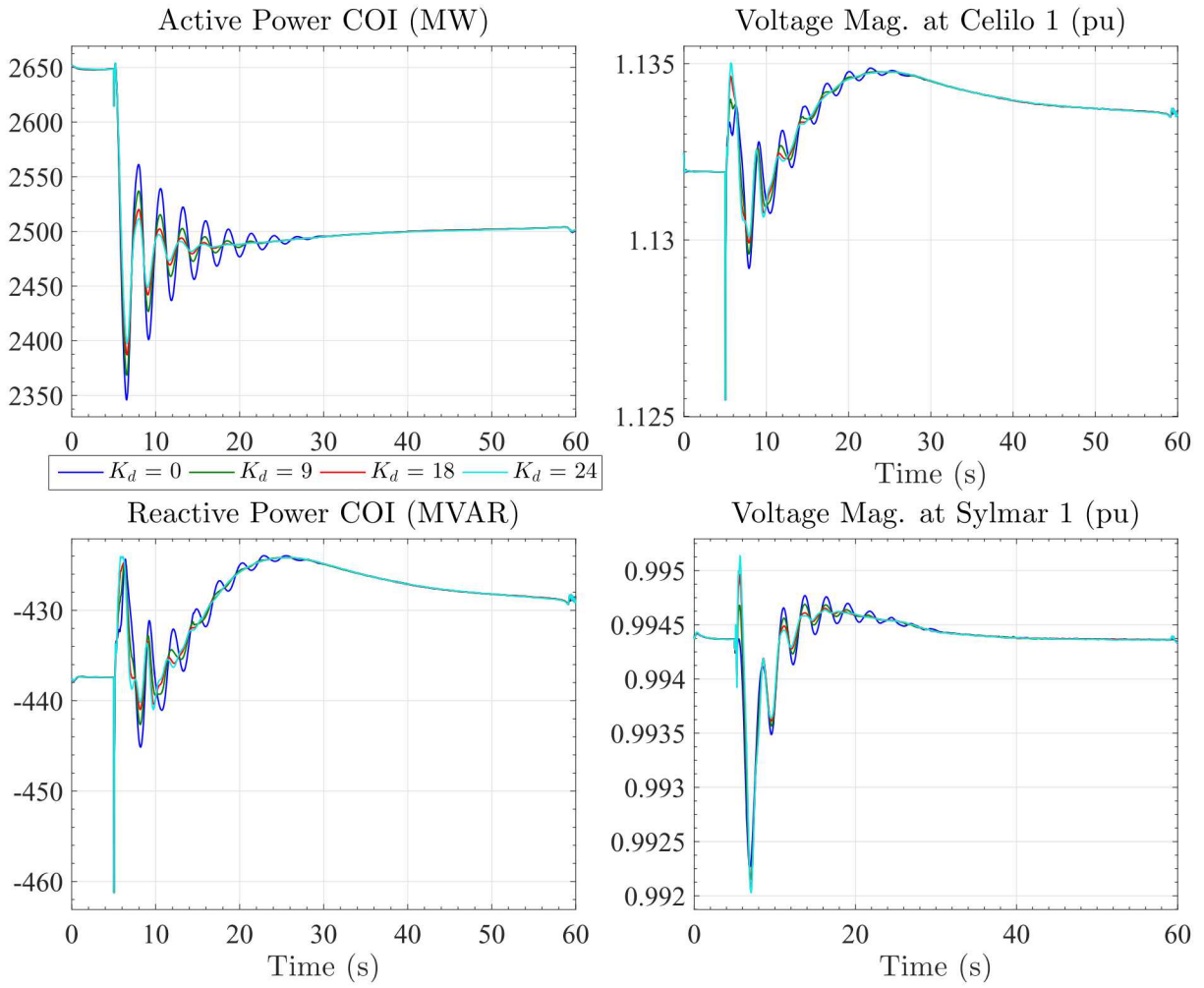


Figure 120. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: BC-AB Separation

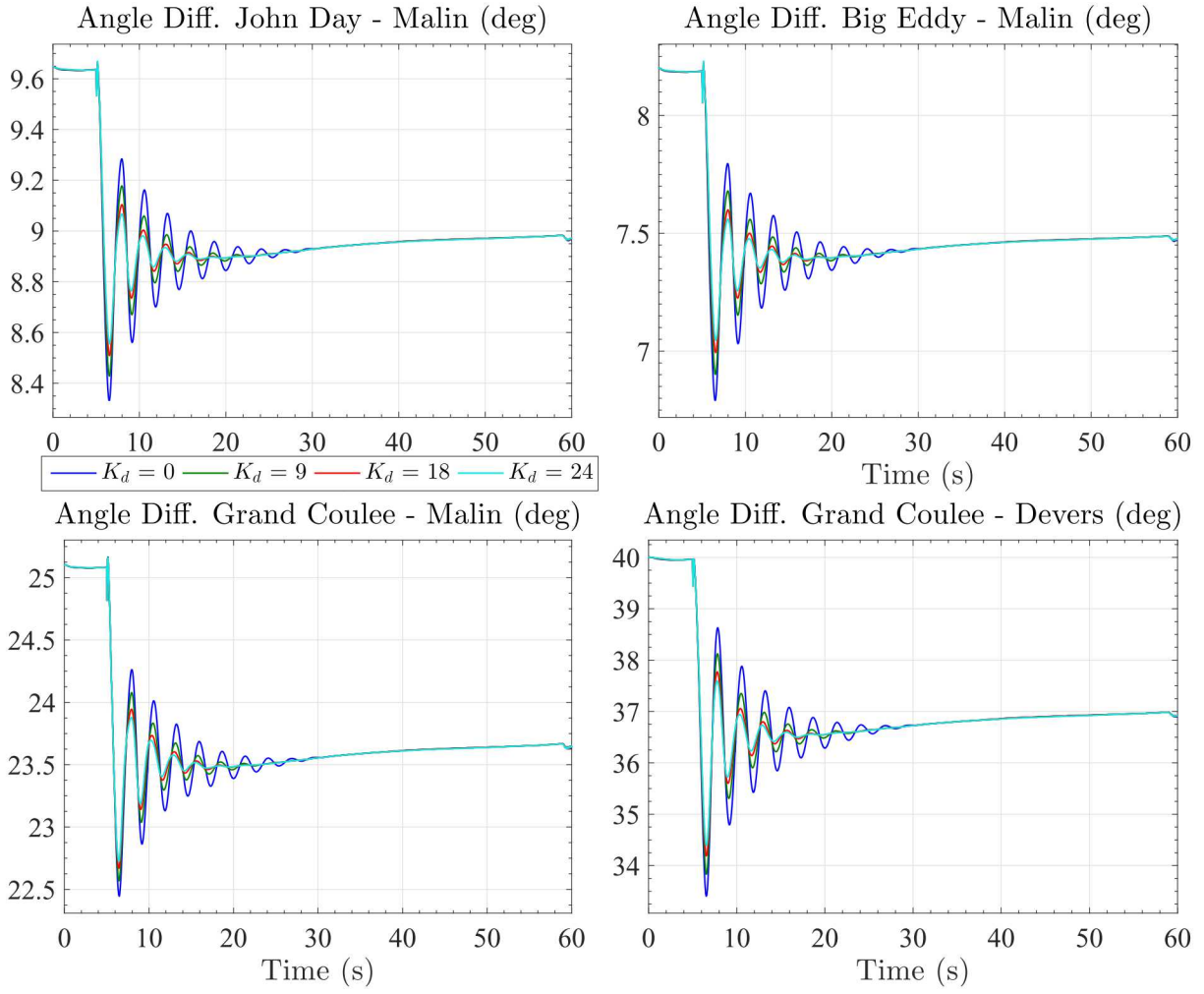


Figure 121. Angle differences. Event: BC-AB Separation

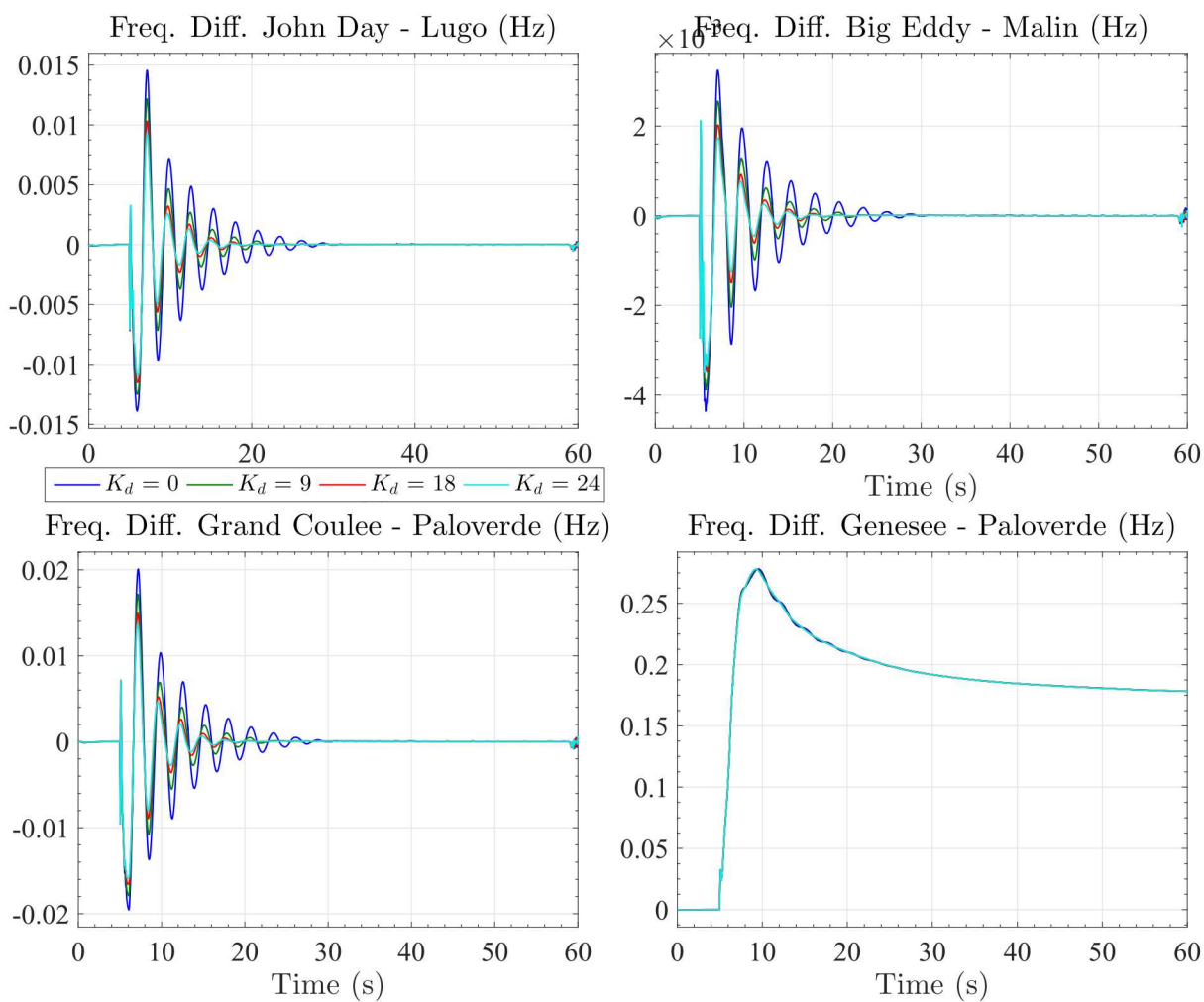


Figure 122. Frequency differences. Event: BC-AB Separation

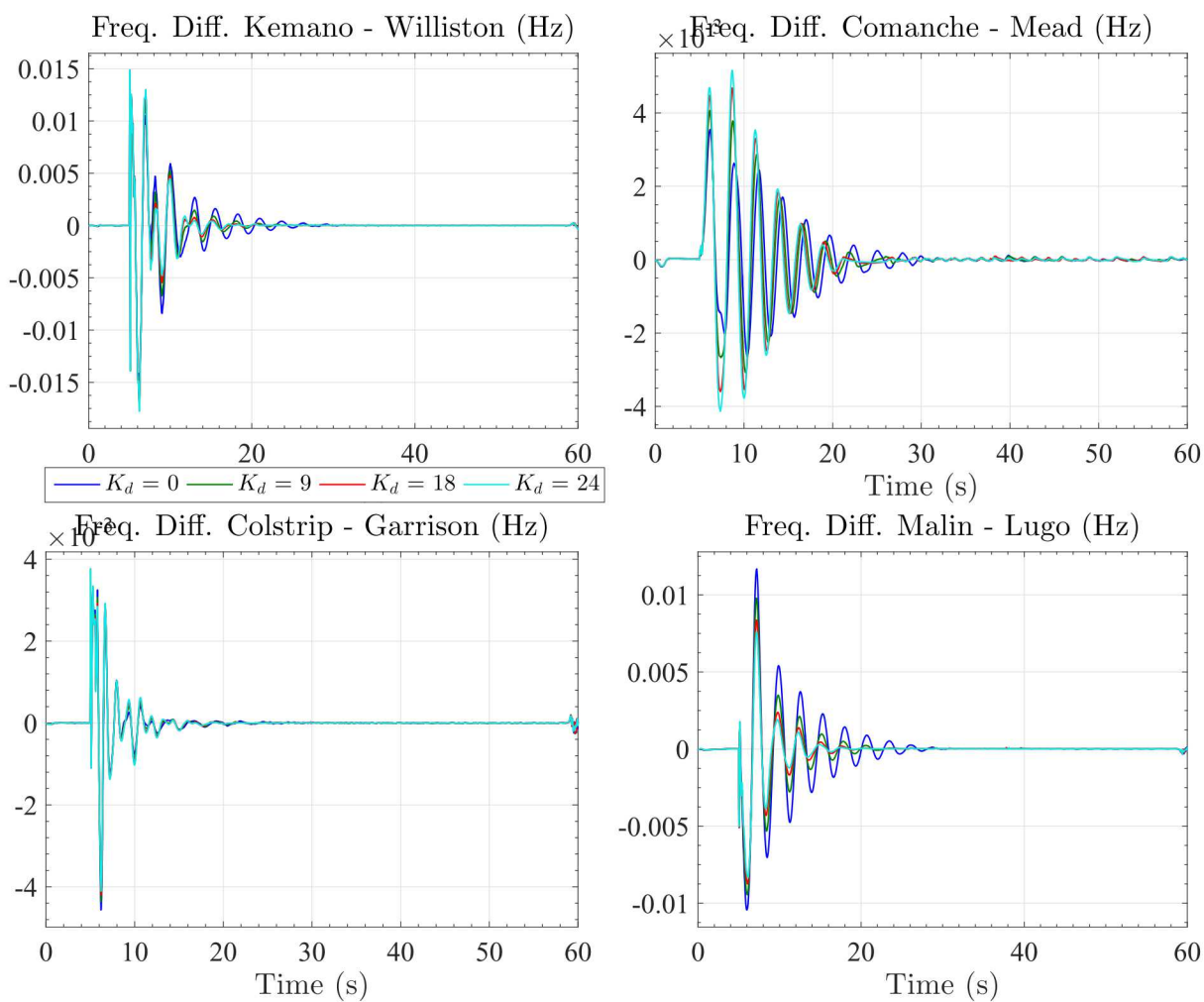


Figure 123. Frequency differences. Event: BC-AB Separation

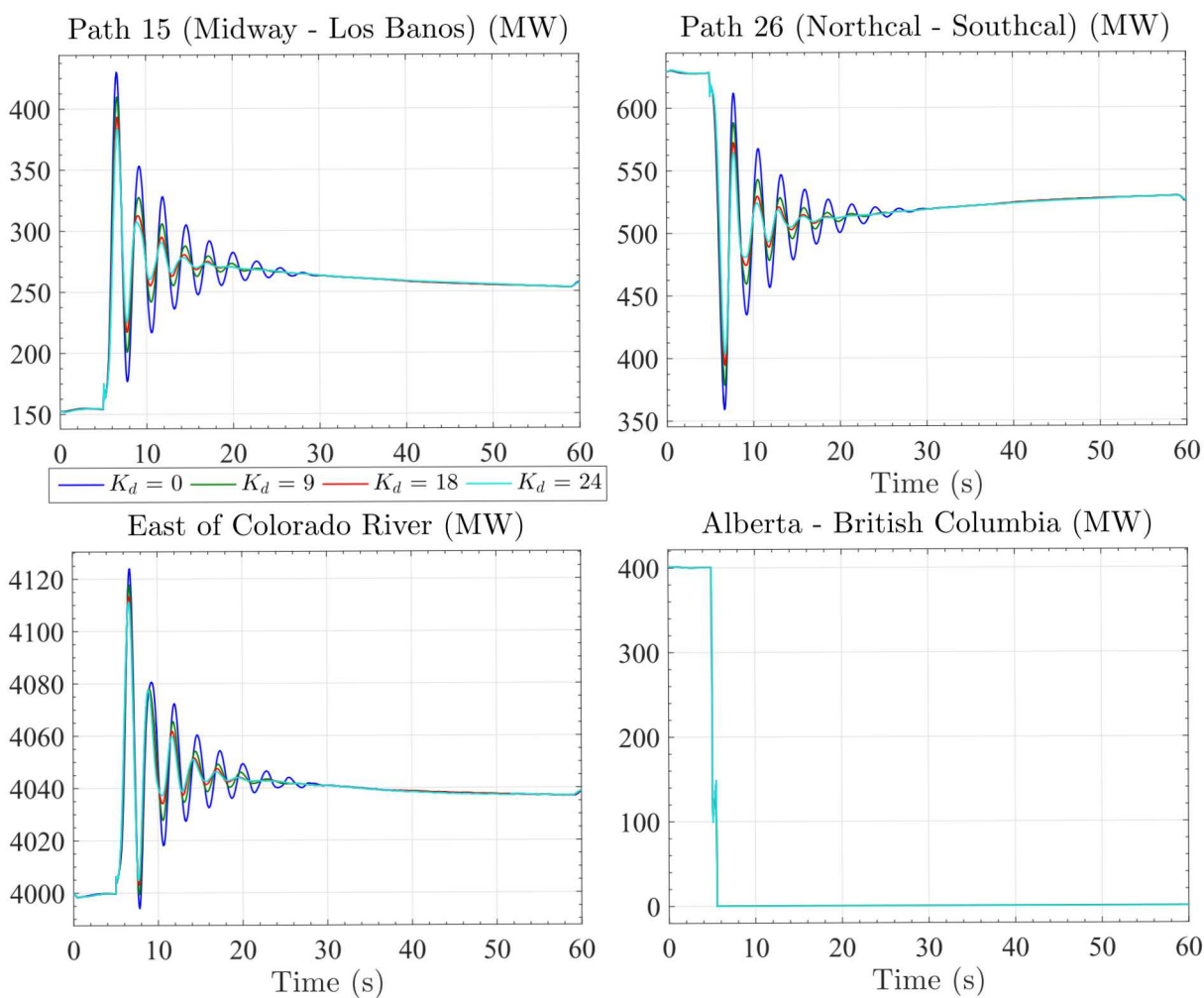


Figure 124. Active power flows. Event: BC-AB Separation

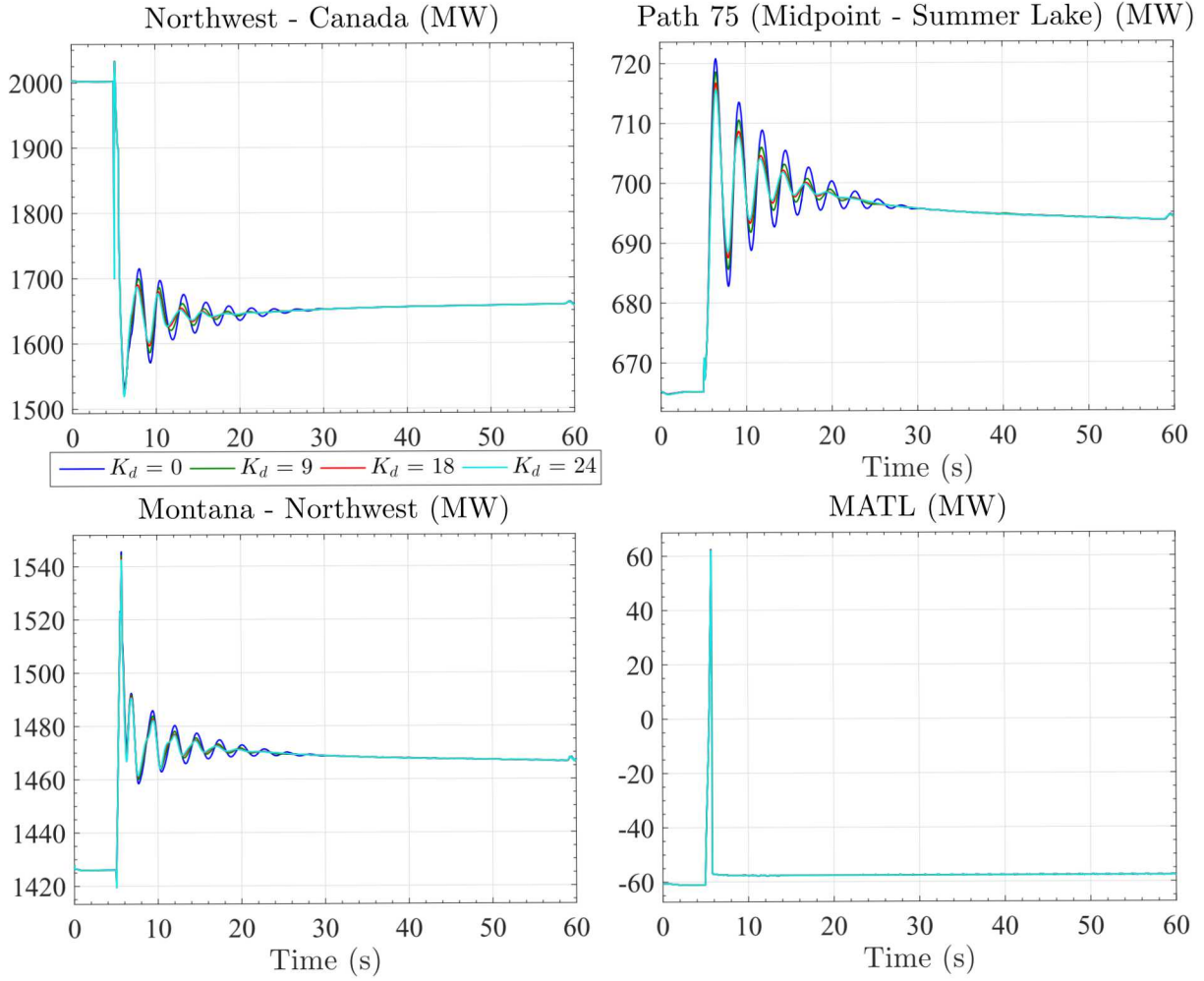


Figure 125. Active power flows. Event: BC-AB Separation

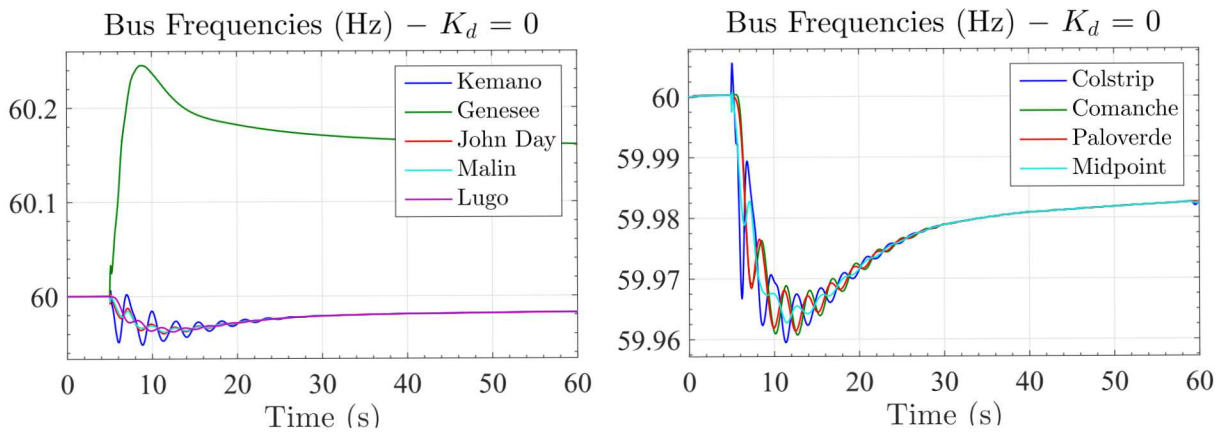


Figure 126. Bus frequencies. Event: BC-AB Separation

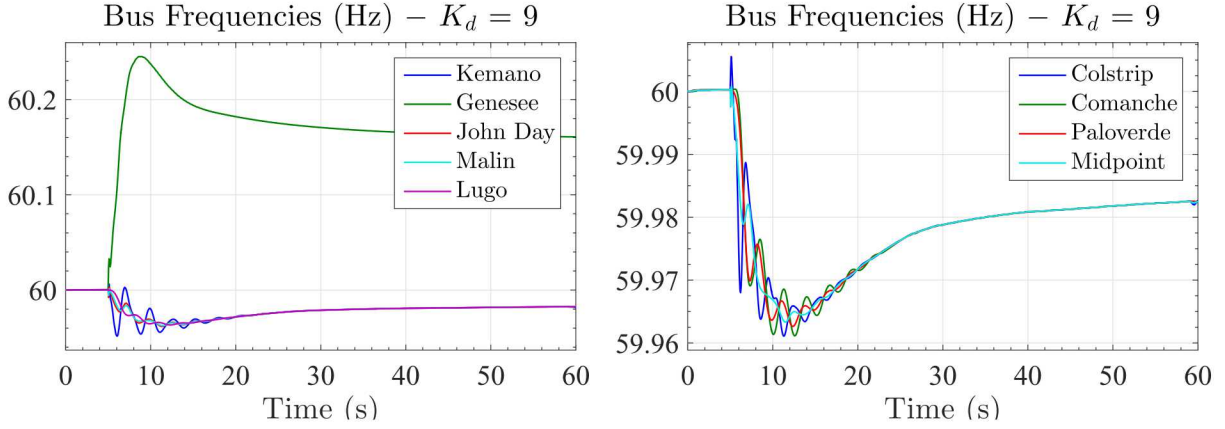


Figure 127. Bus frequencies. Event: BC-AB Separation

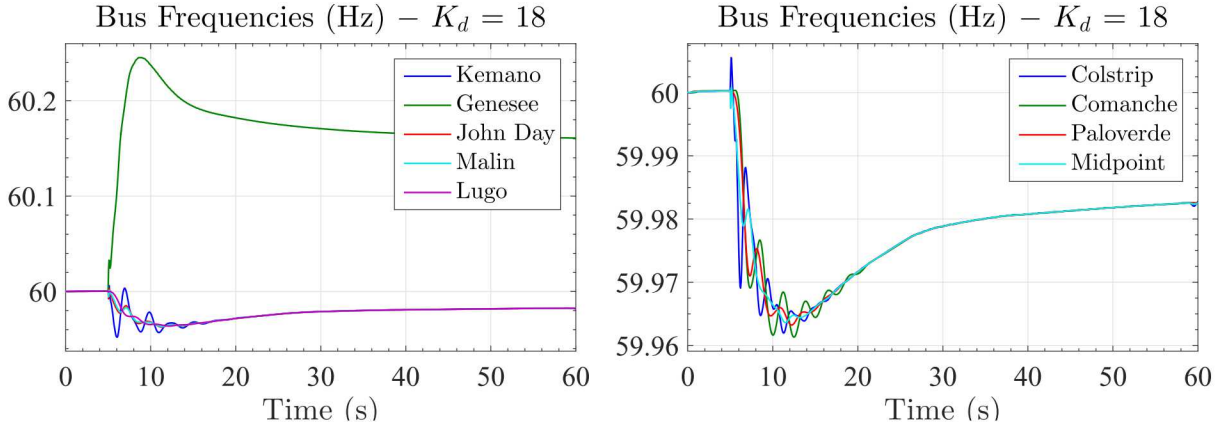


Figure 128. Bus frequencies. Event: BC-AB Separation

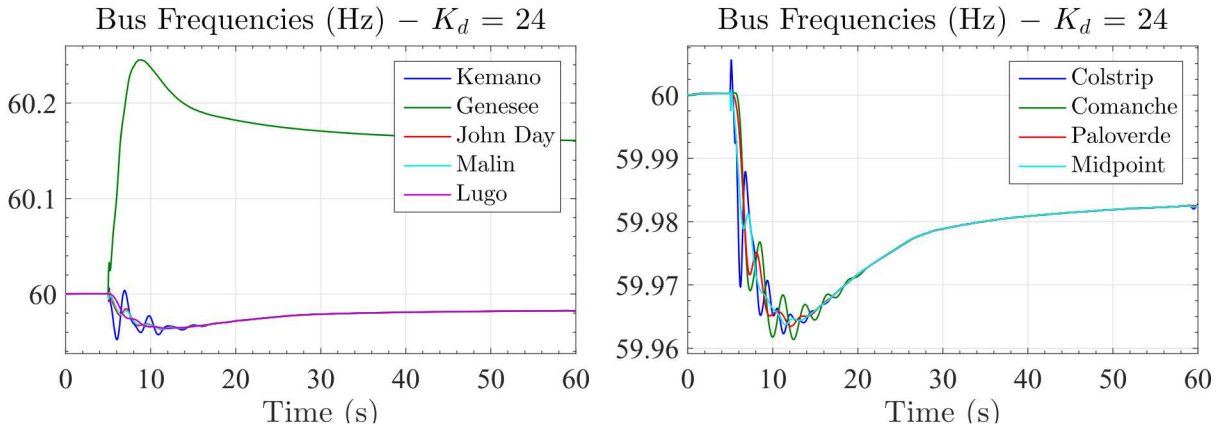


Figure 129. Bus frequencies. Event: BC-AB Separation

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

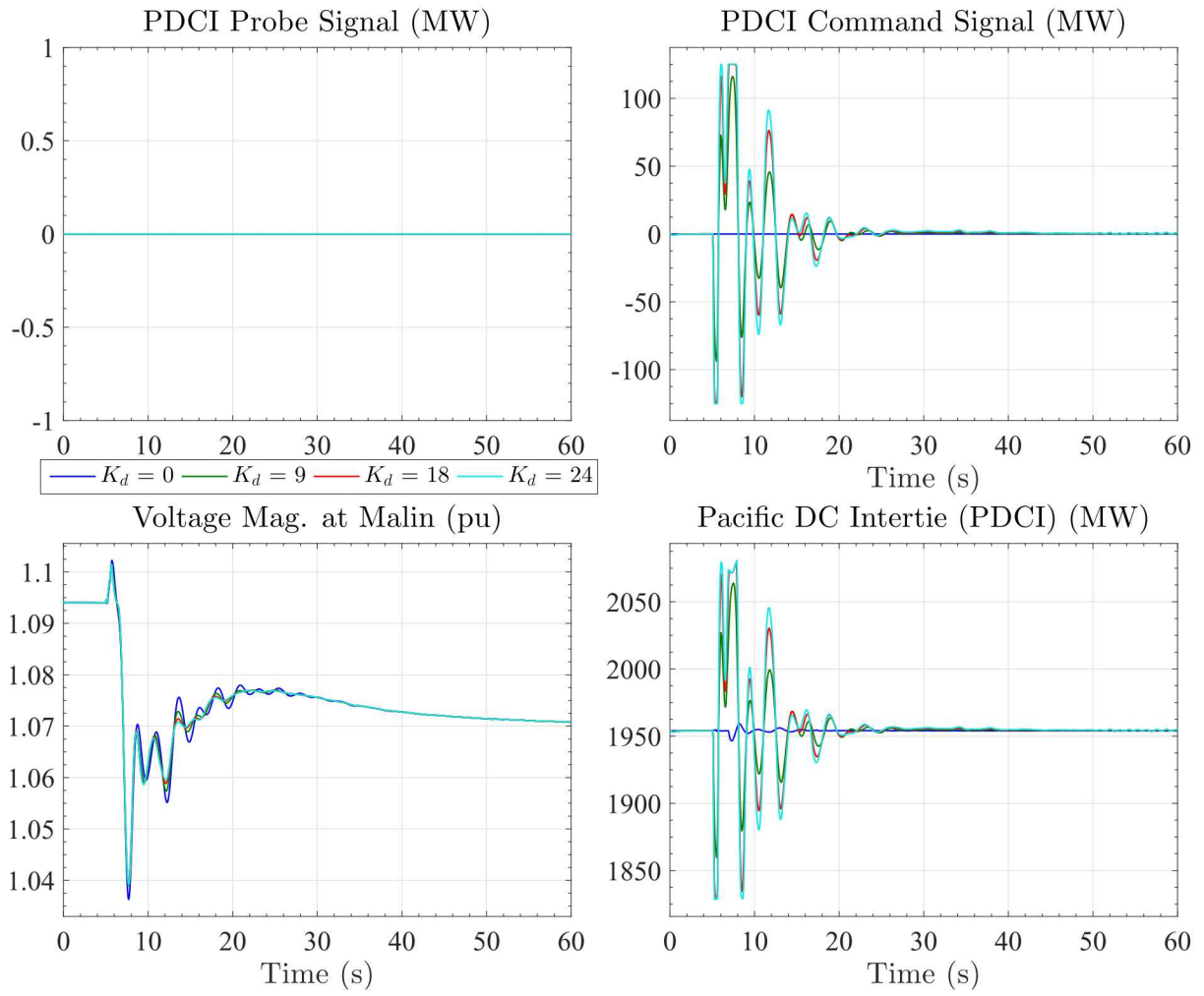


Figure 130. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + 2PV

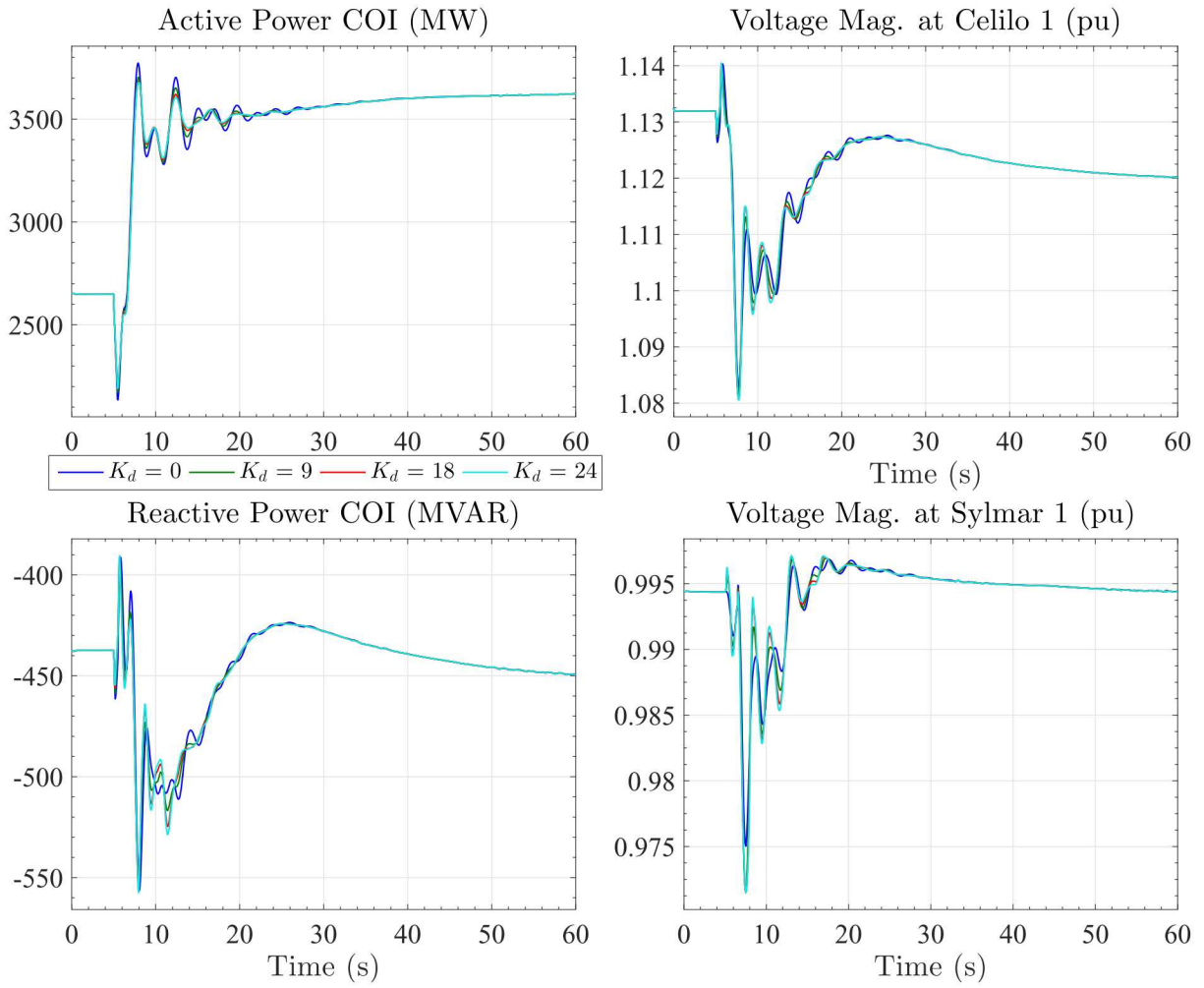


Figure 131. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + 2PV

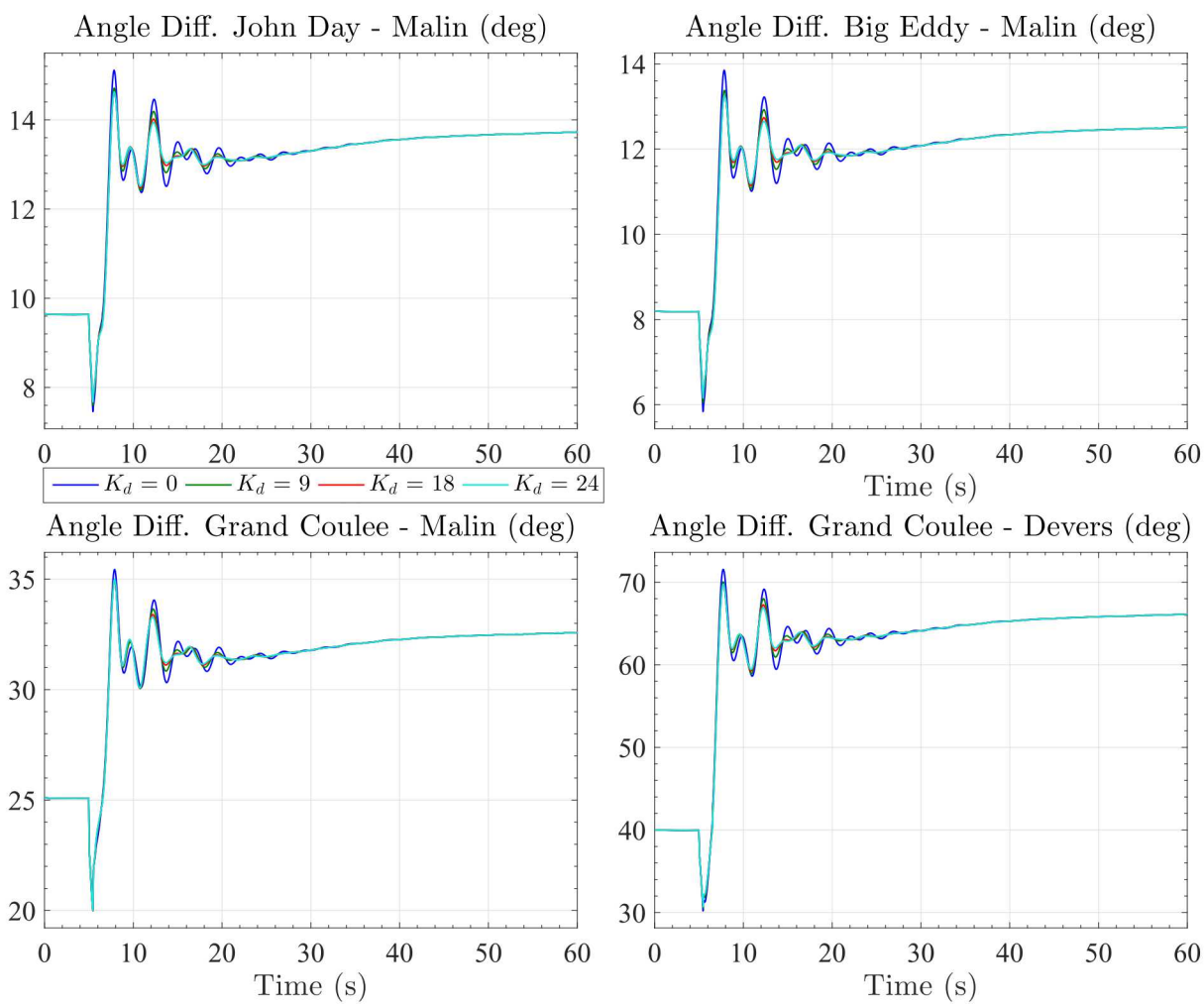


Figure 132. Angle differences. Event: CJB + 2PV

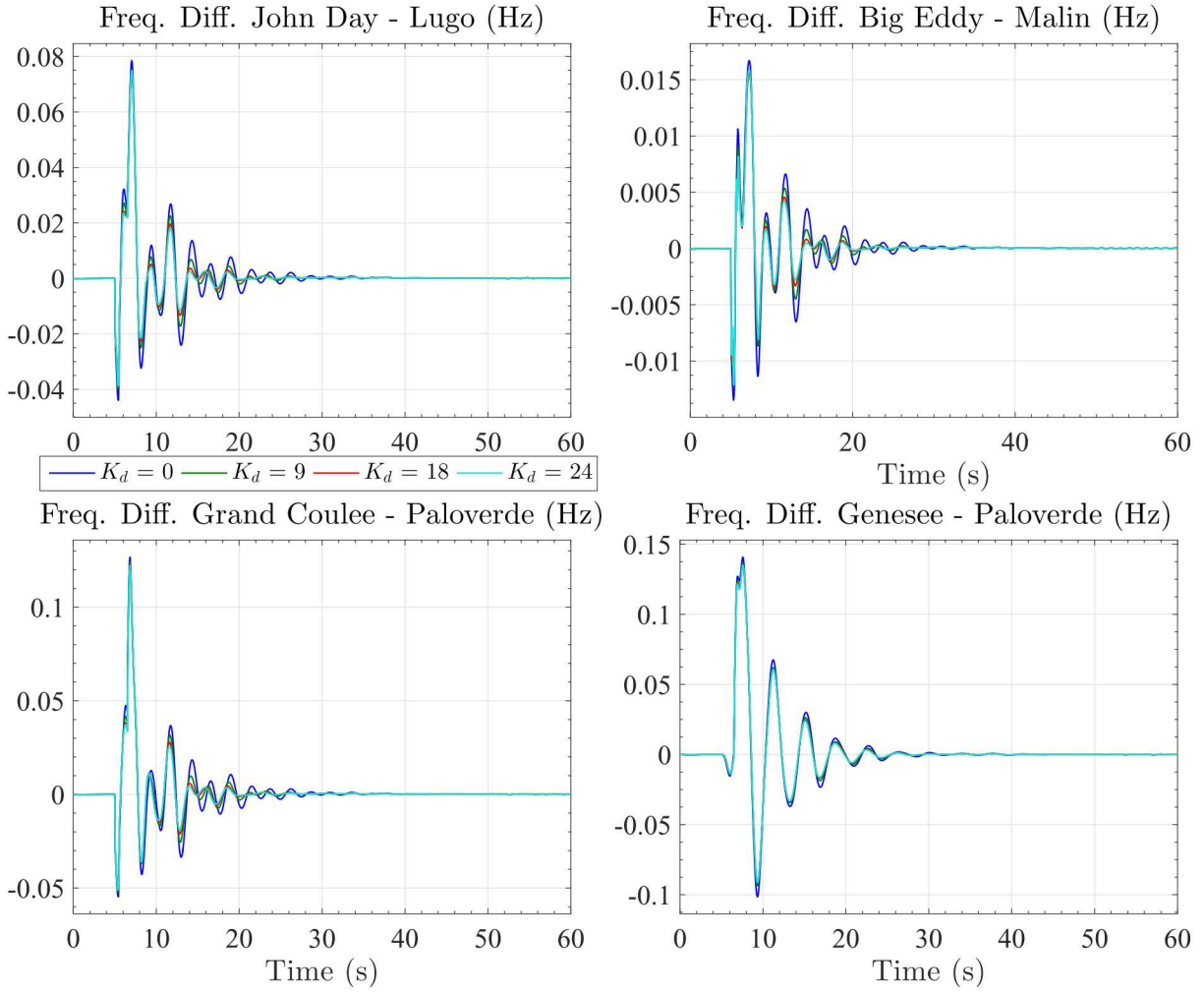


Figure 133. Frequency differences. Event: CJB + 2PV

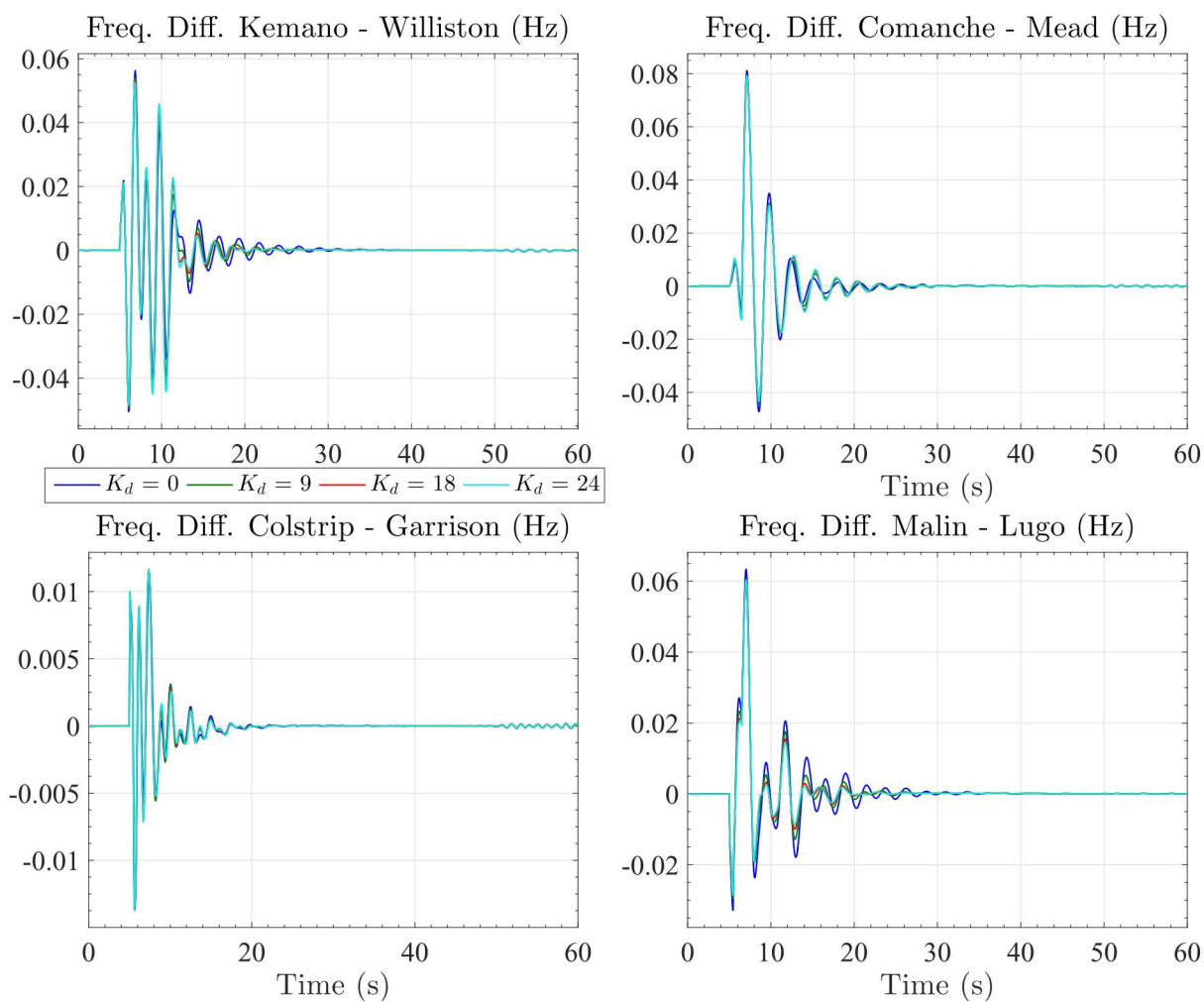


Figure 134. Frequency differences. Event: CJB + 2PV

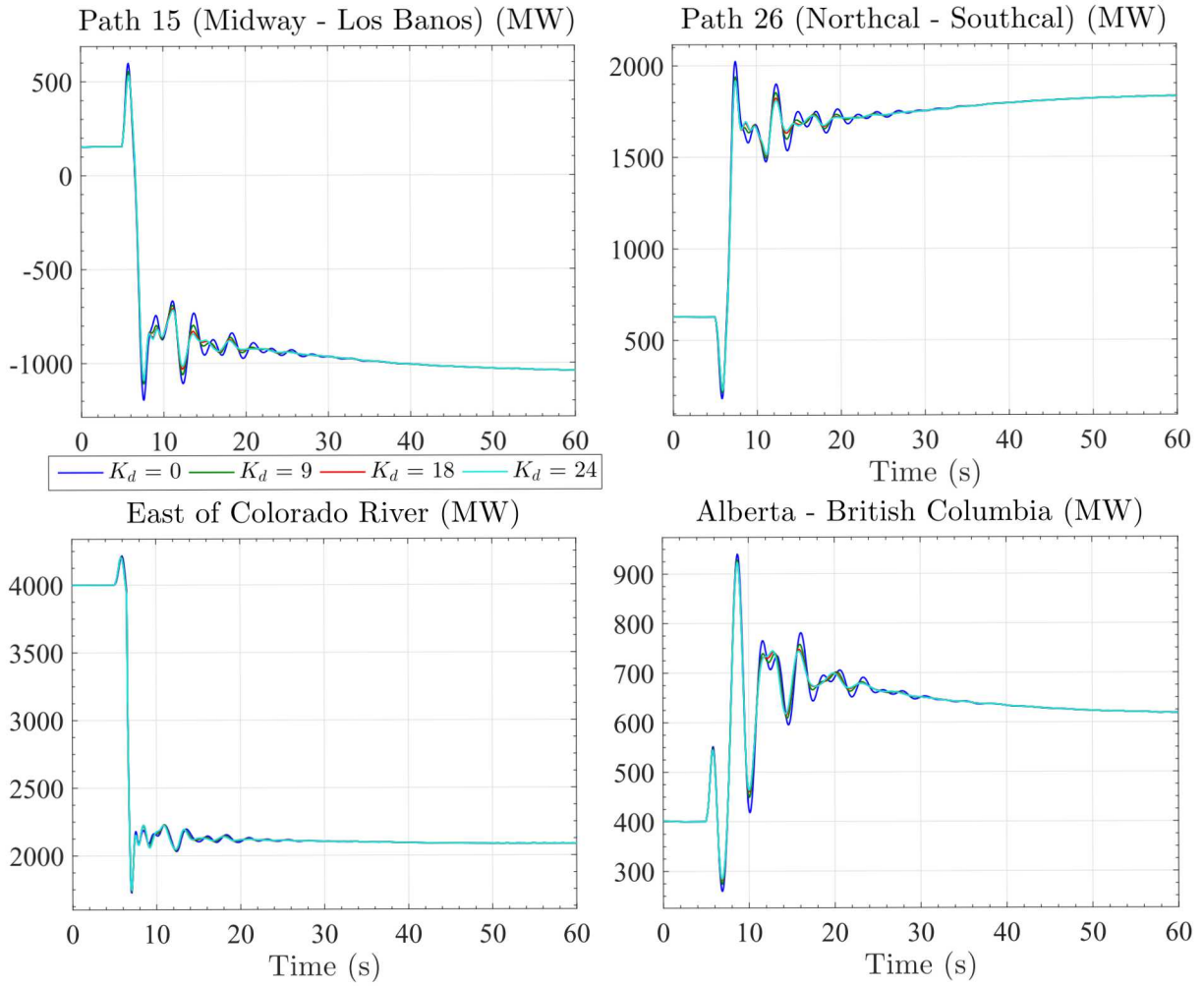


Figure 135. Active power flows. Event: CJB + 2PV

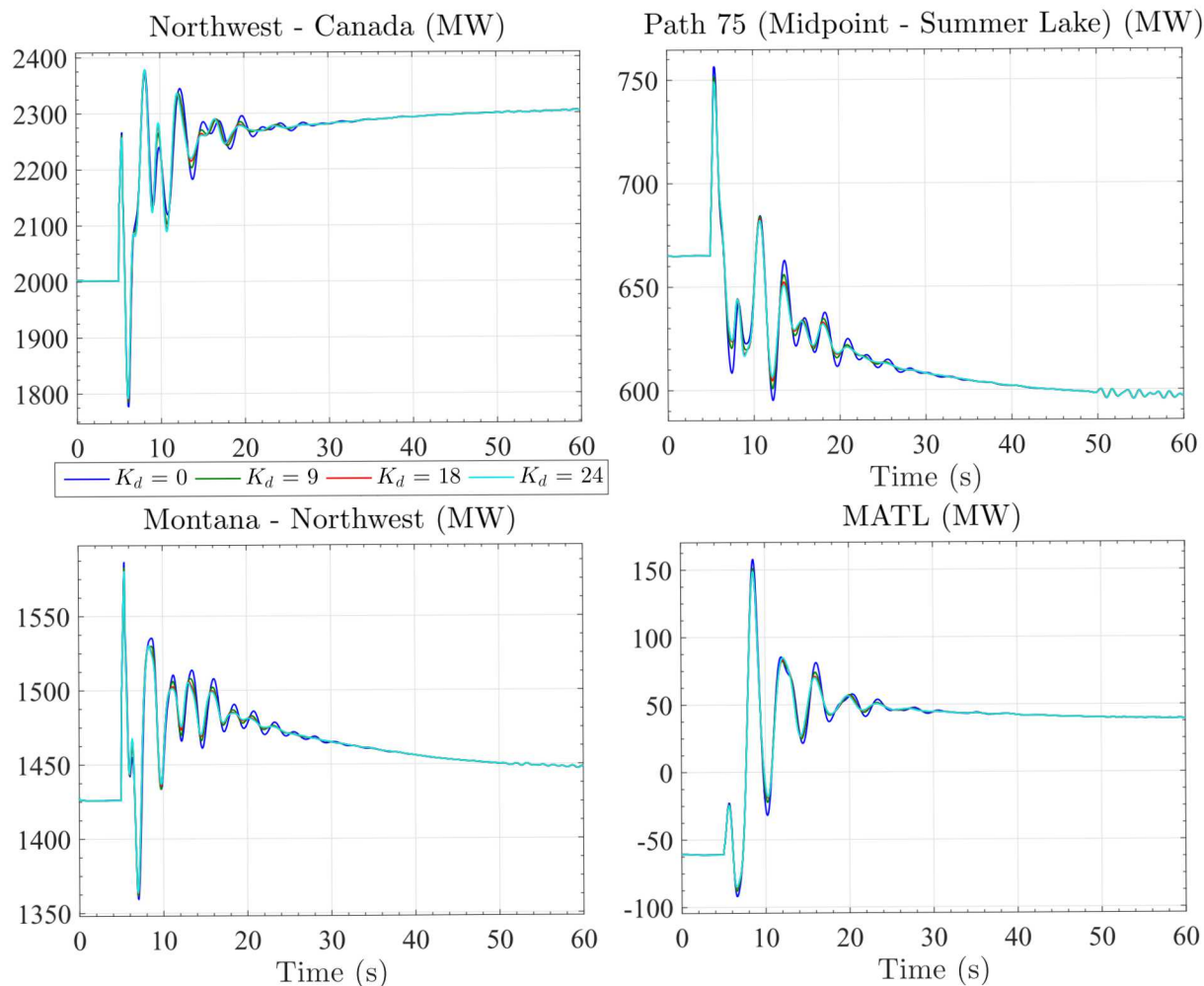


Figure 136. Active power flows. Event: CJB + 2PV

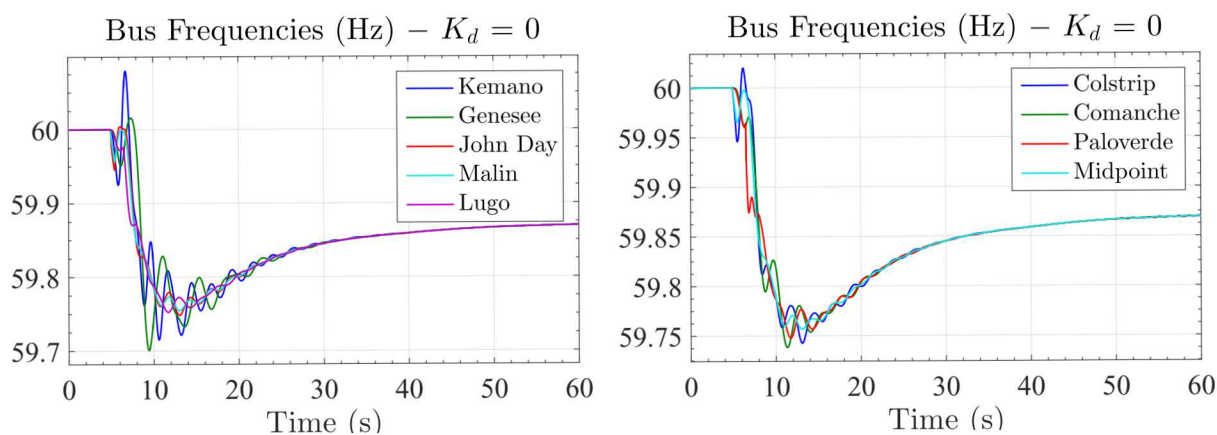


Figure 137. Bus frequencies. Event: CJB + 2PV

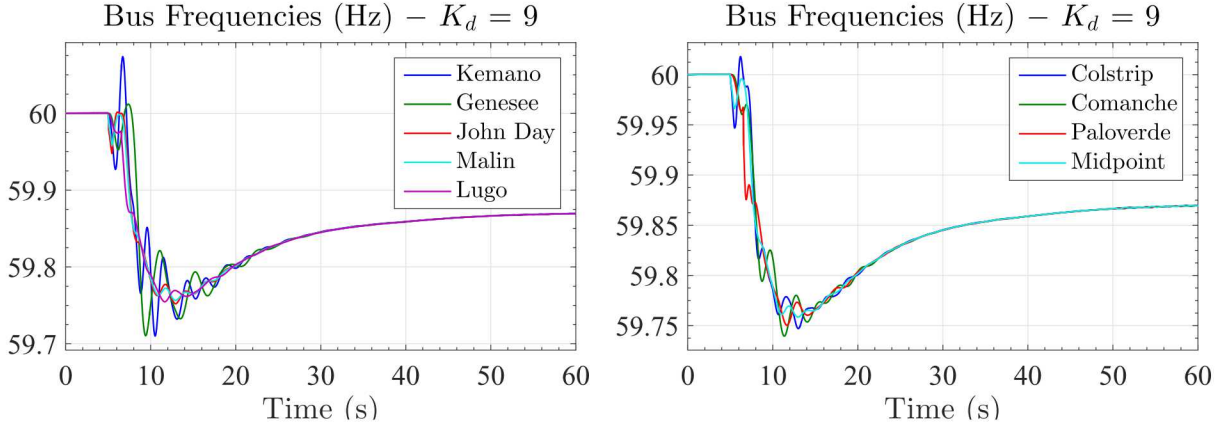


Figure 138. Bus frequencies. Event: CJB + 2PV

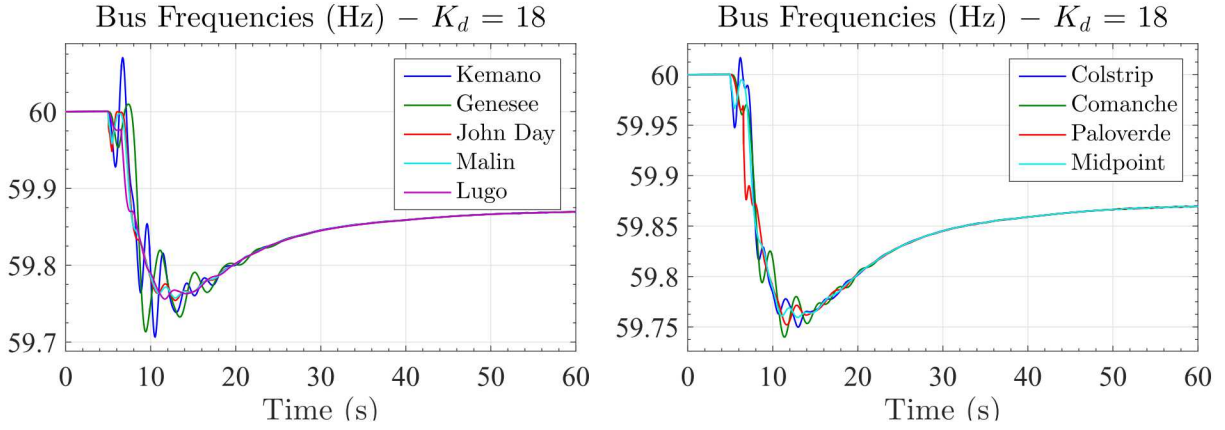


Figure 139. Bus frequencies. Event: CJB + 2PV

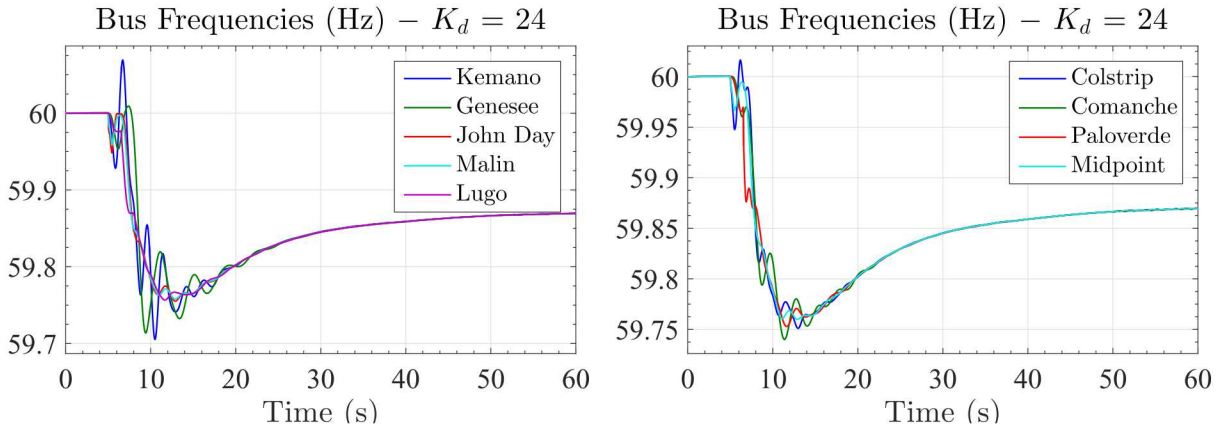


Figure 140. Bus frequencies. Event: CJB + 2PV

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

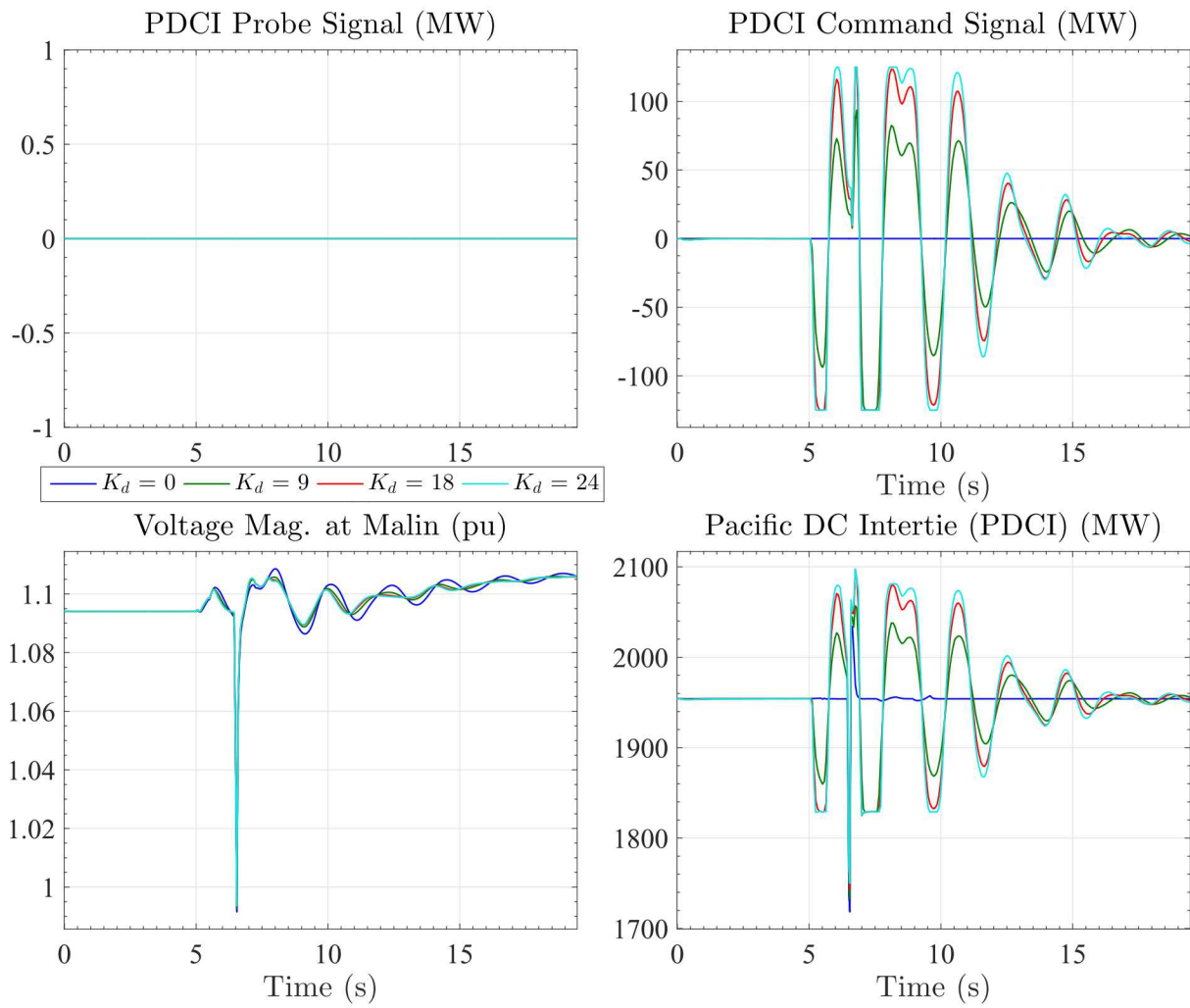


Figure 141. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCUS Separation

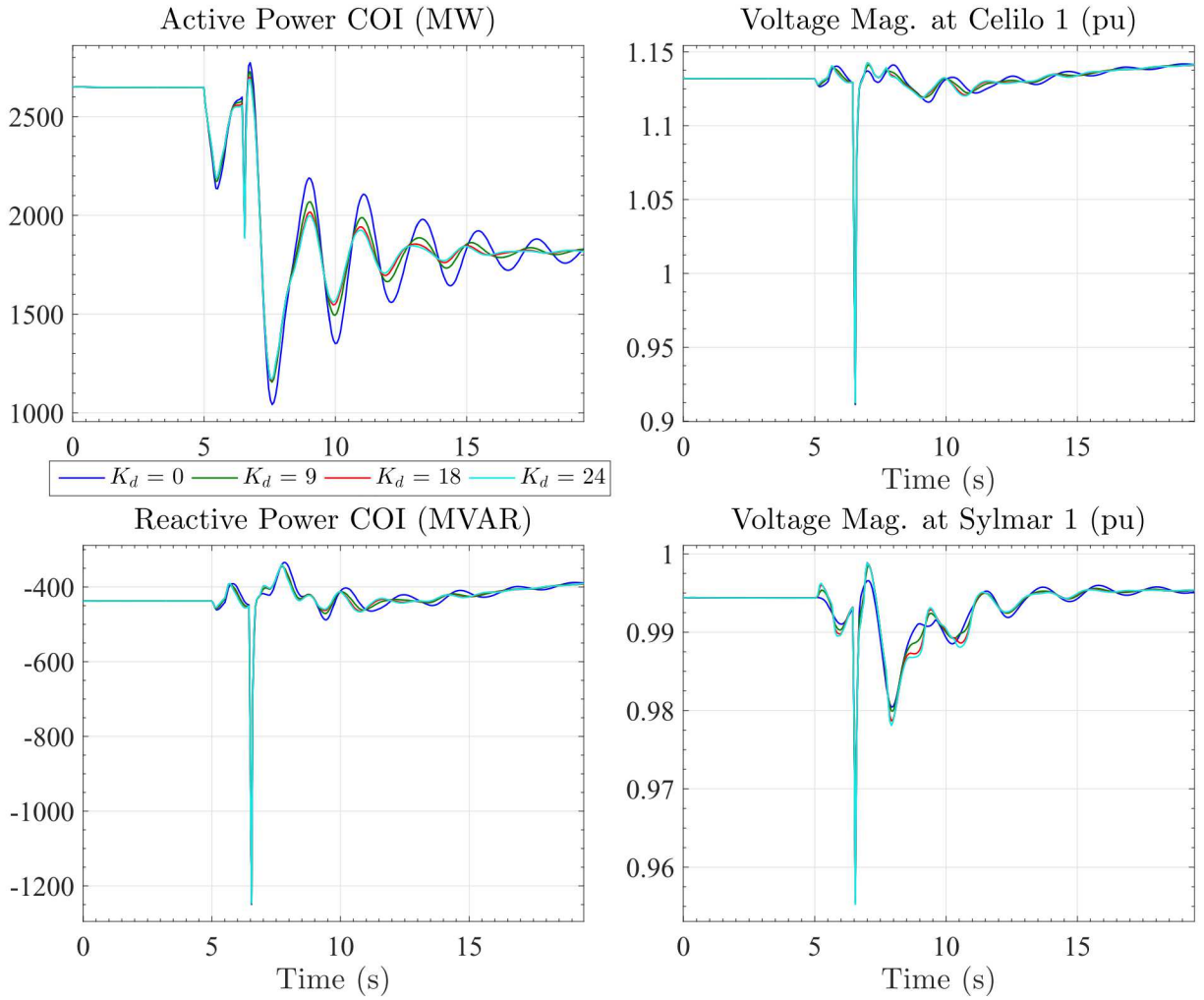


Figure 142. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCUS Separation

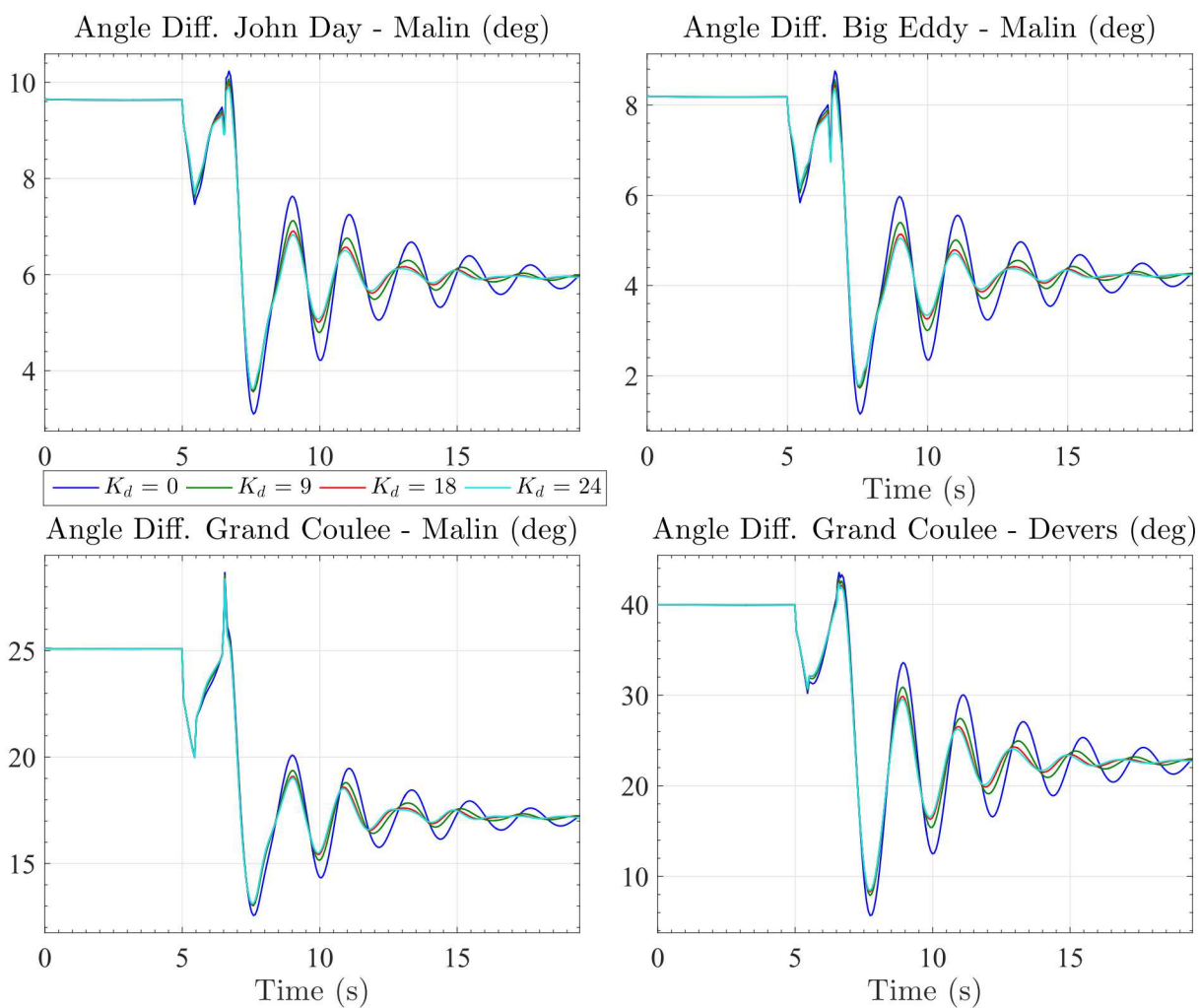


Figure 143. Angle differences. Event: CJB + BCUS Separation

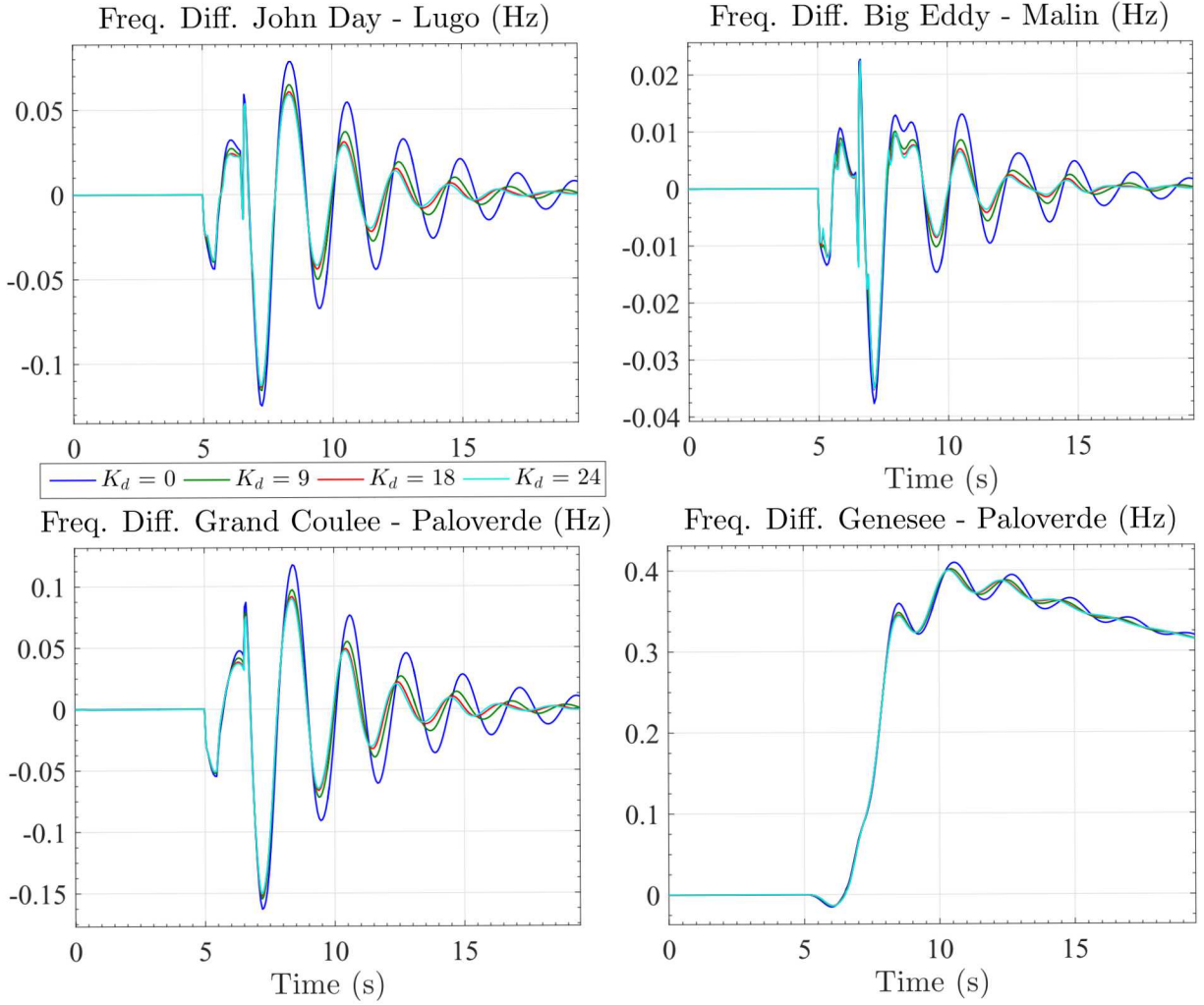


Figure 144. Frequency differences. Event: CJB + BCUS Separation

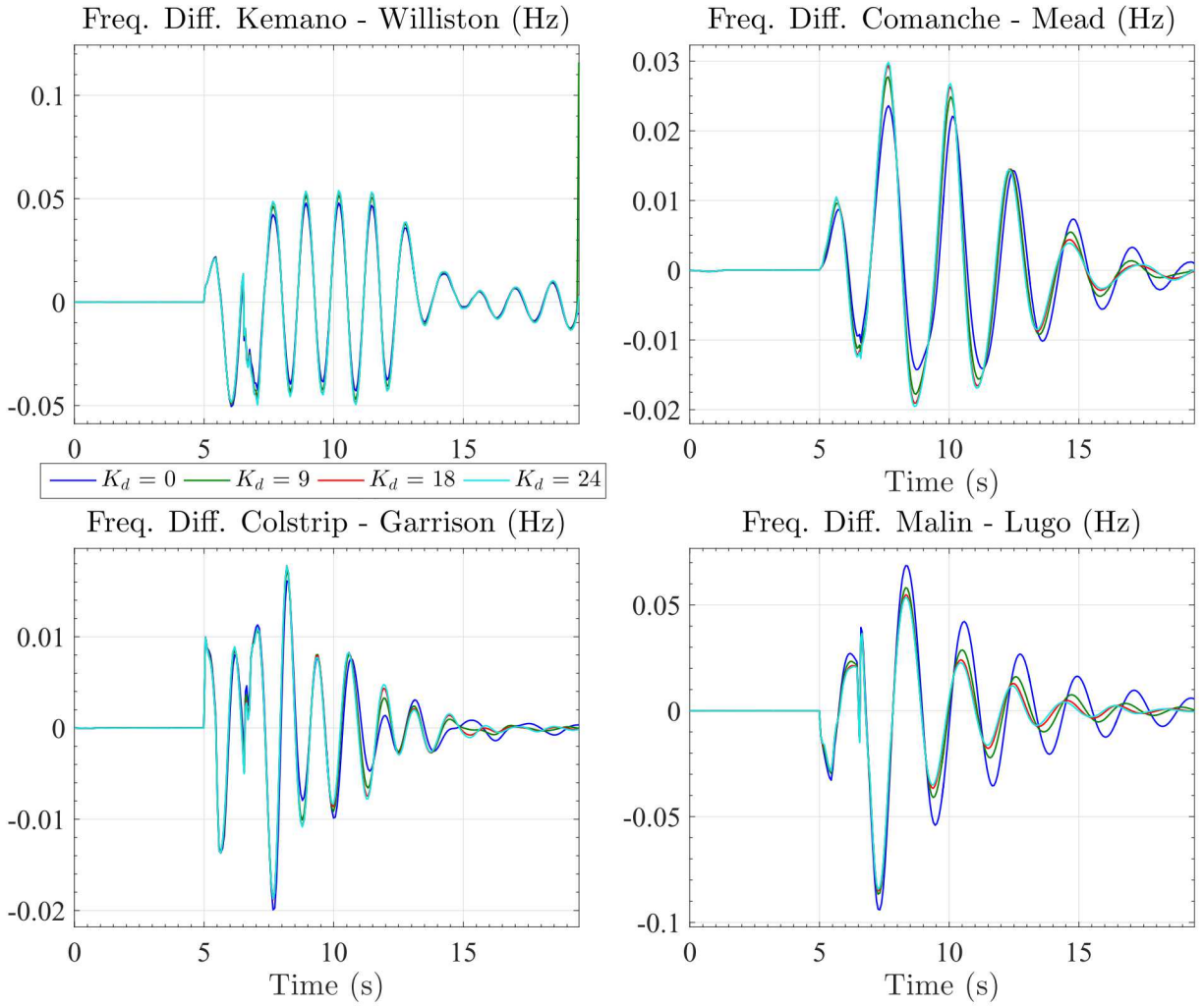


Figure 145. Frequency differences. Event: CJB + BCUS Separation

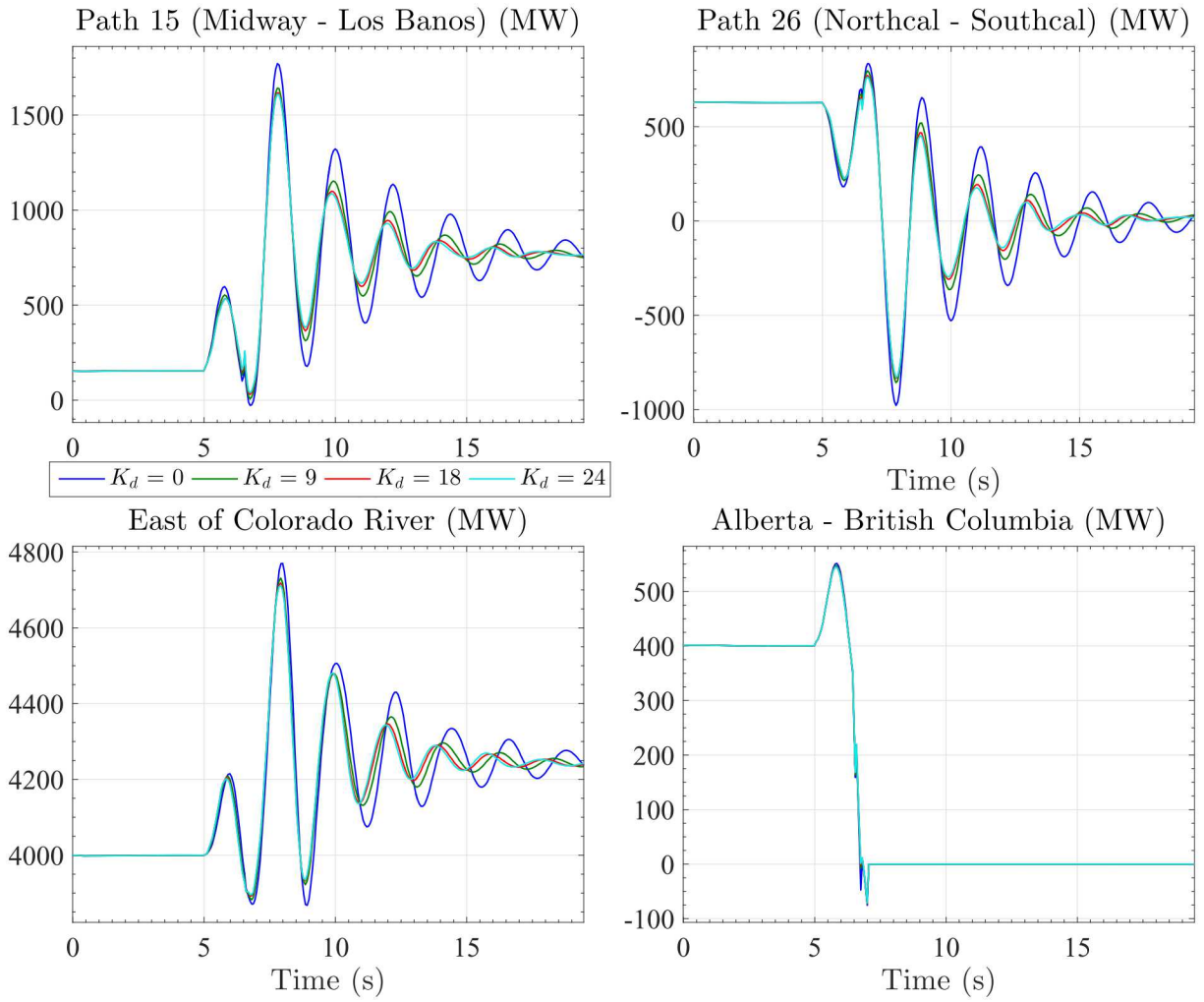


Figure 146. Active power flows. Event: CJB + BCUS Separation

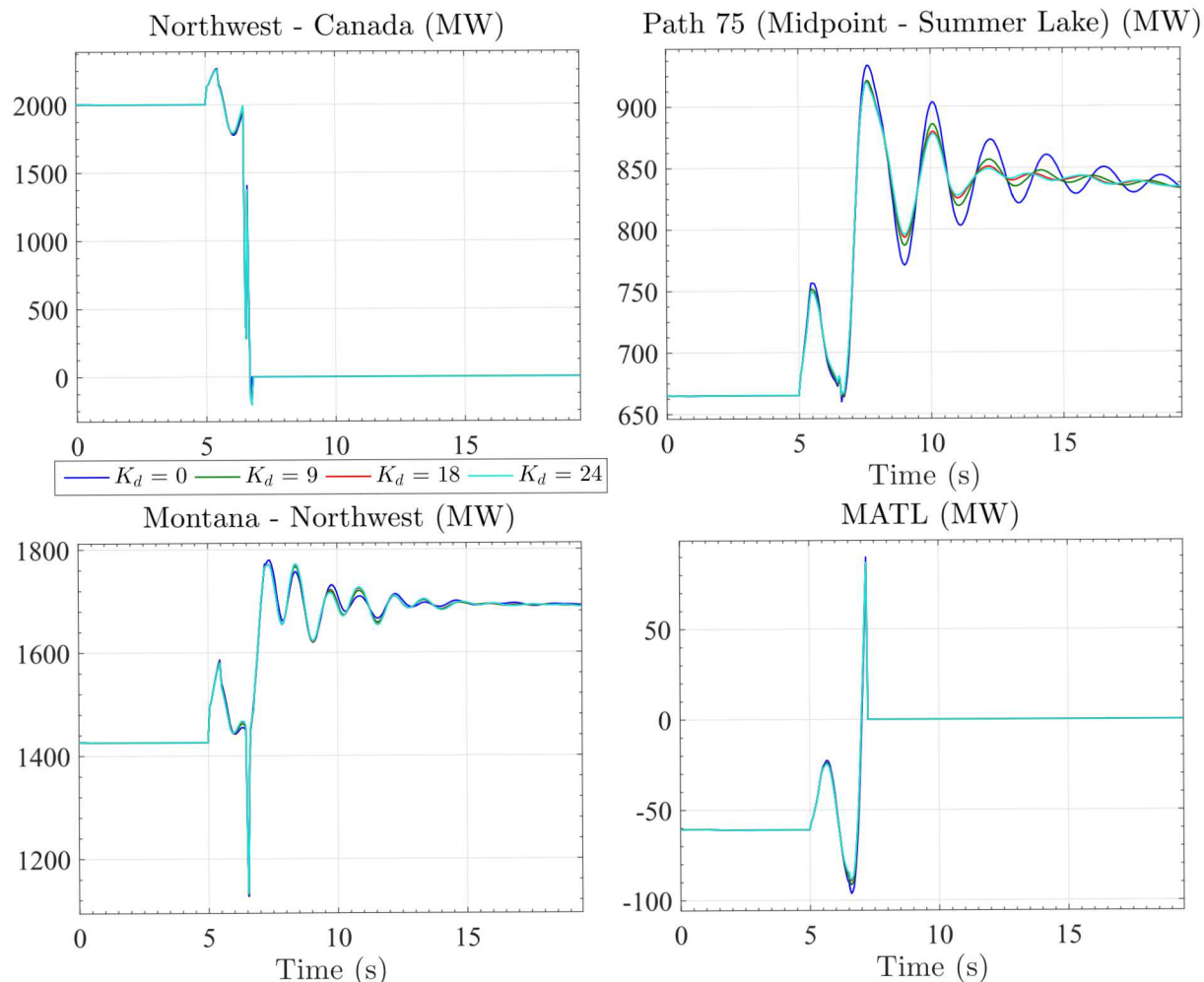


Figure 147. Active power flows. Event: CJB + BCUS Separation

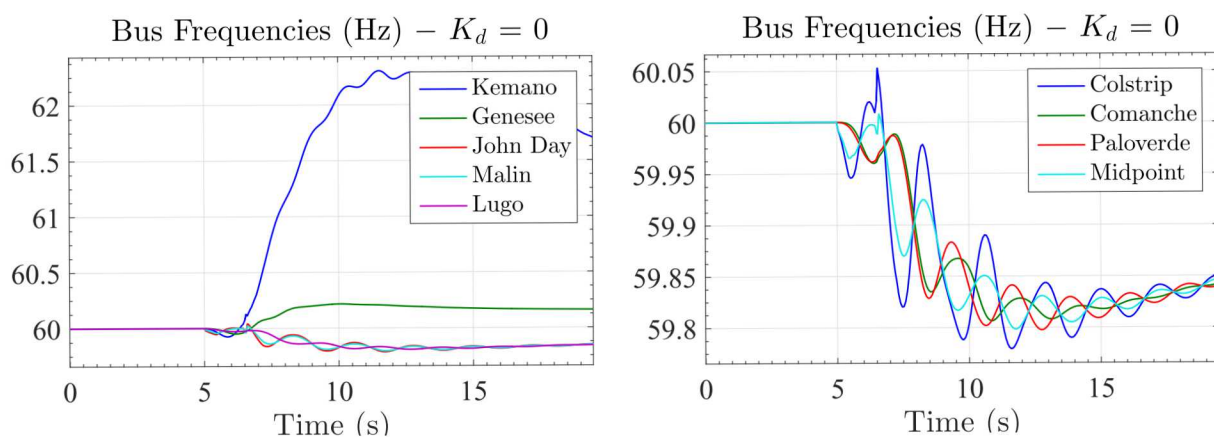


Figure 148. Bus frequencies. Event: CJB + BCUS Separation

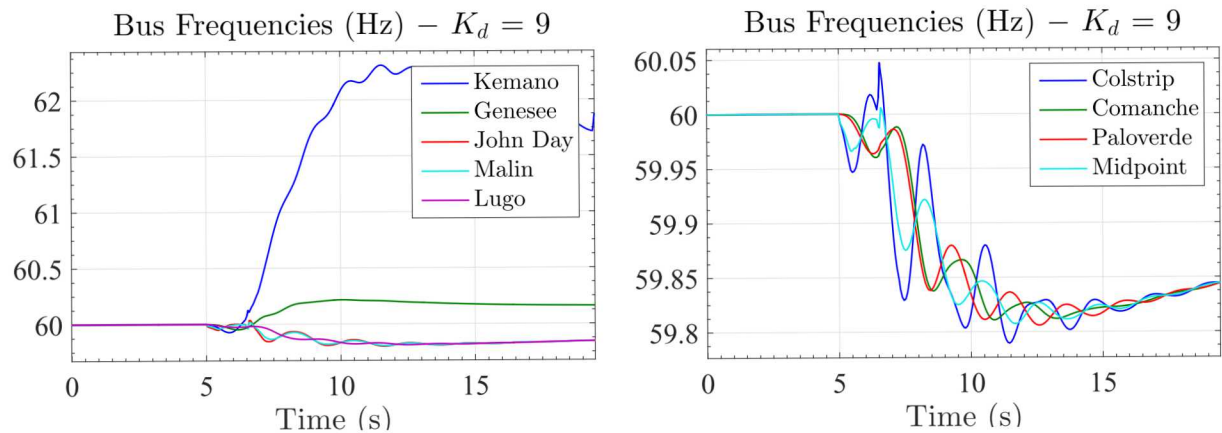


Figure 149. Bus frequencies. Event: CJB + BCUS Separation

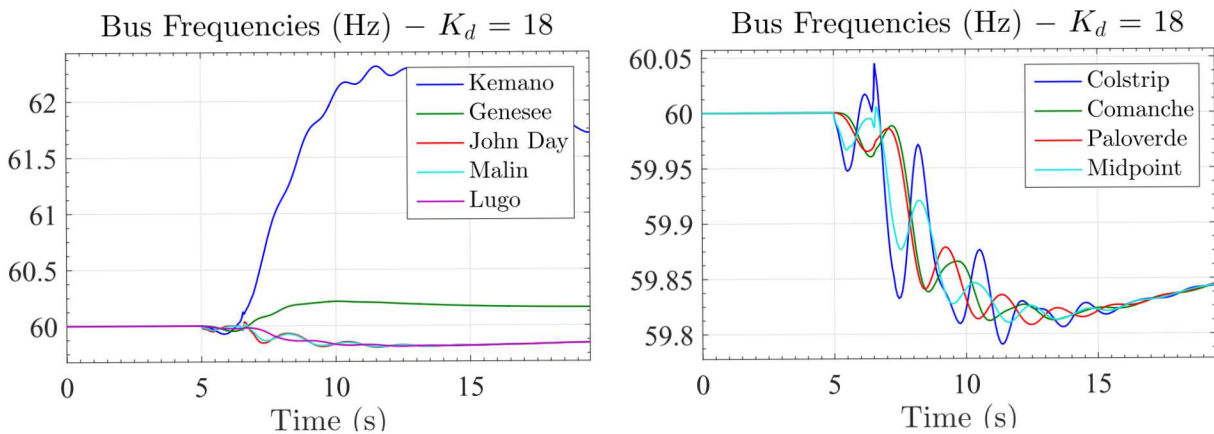


Figure 150. Bus frequencies. Event: CJB + BCUS Separation

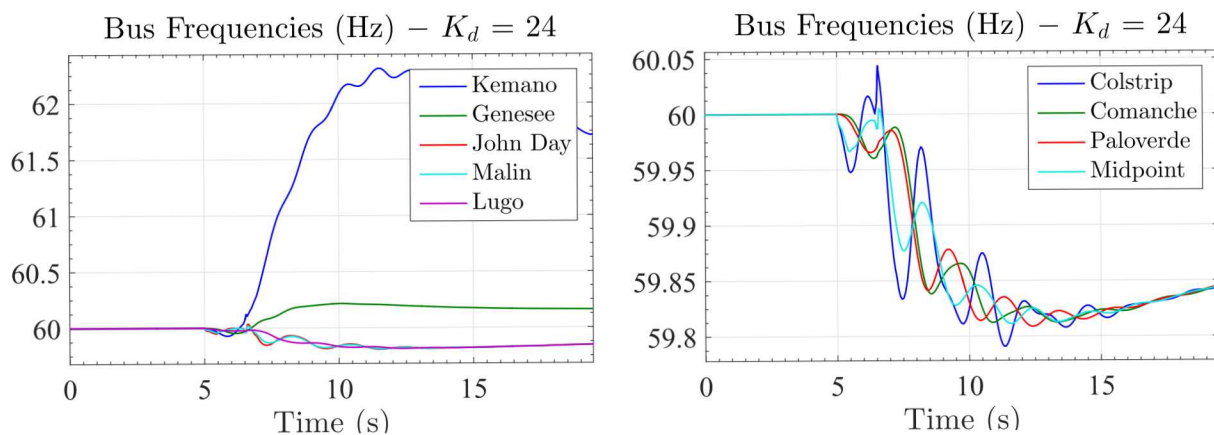


Figure 151. Bus frequencies. Event: CJB + BCUS Separation

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

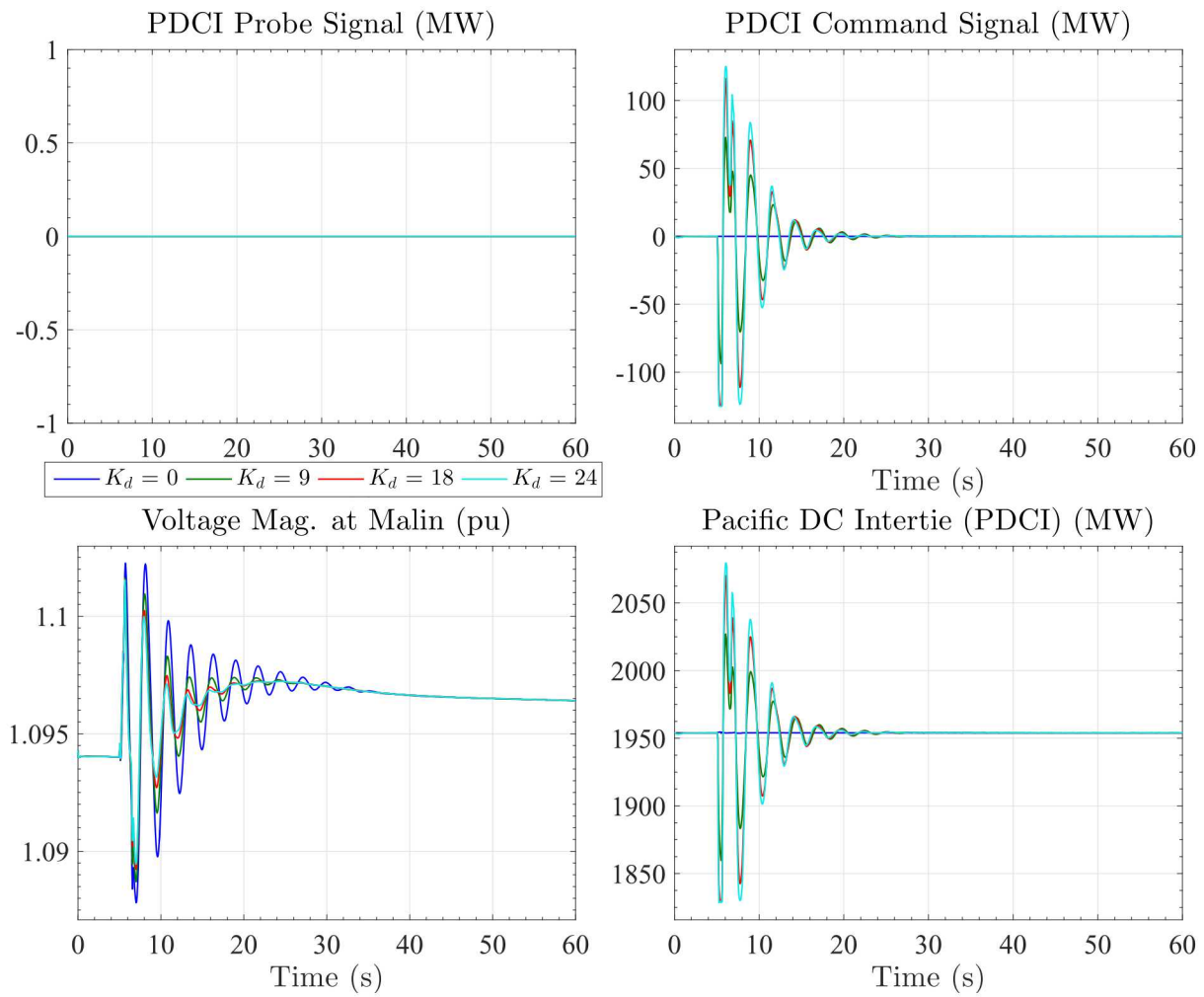


Figure 152. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: CJB + BCAB Separation

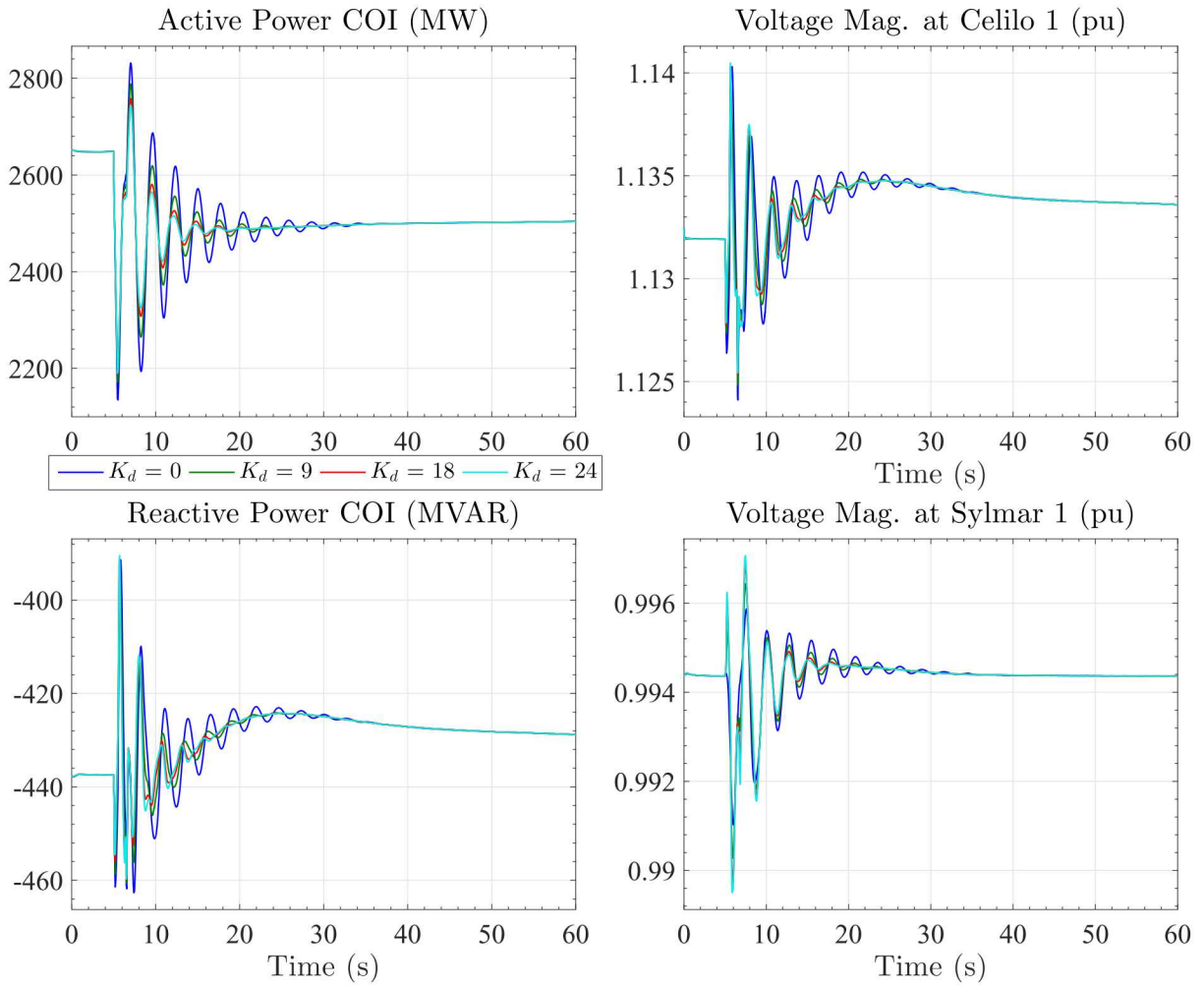


Figure 153. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: CJB + BCAB Separation

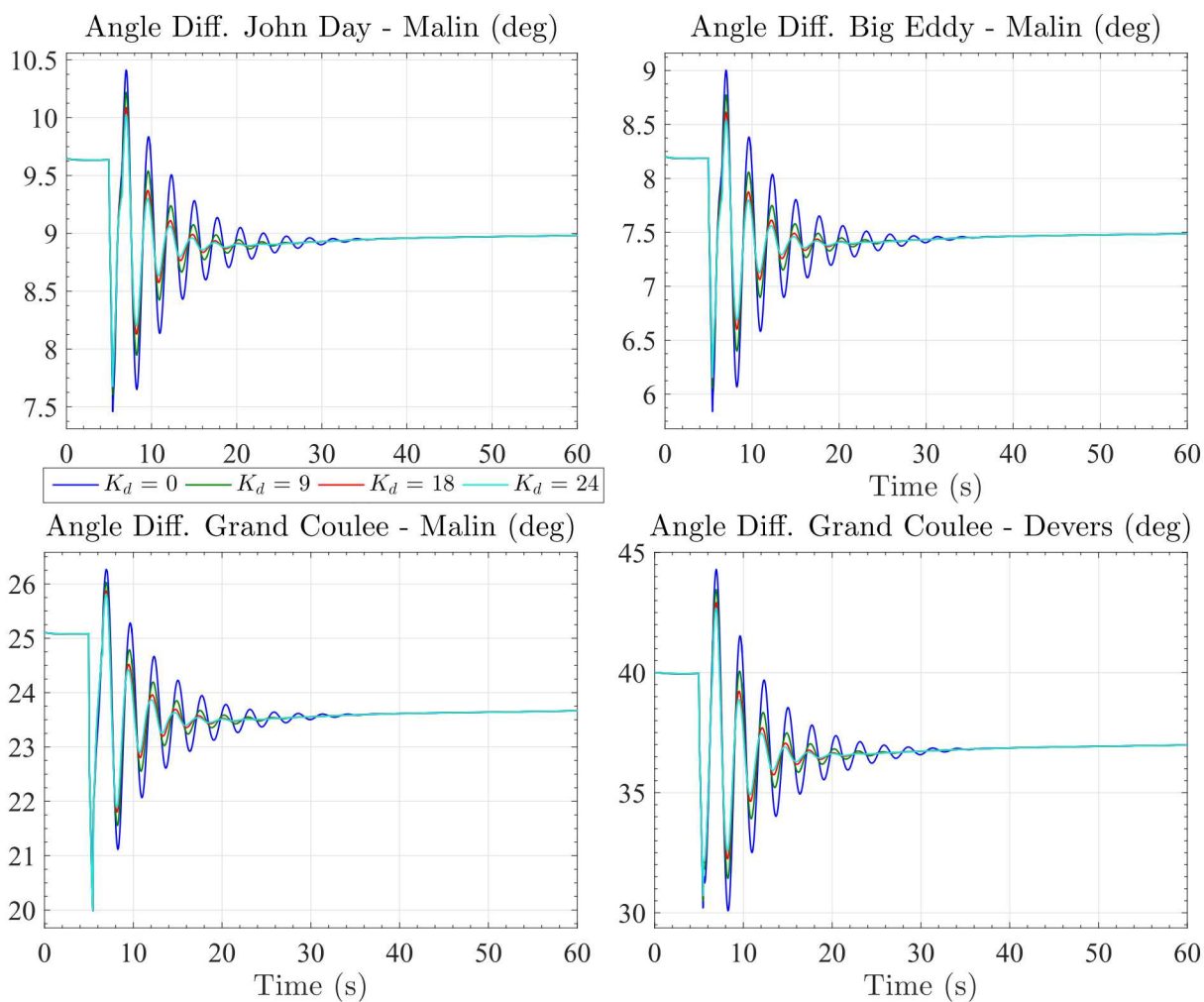


Figure 154. Angle differences. Event: CJB + BCAB Separation

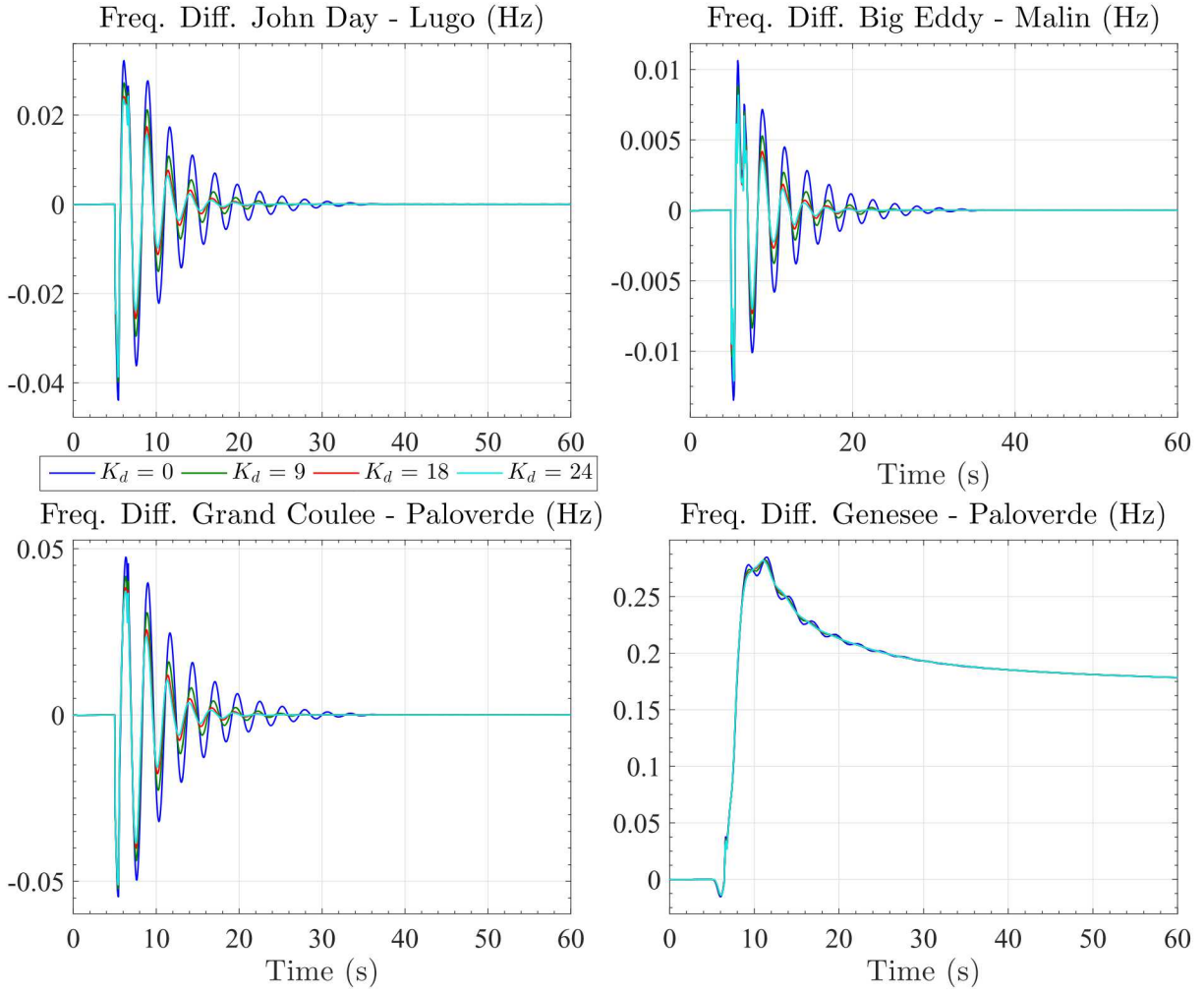


Figure 155. Frequency differences. Event: CJB + BCAB Separation

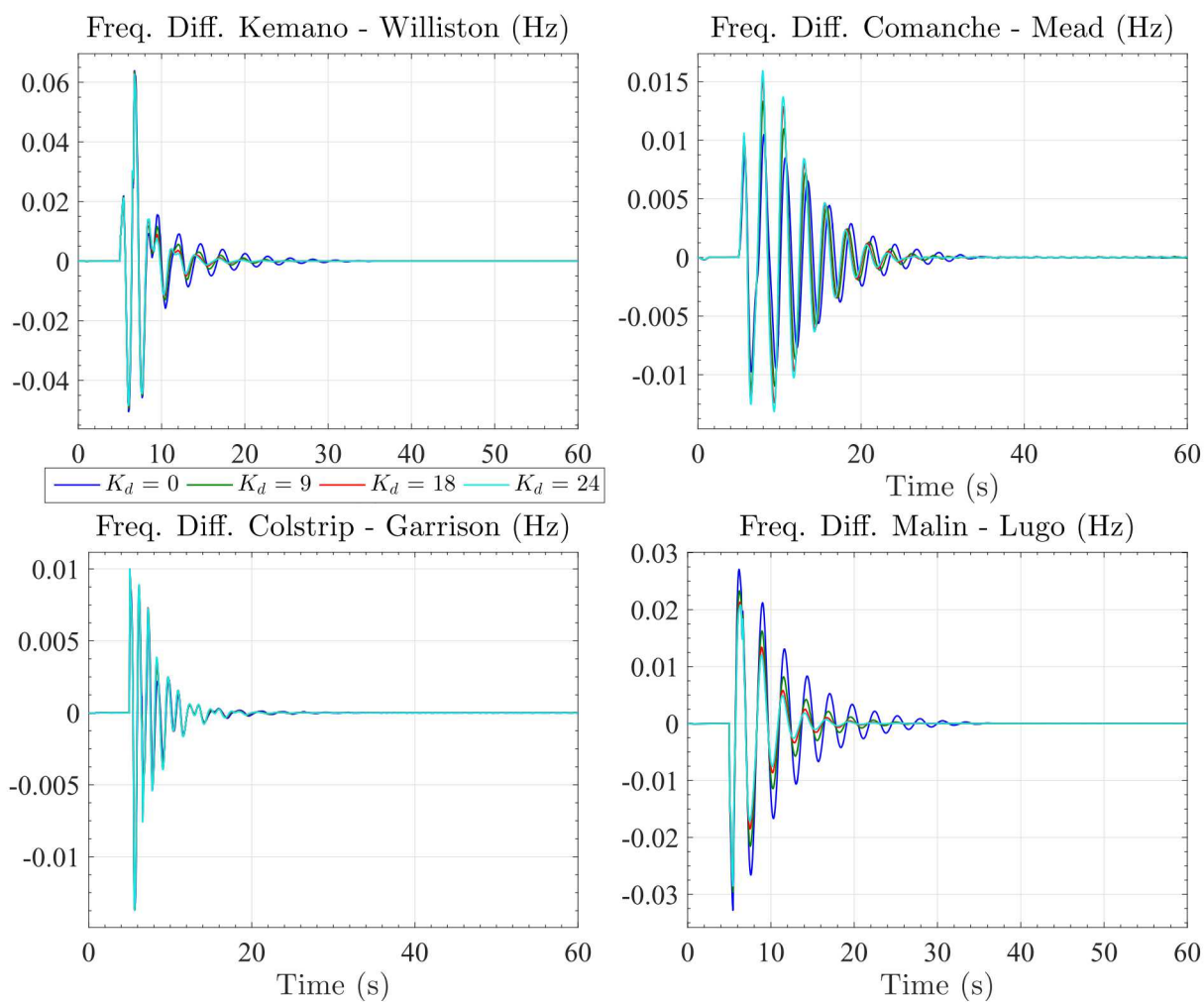


Figure 156. Frequency differences. Event: CJB + BCAB Separation

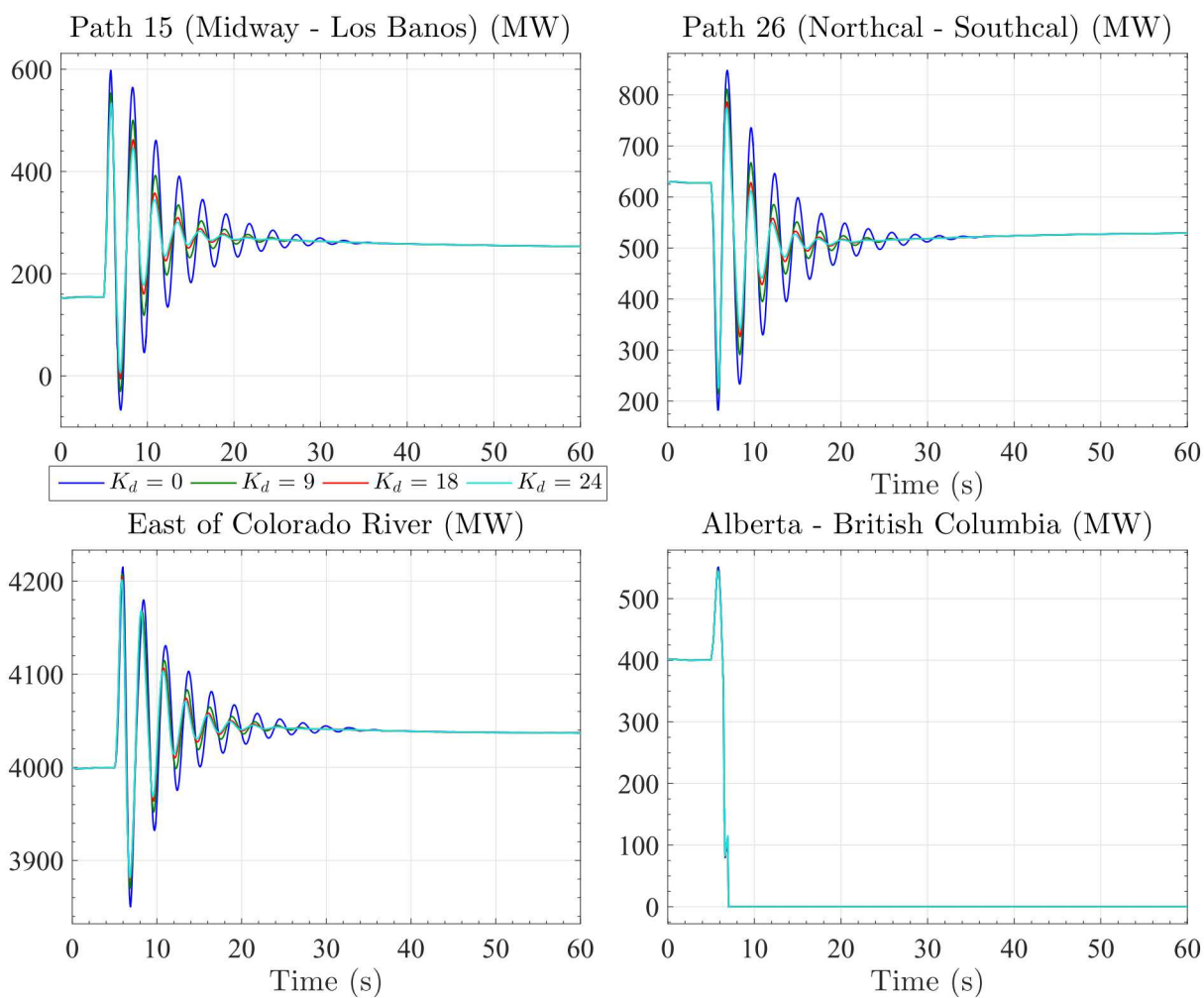


Figure 157. Active power flows. Event: CJB + BCAB Separation

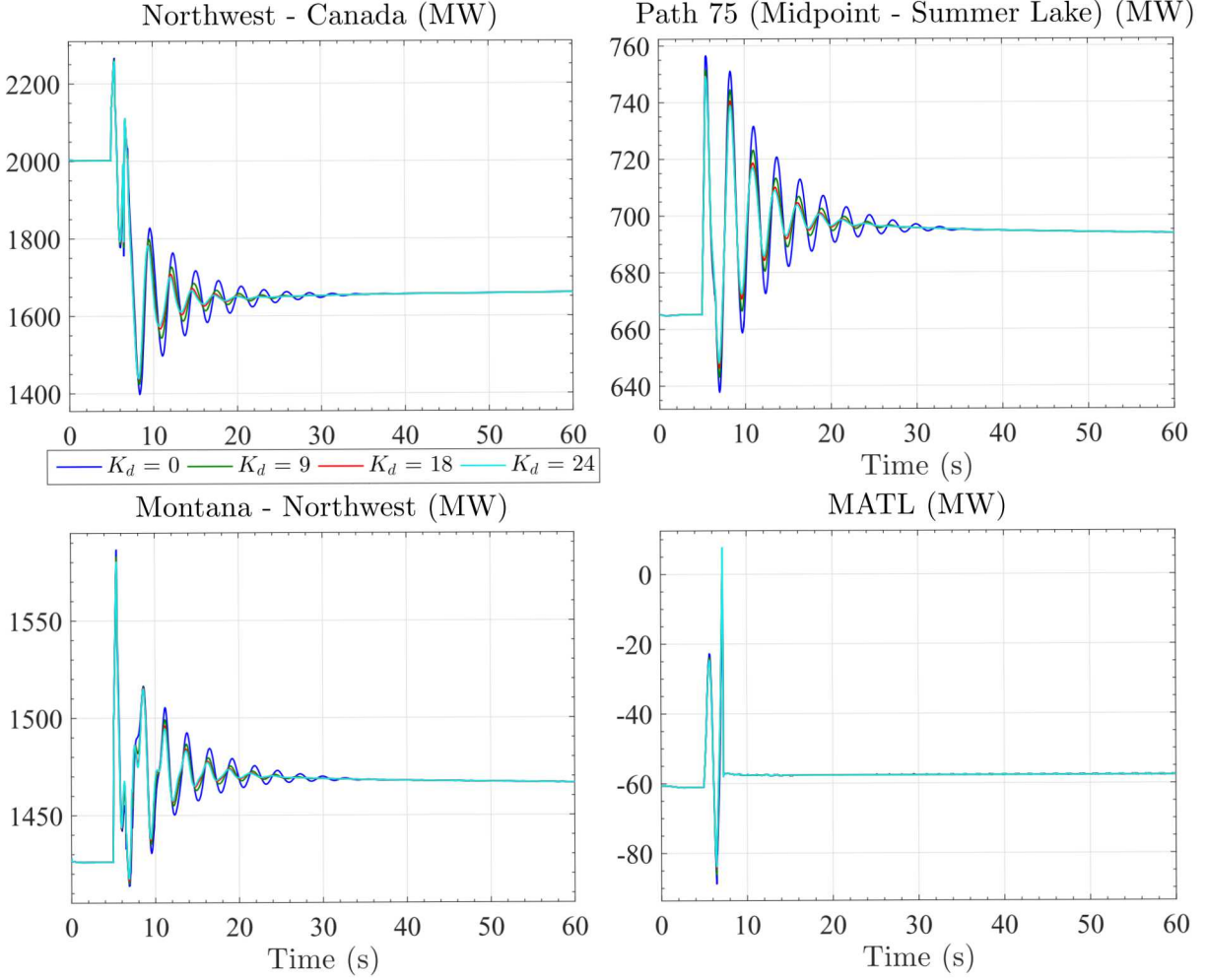


Figure 158. Active power flows. Event: CJB + BCAB Separation

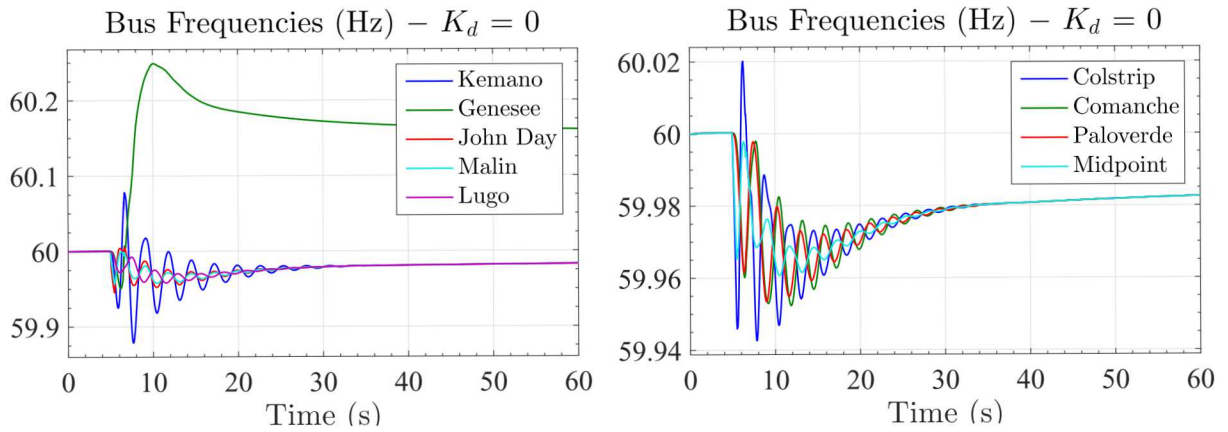


Figure 159. Bus frequencies. Event: CJB + BCAB Separation

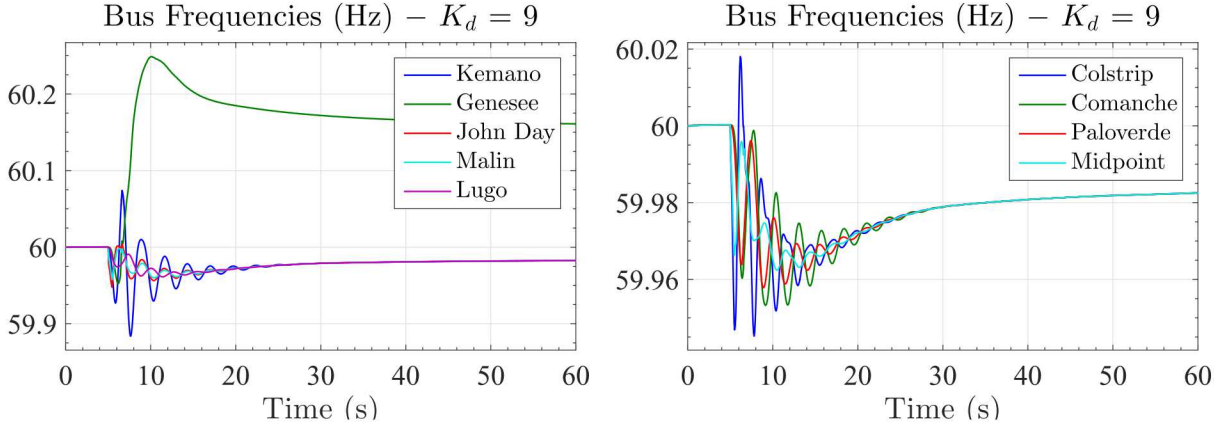


Figure 160. Bus frequencies. Event: CJB + BCAB Separation

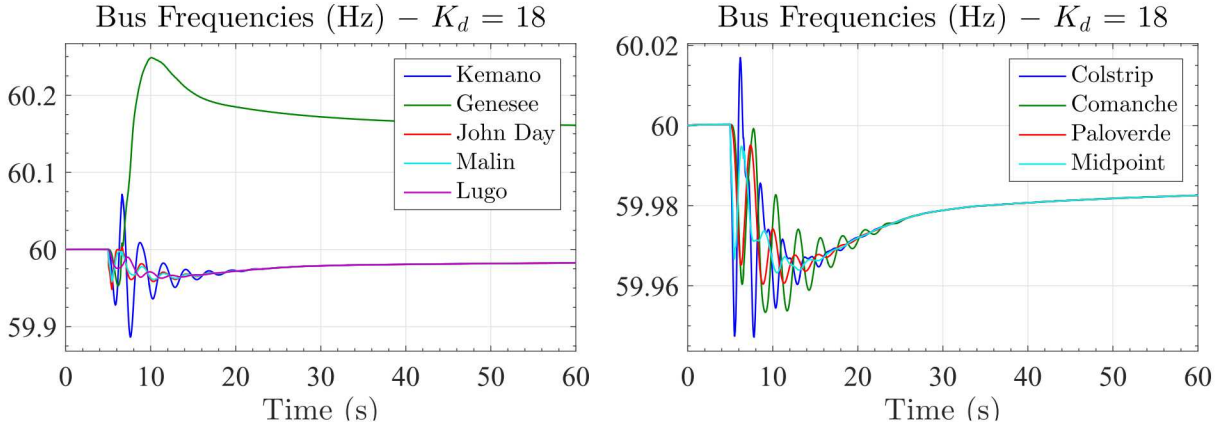


Figure 161. Bus frequencies. Event: CJB + BCAB Separation

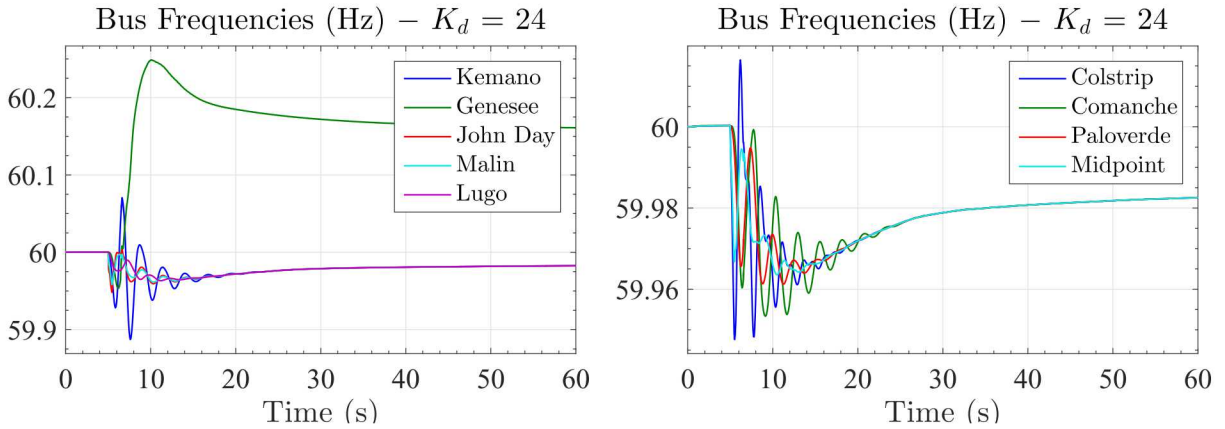


Figure 162. Bus frequencies. Event: CJB + BCAB Separation

4. CHIEF JOSEPH BRAKE COMPARISON

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

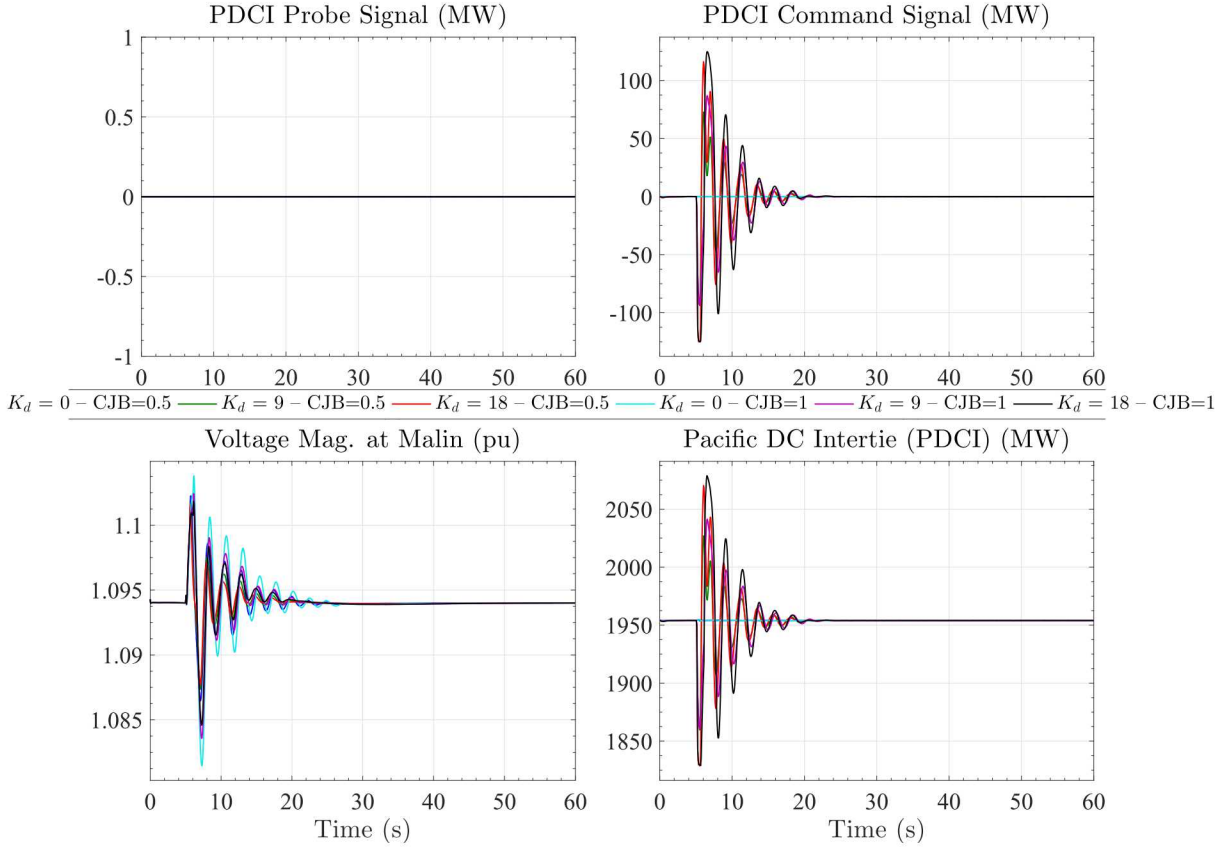


Figure 163. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

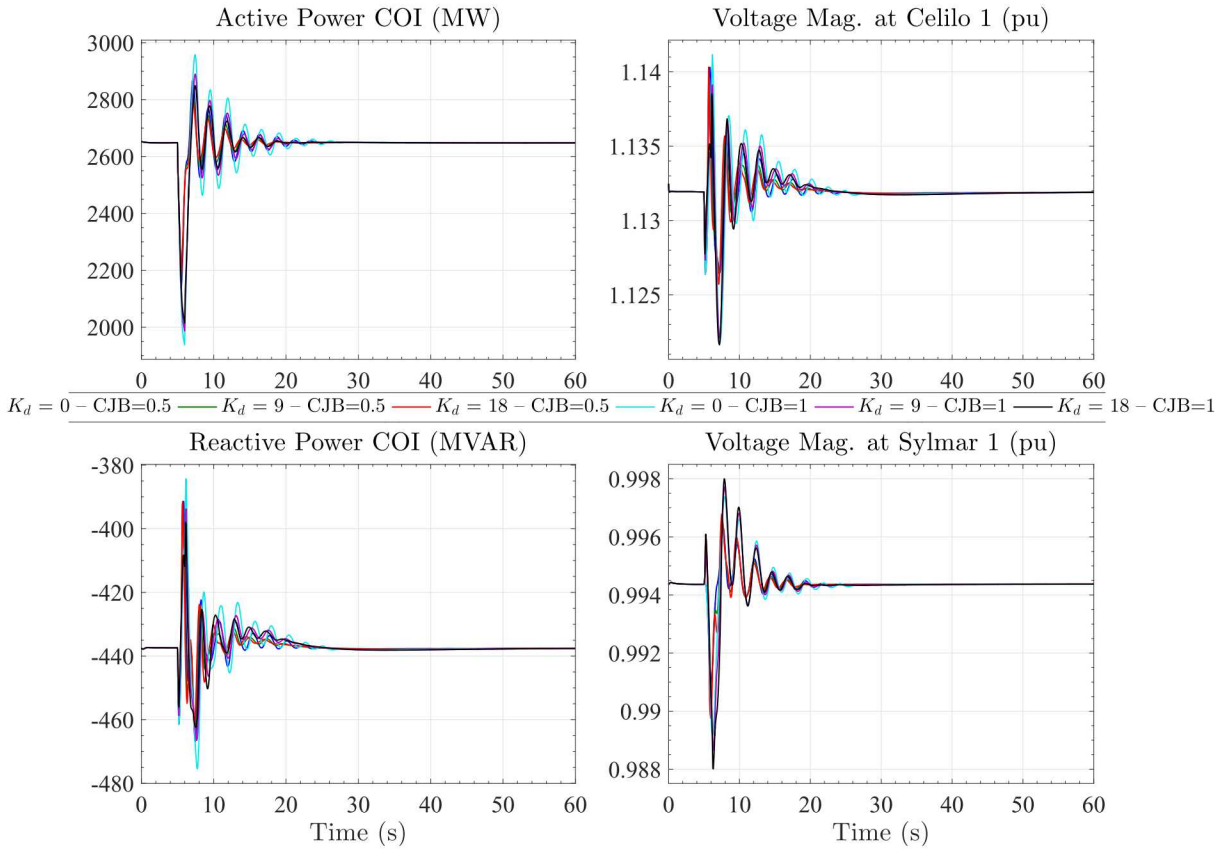


Figure 164. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

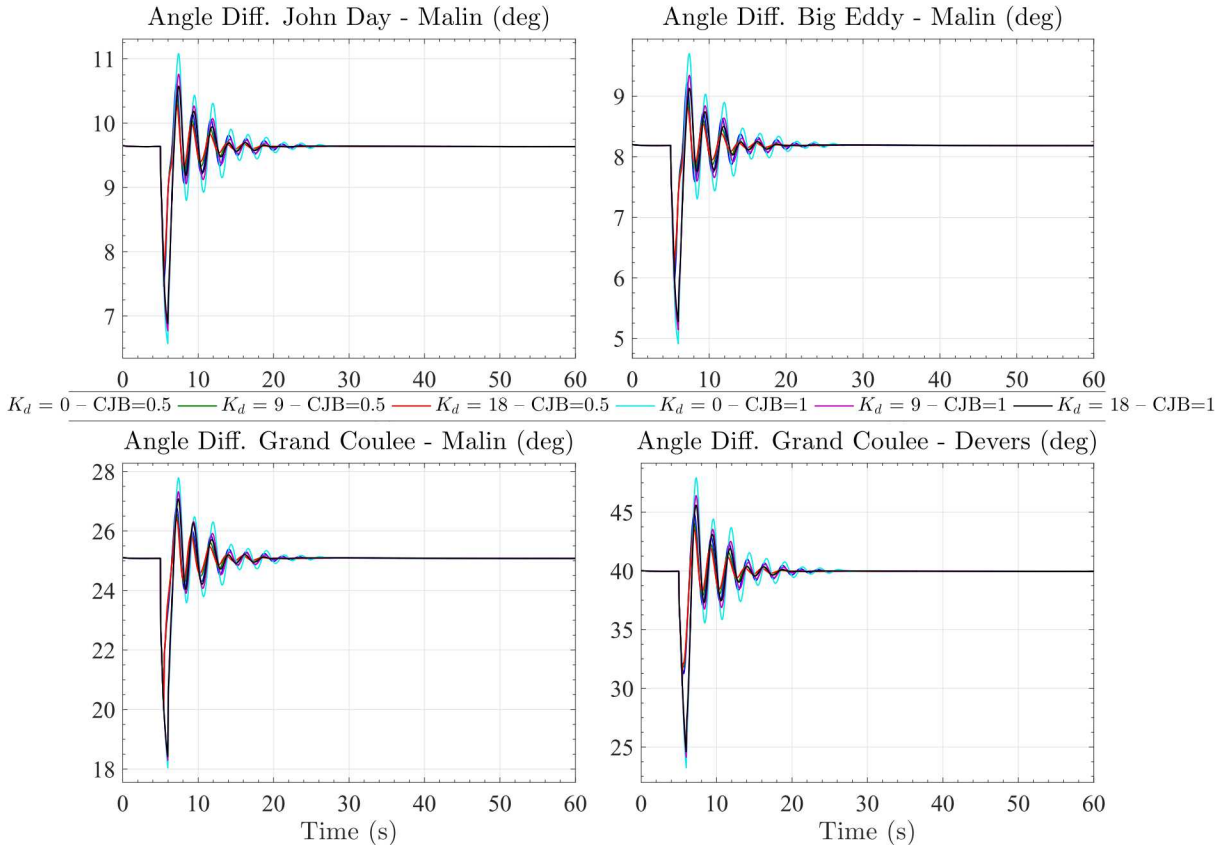


Figure 165. Angle differences. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

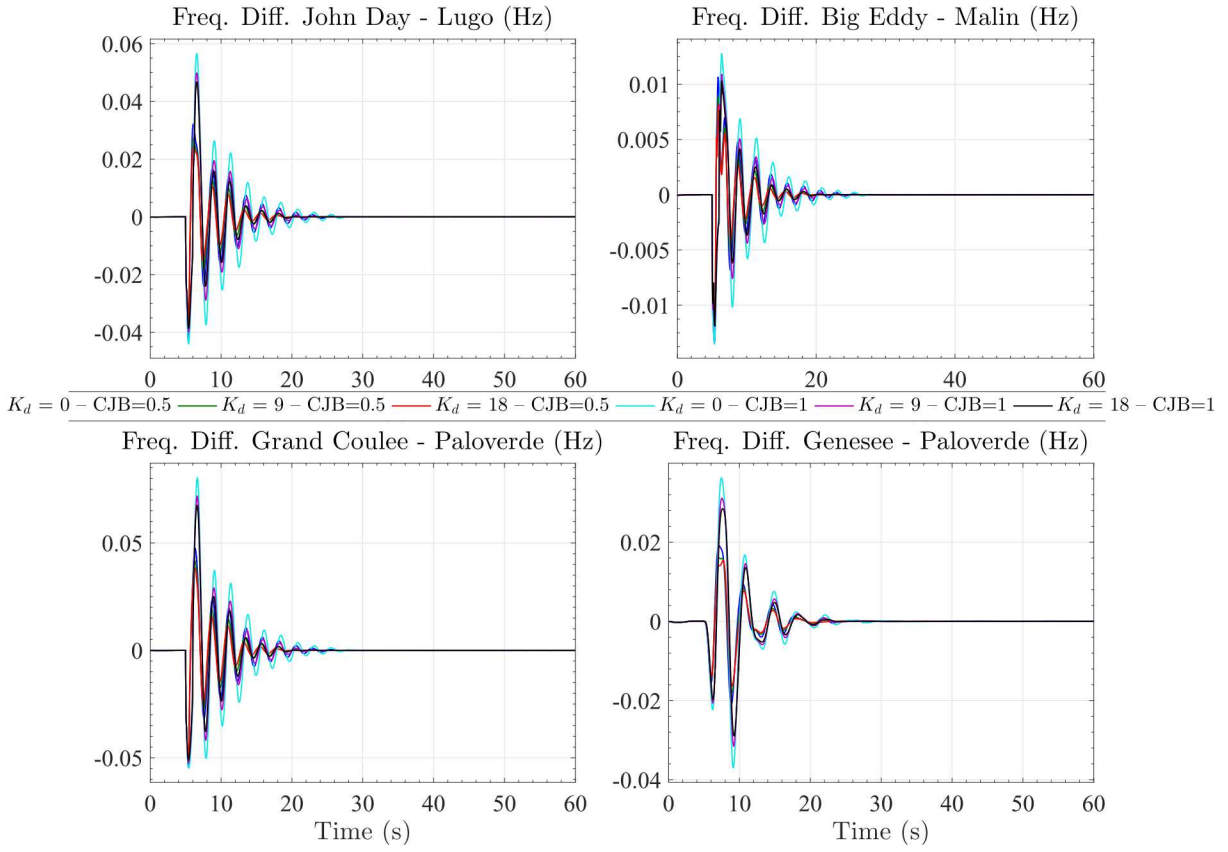


Figure 166. Frequency differences. Event: Chief Joseph Brake 0.5 sec, $Kd = 0$

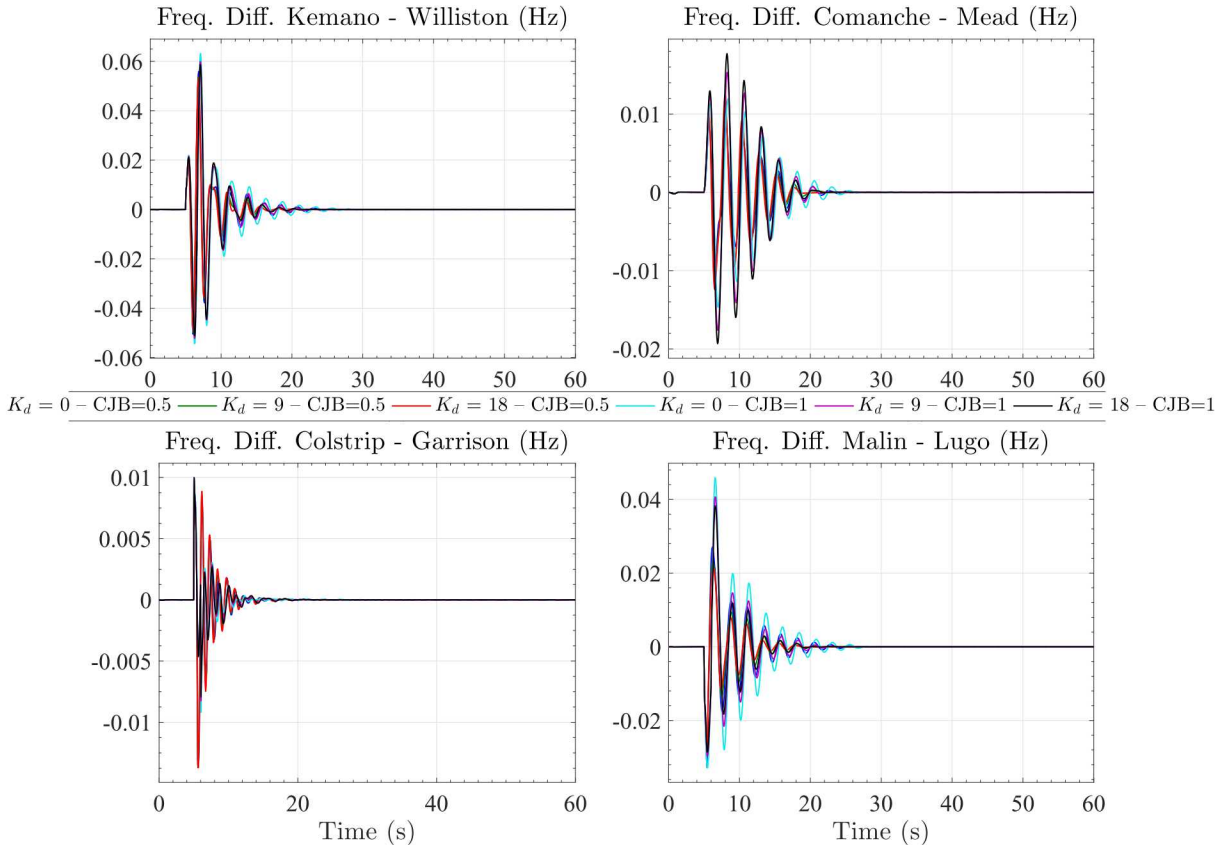


Figure 167. Frequency differences. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

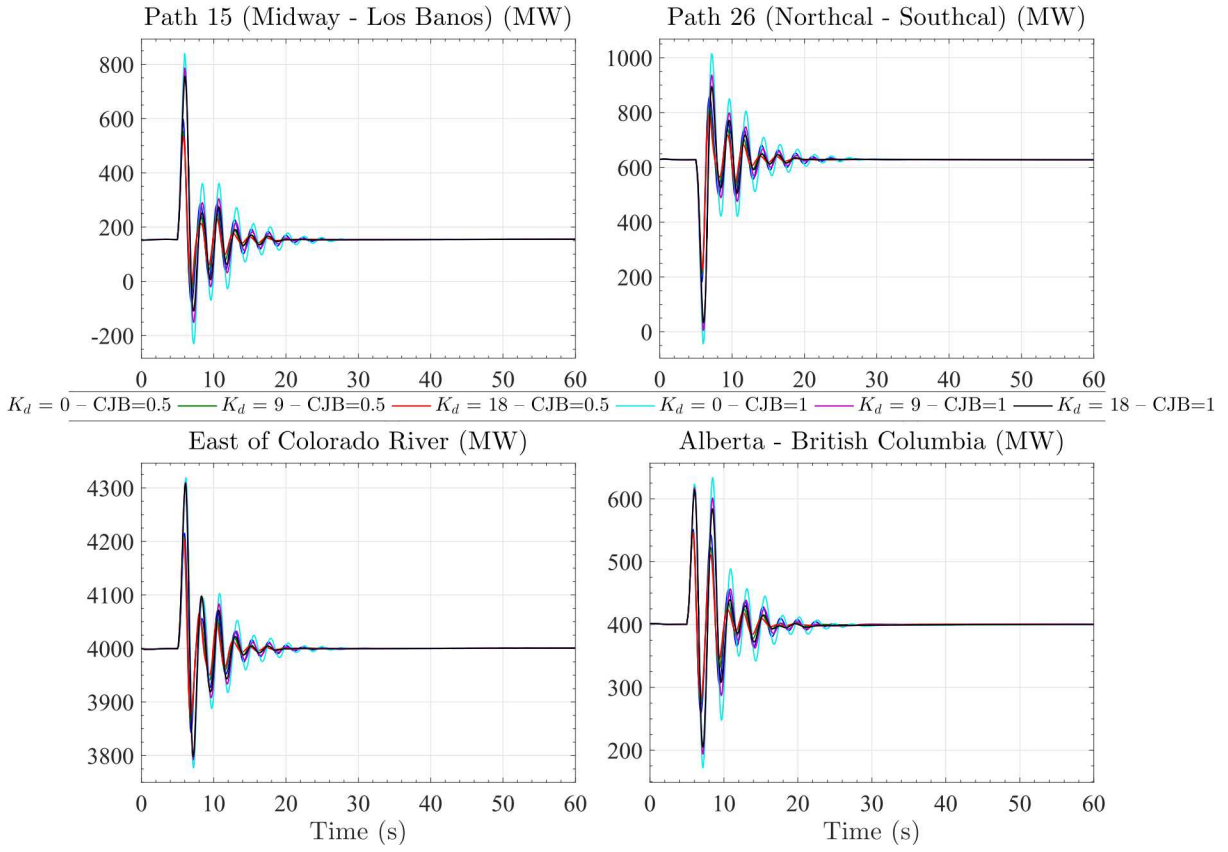


Figure 168. Active power flows. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

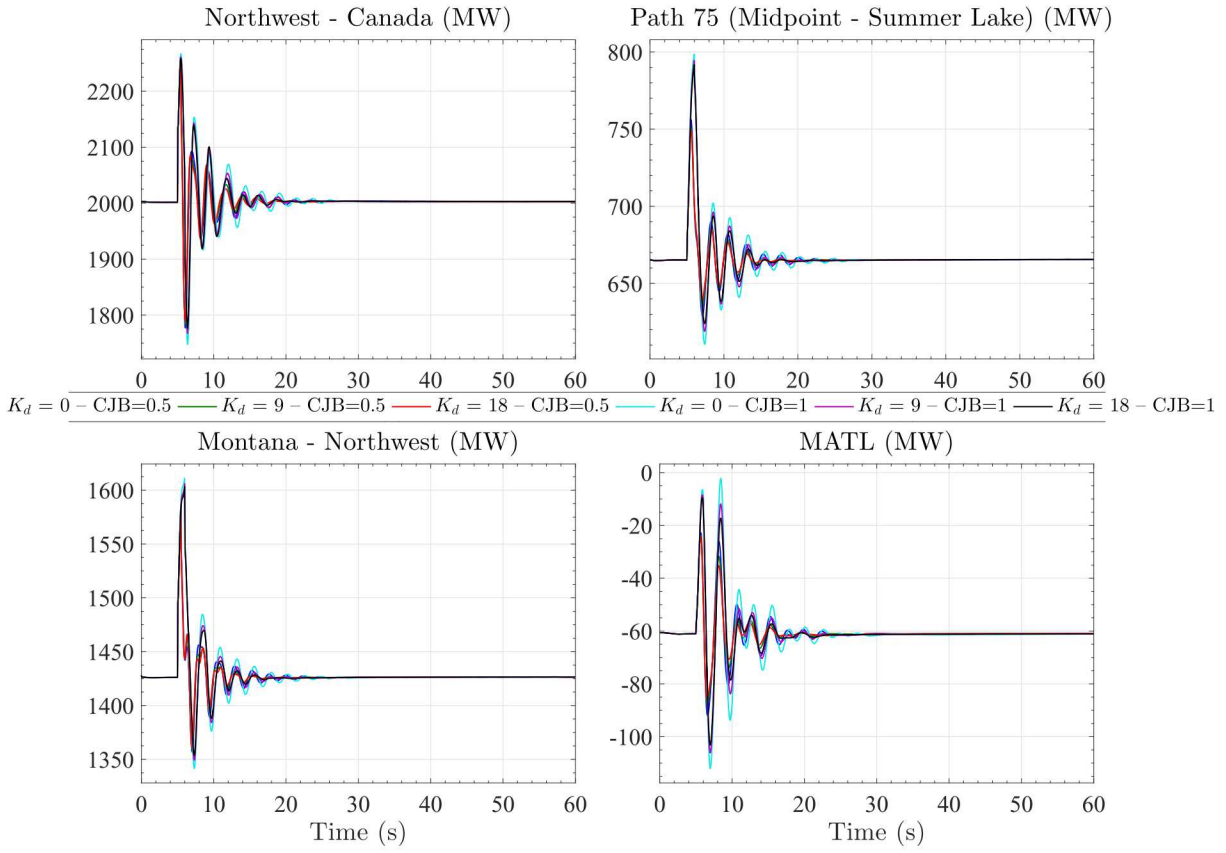


Figure 169. Active power flows. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

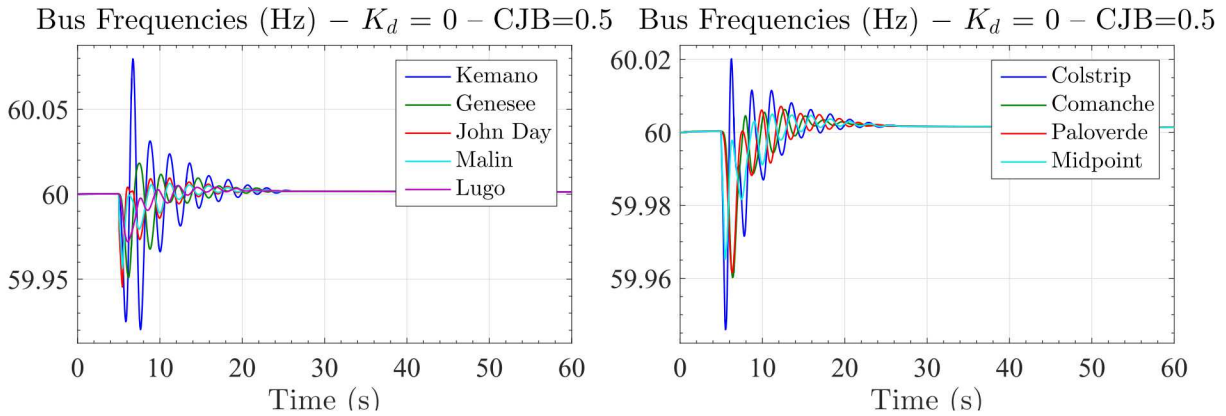


Figure 170. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

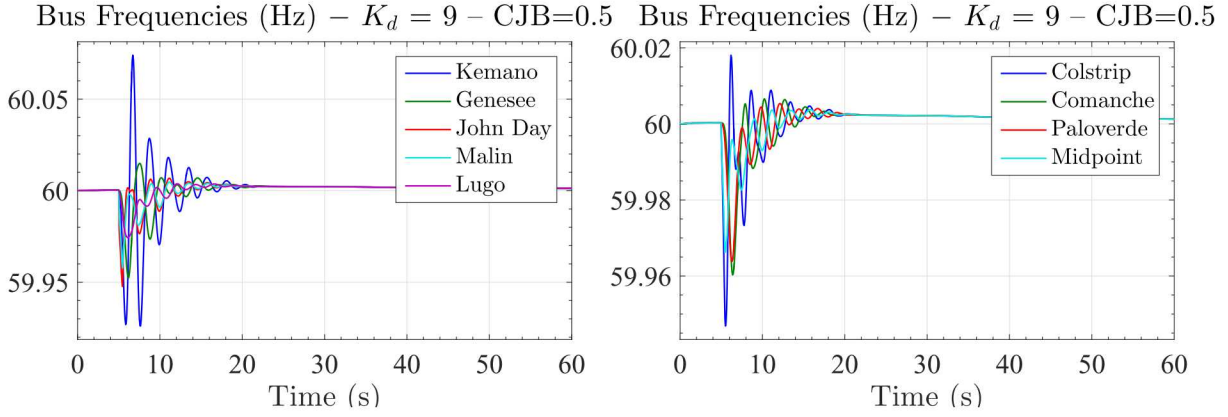


Figure 171. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

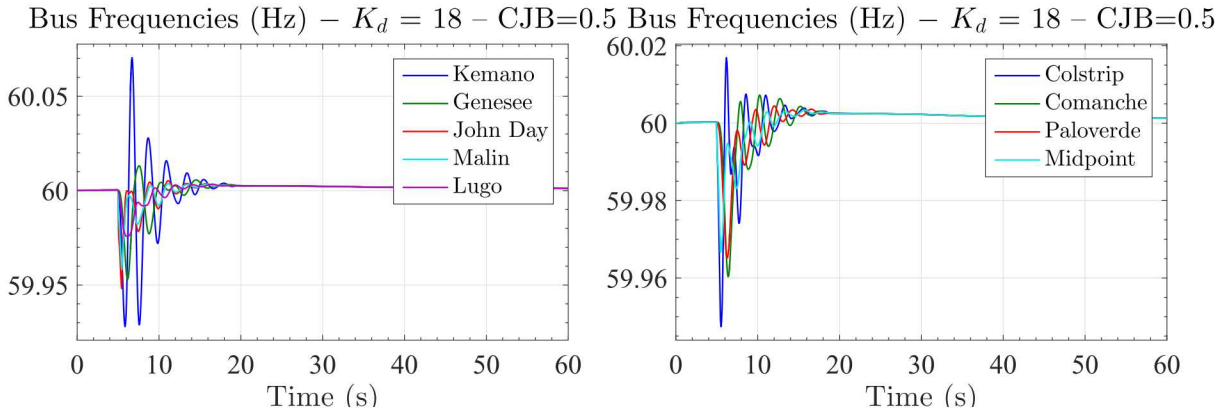


Figure 172. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

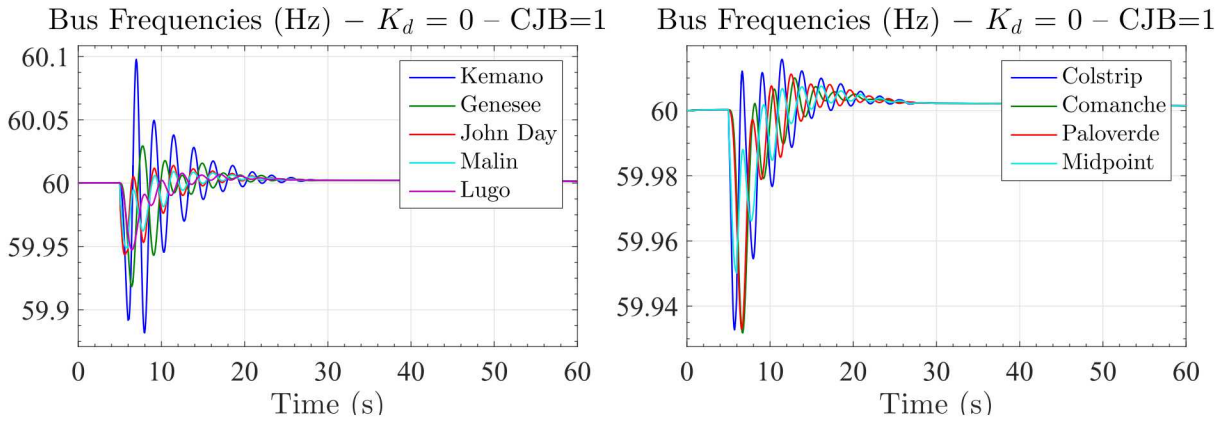


Figure 173. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

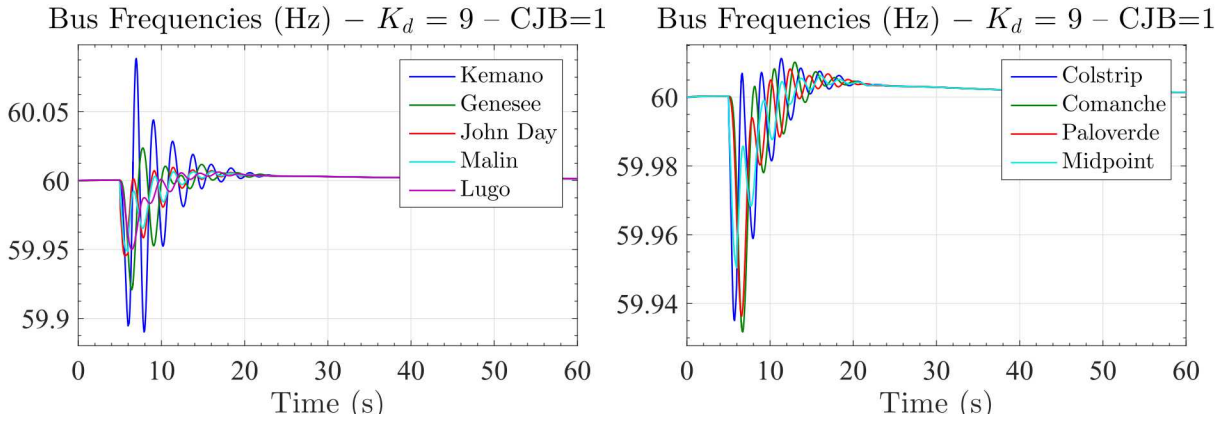


Figure 174. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

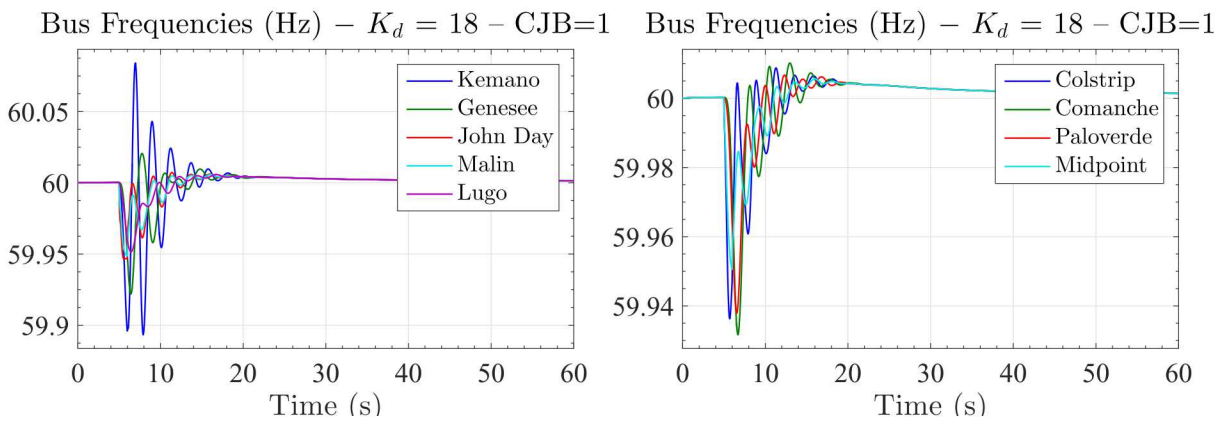


Figure 175. Bus frequencies. Event: Chief Joseph Brake 0.5 sec, $K_d = 0$

5. FORCED OSCILLATIONS (HIGHER FREQUENCIES)

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

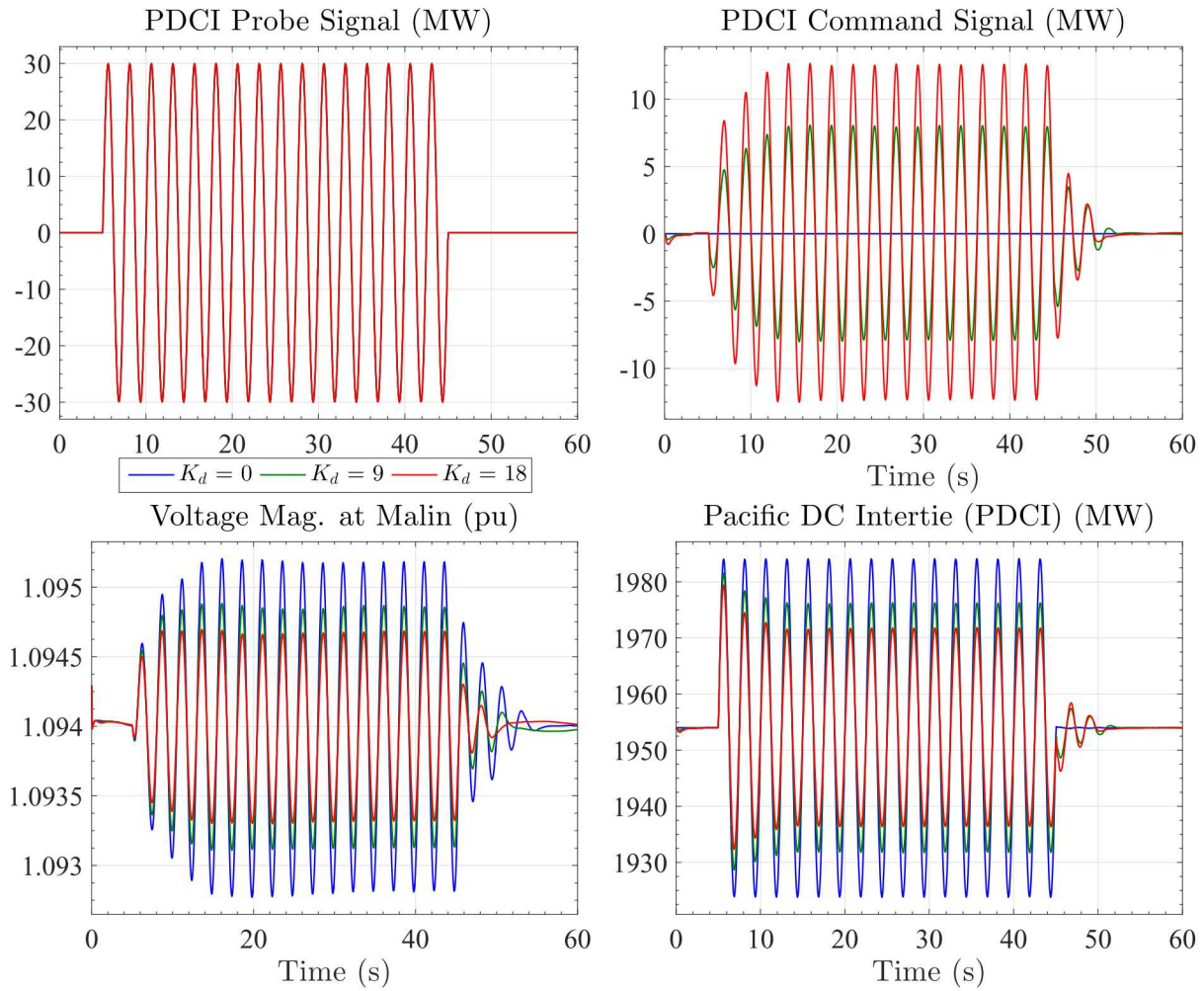


Figure 176. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

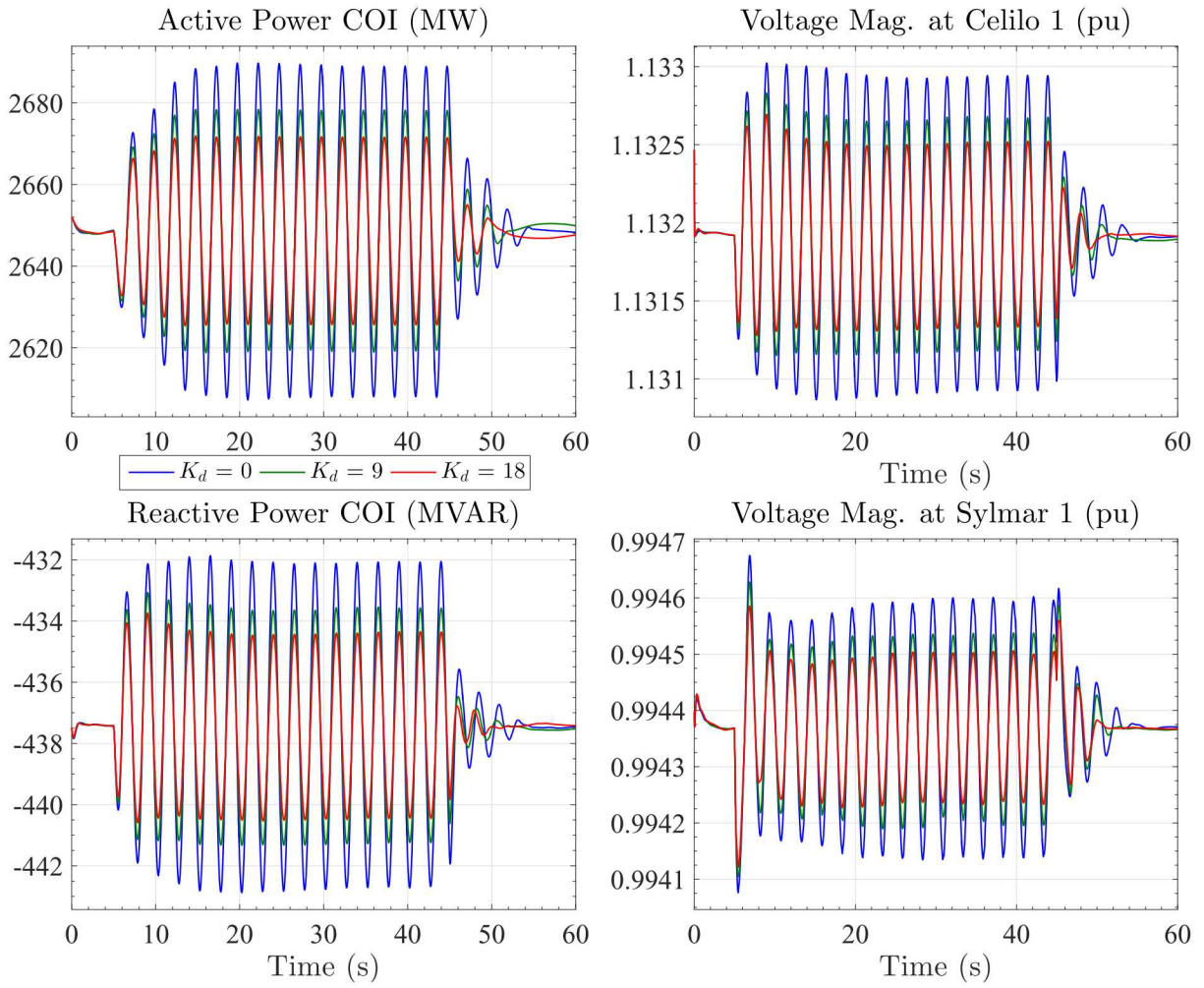


Figure 177. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

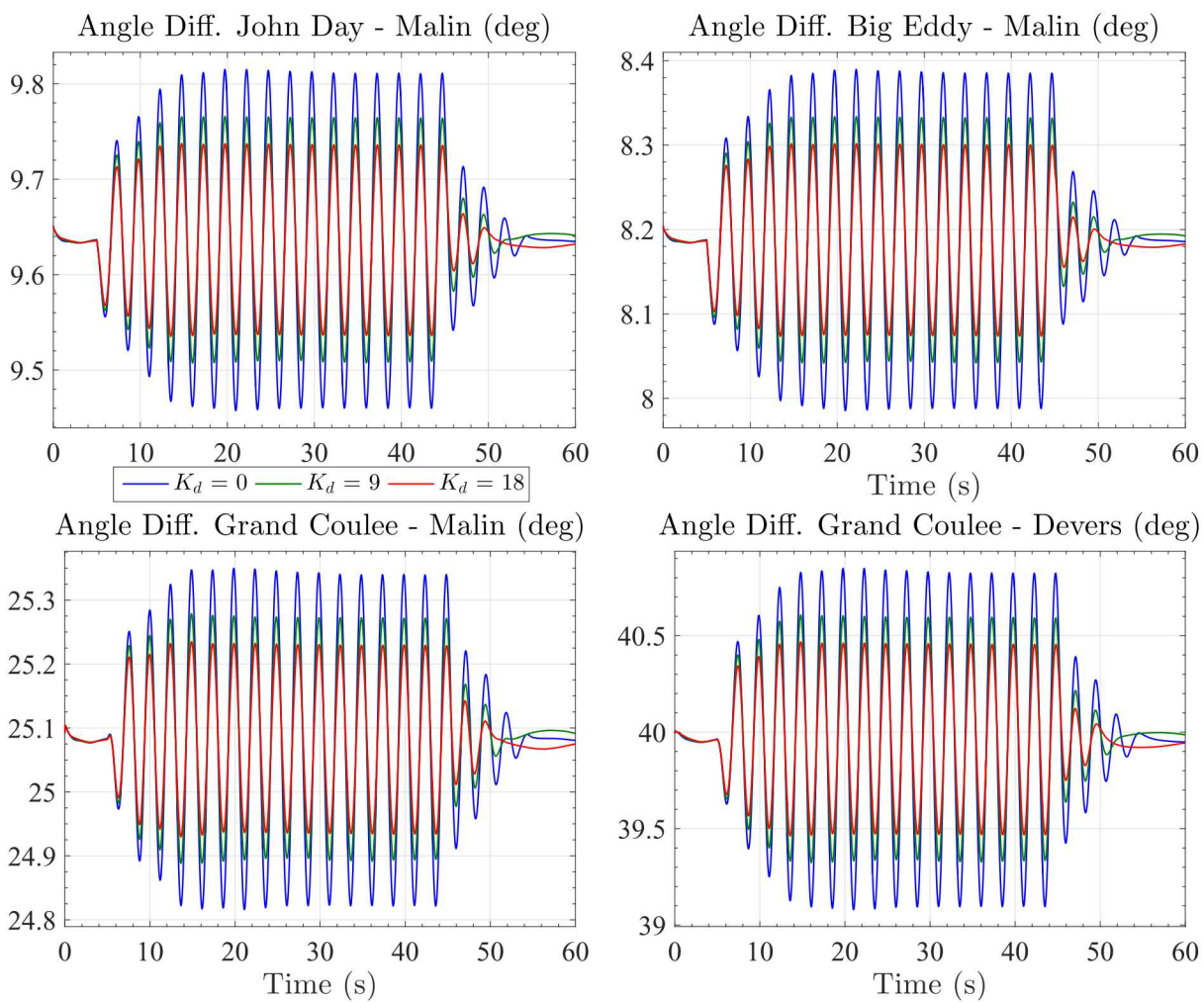


Figure 178. Angle differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

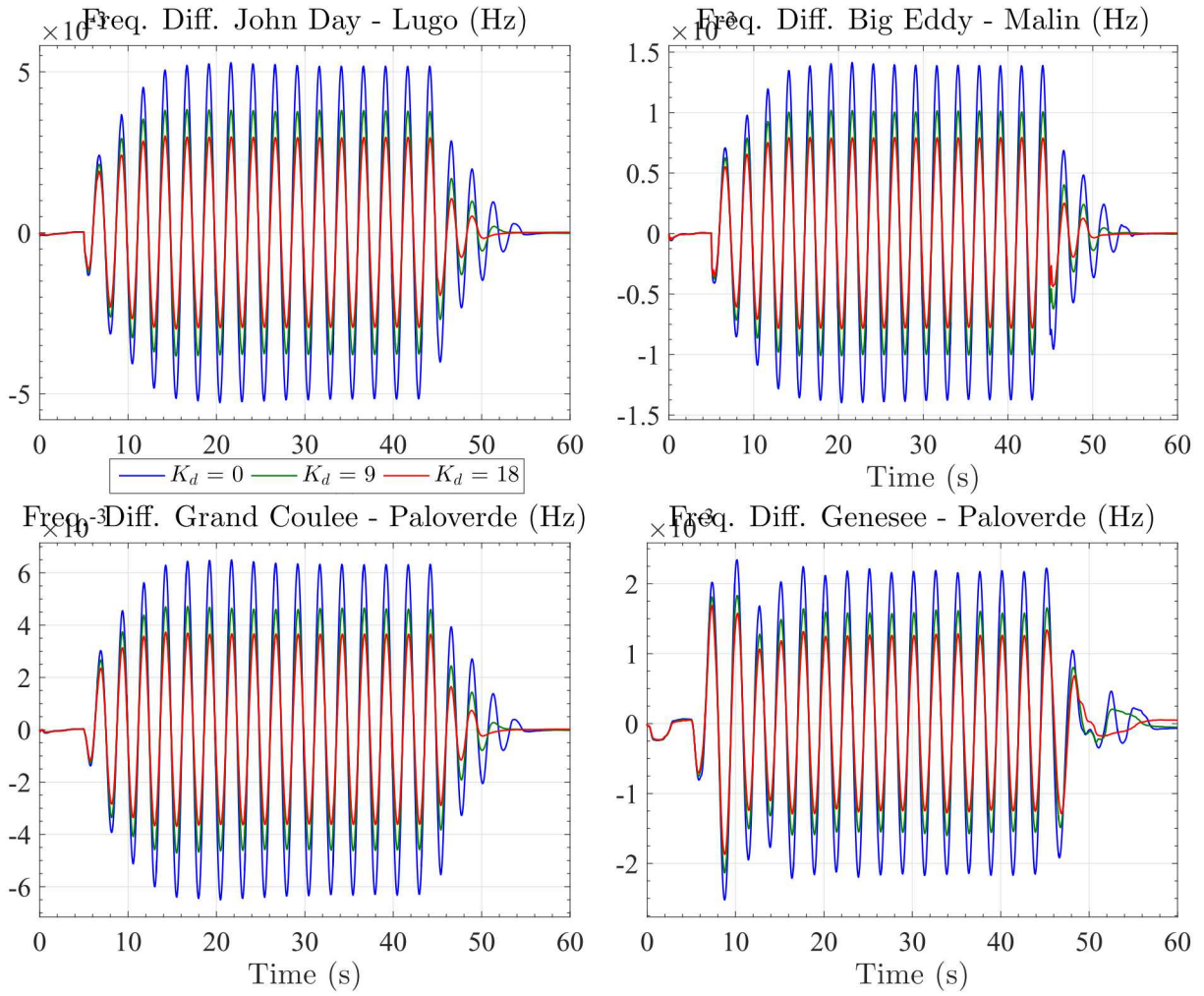


Figure 179. Frequency differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

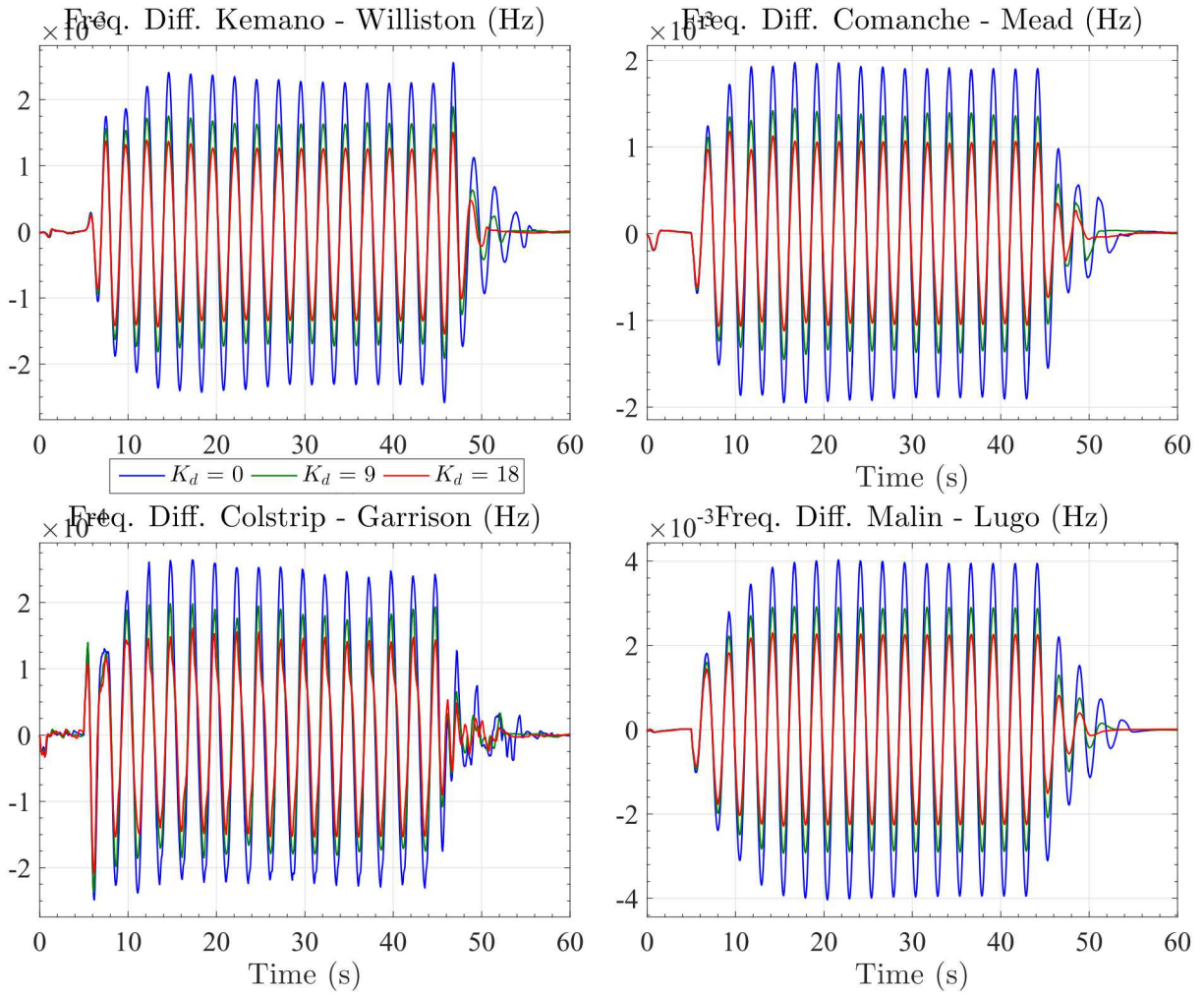


Figure 180. Frequency differences. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

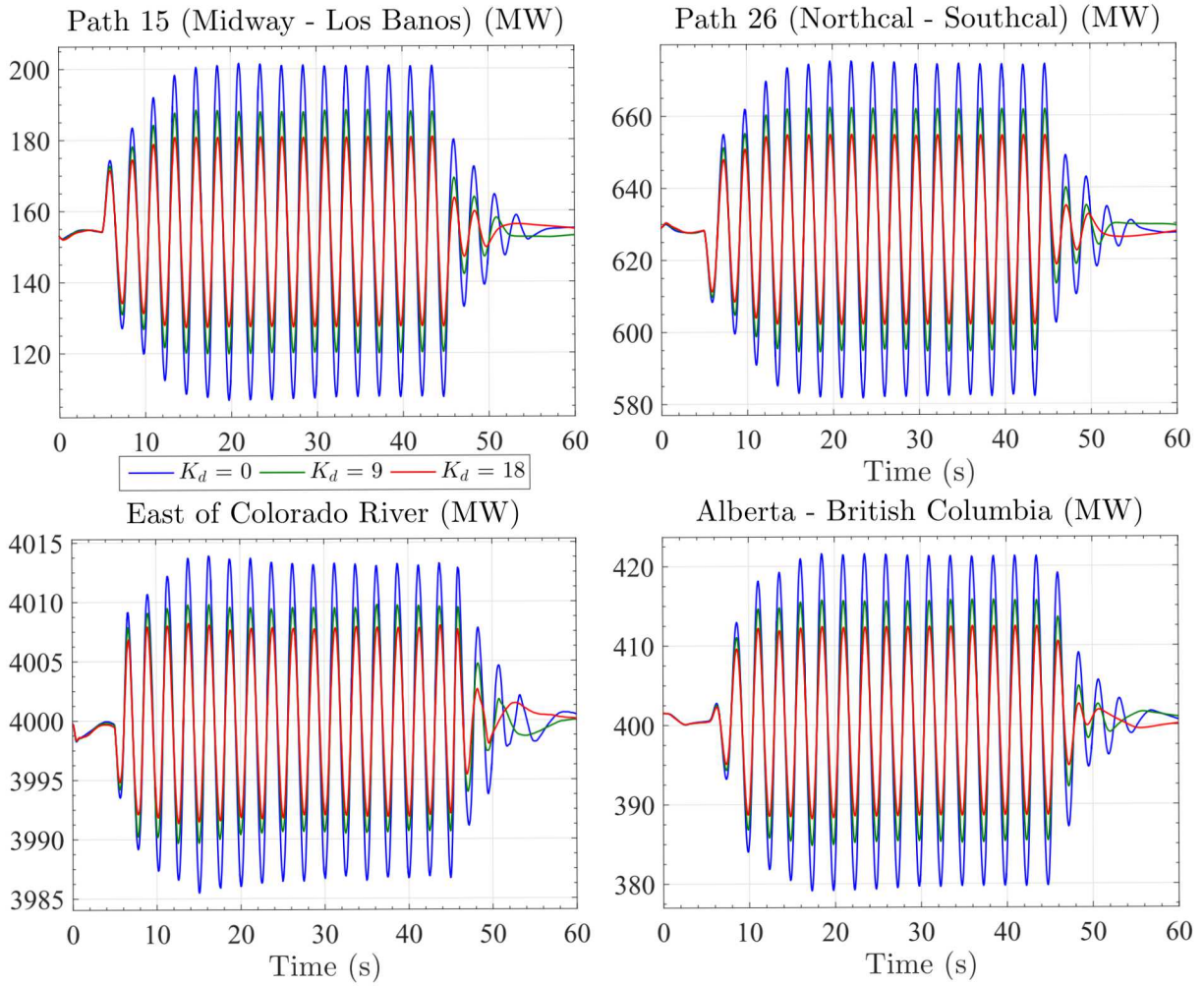


Figure 181. Active power flows. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

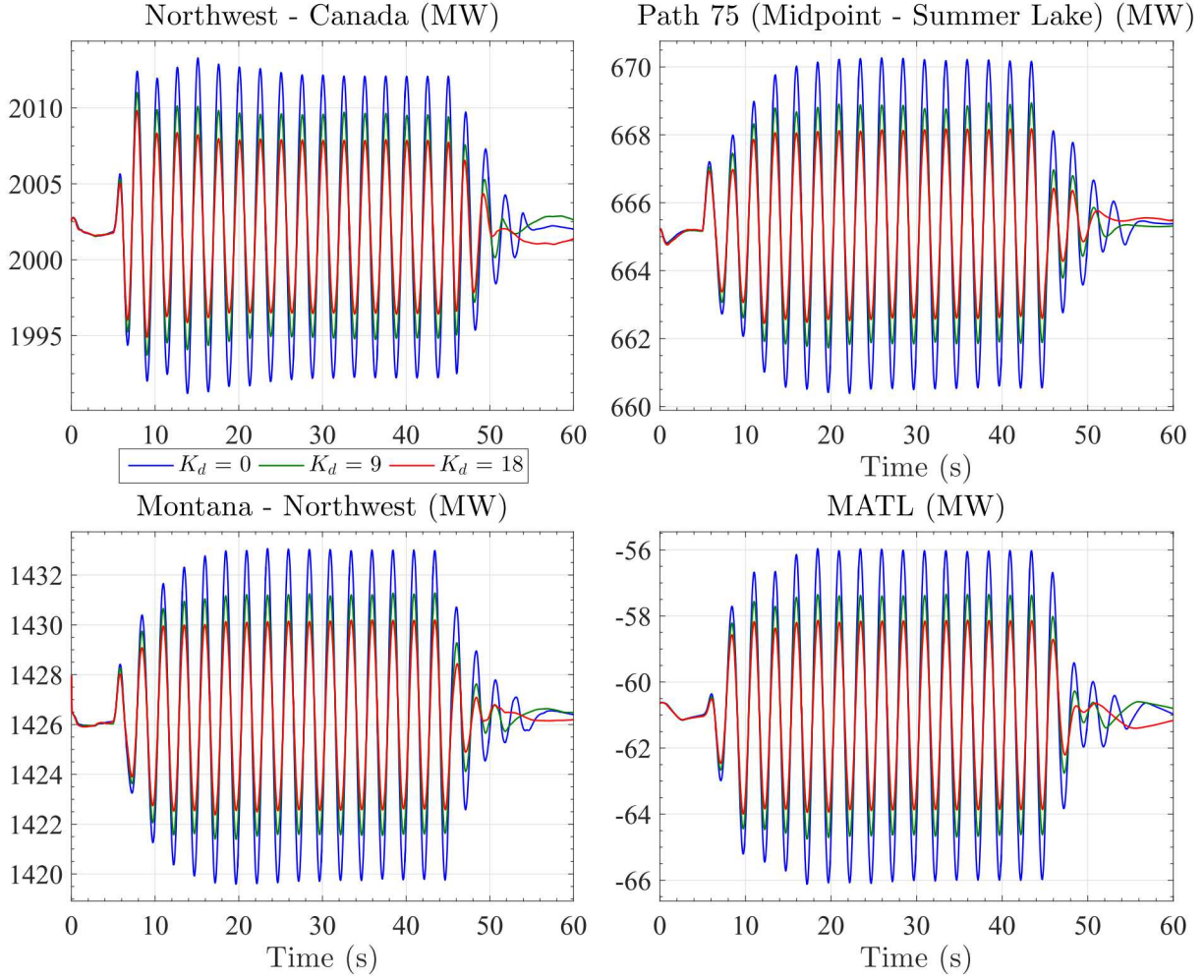


Figure 182. Active power flows. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

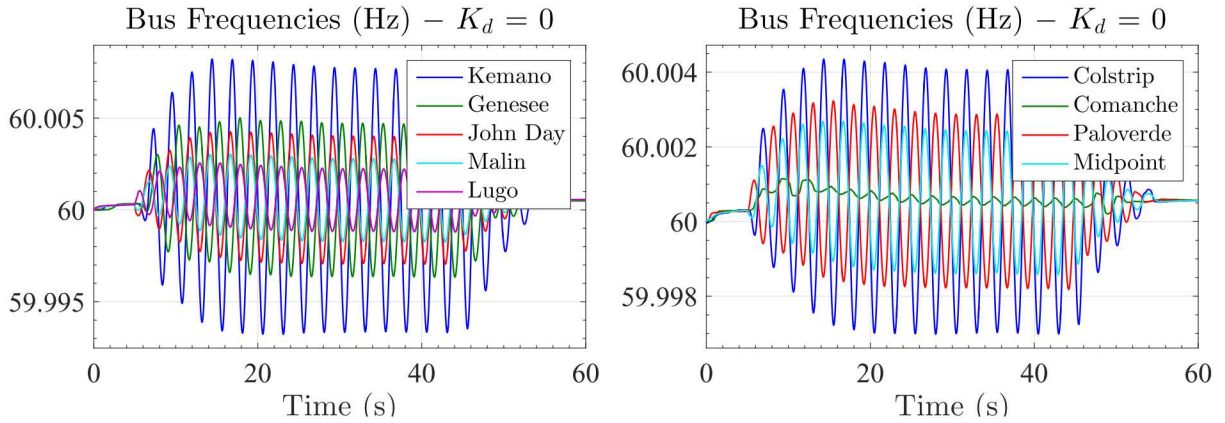


Figure 183. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

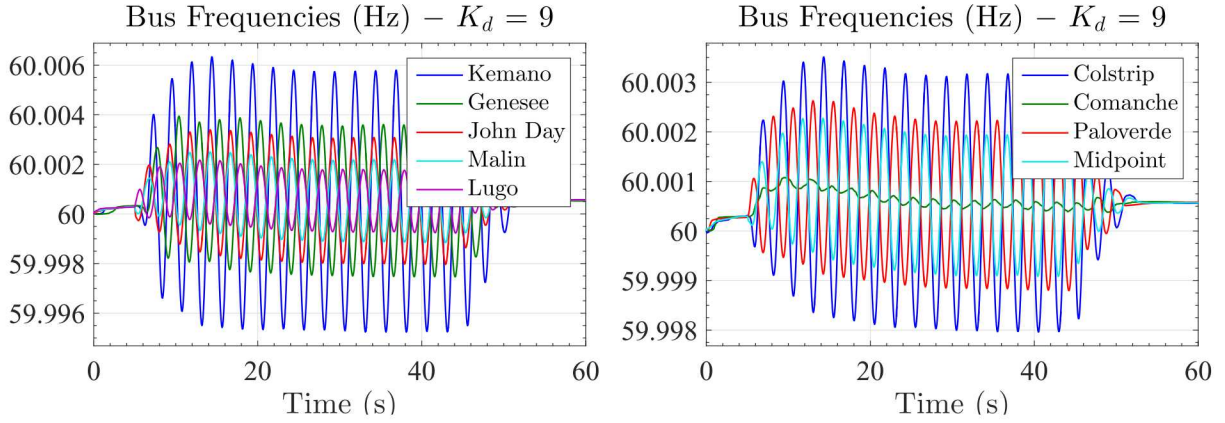


Figure 184. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

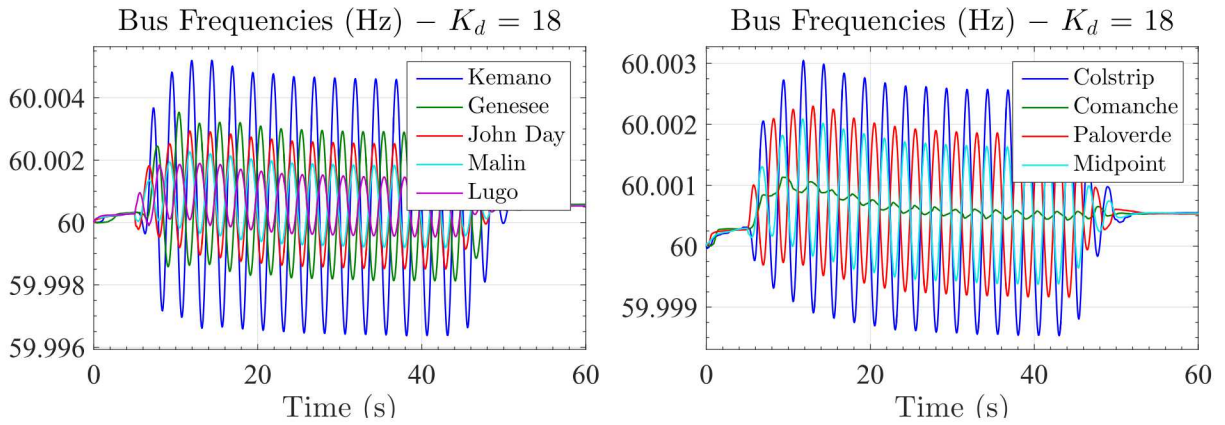


Figure 185. Bus frequencies. Event: PDCI probing. Test signal: 0.4 Hz Signal (30 MW)

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

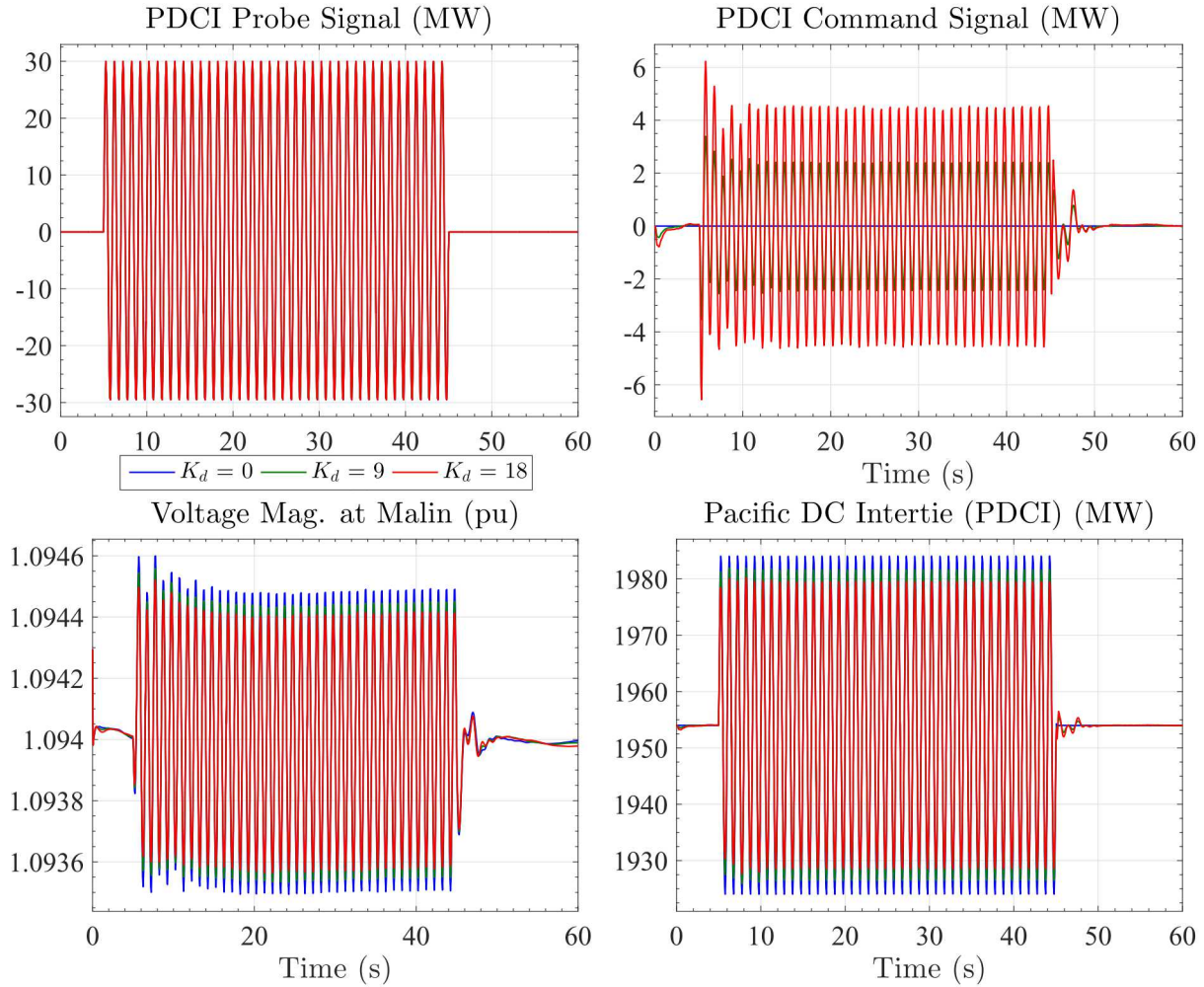


Figure 186. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

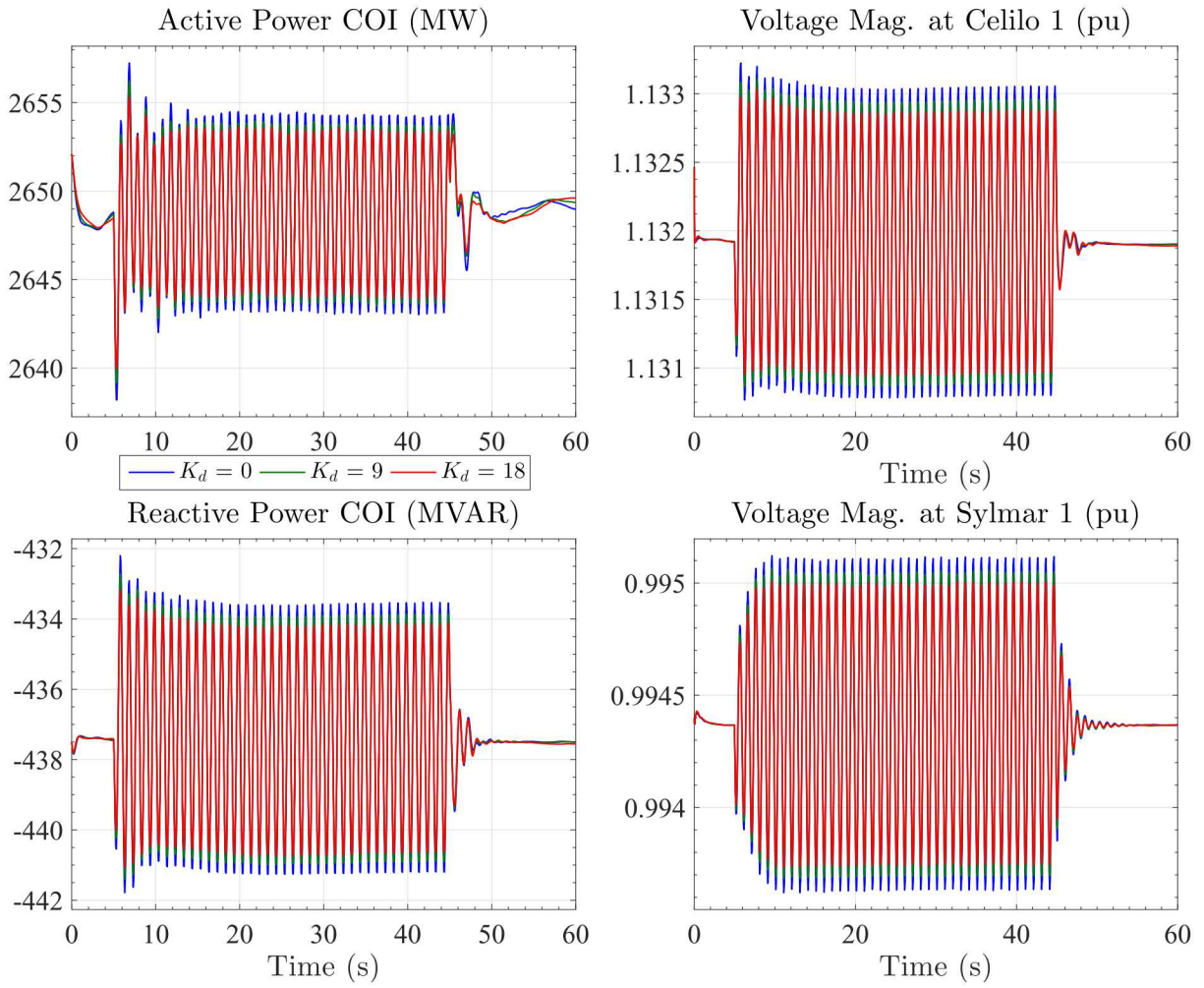


Figure 187. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

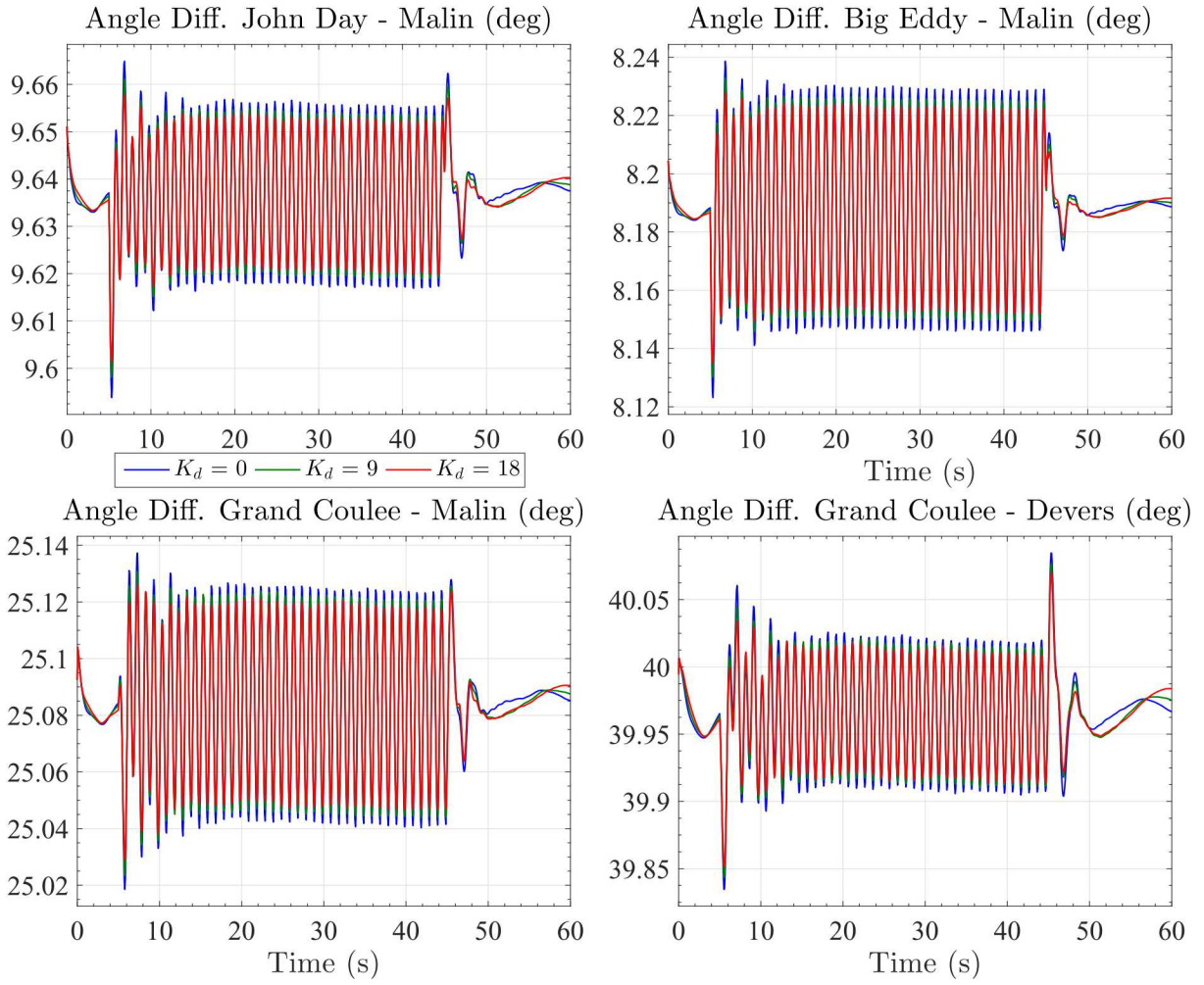


Figure 188. Angle differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

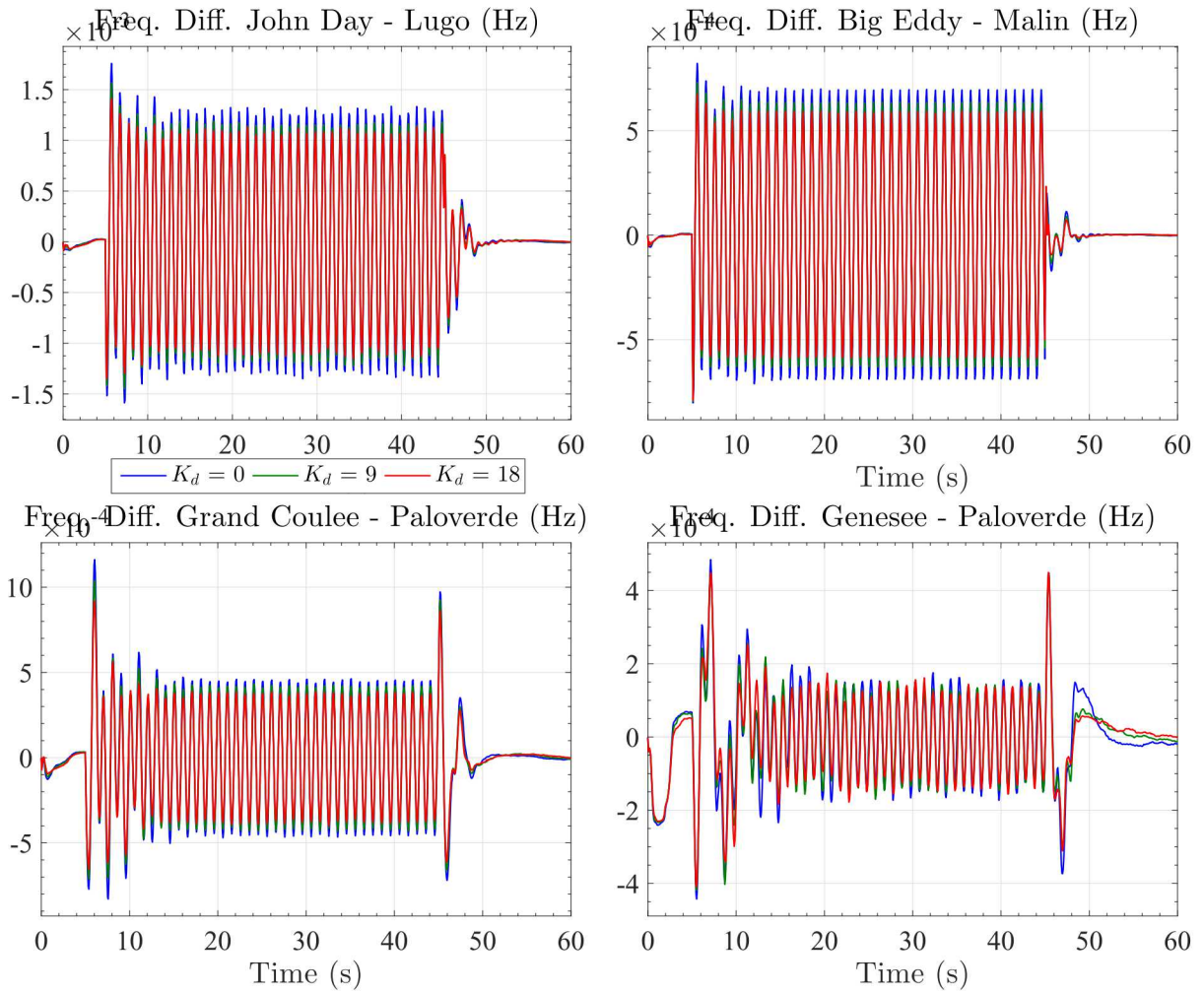


Figure 189. Frequency differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

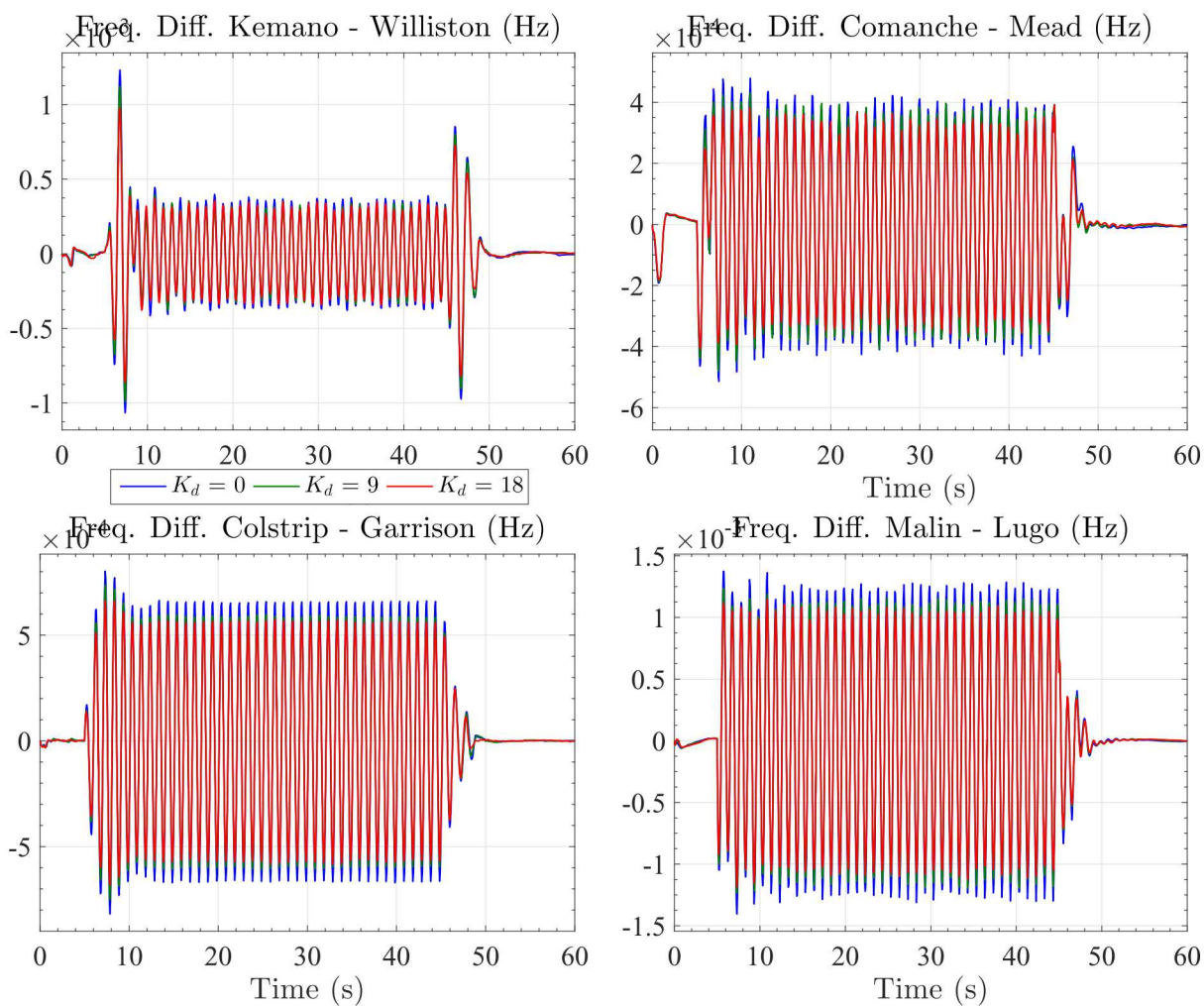


Figure 190. Frequency differences. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

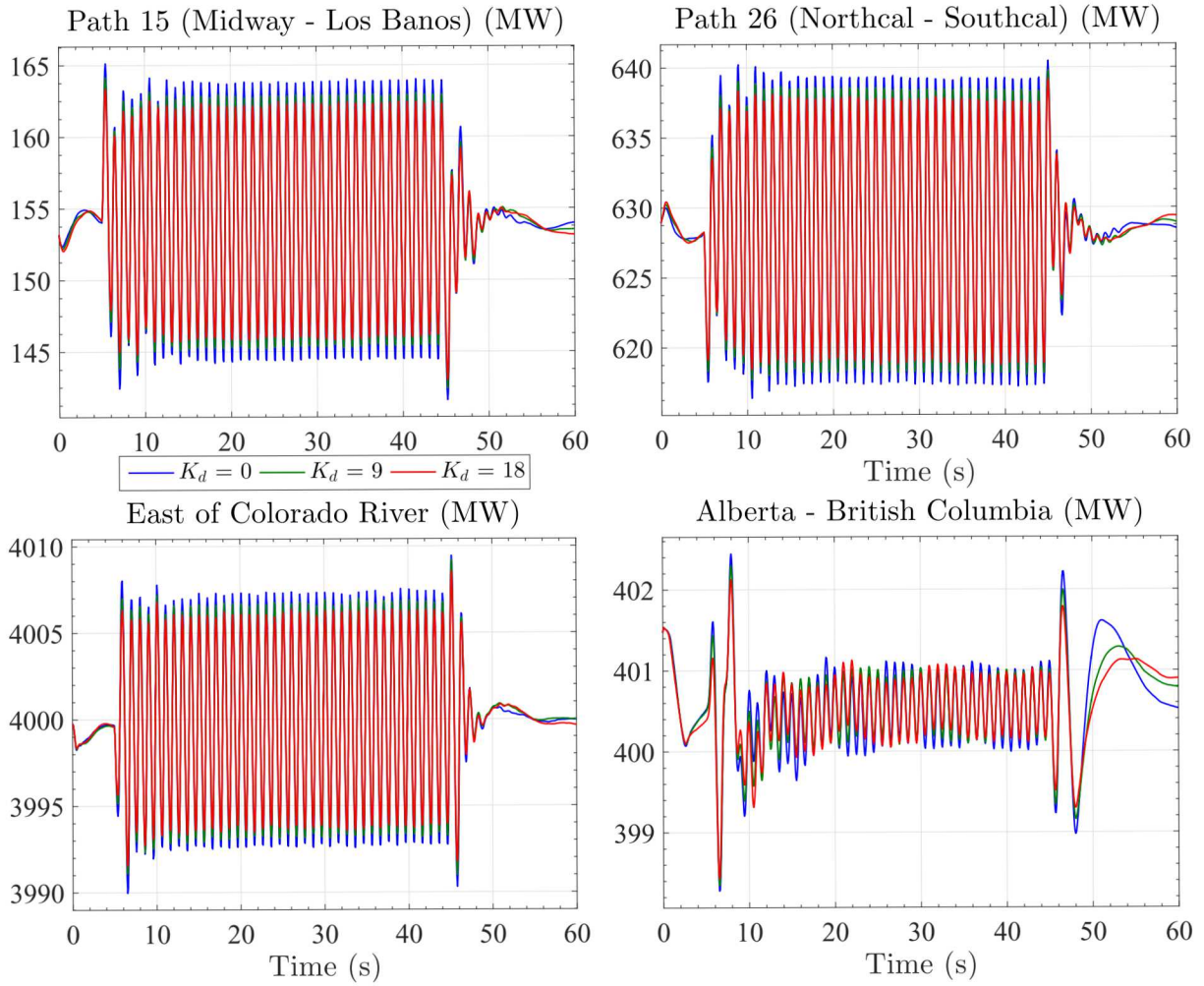


Figure 191. Active power flows. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

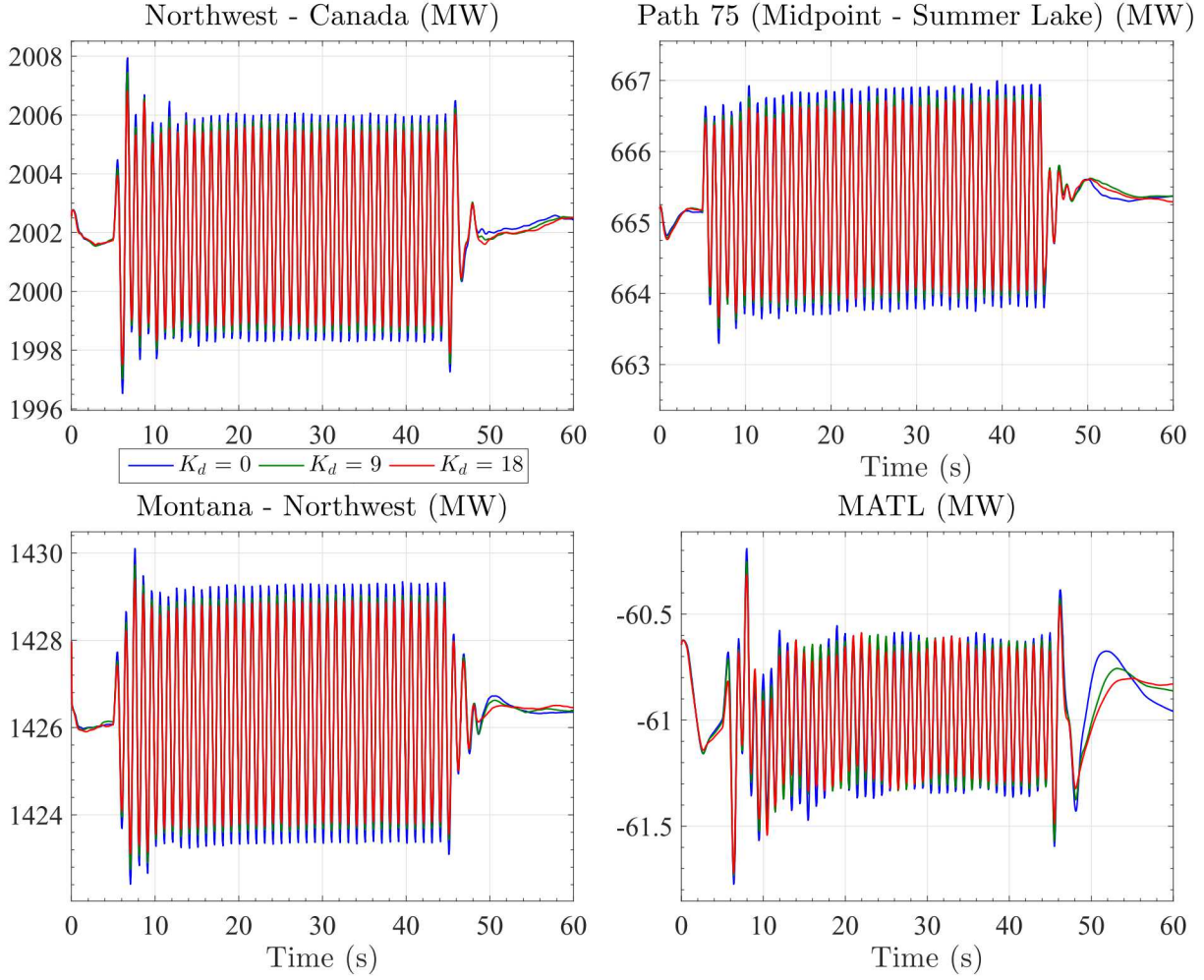


Figure 192. Active power flows. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

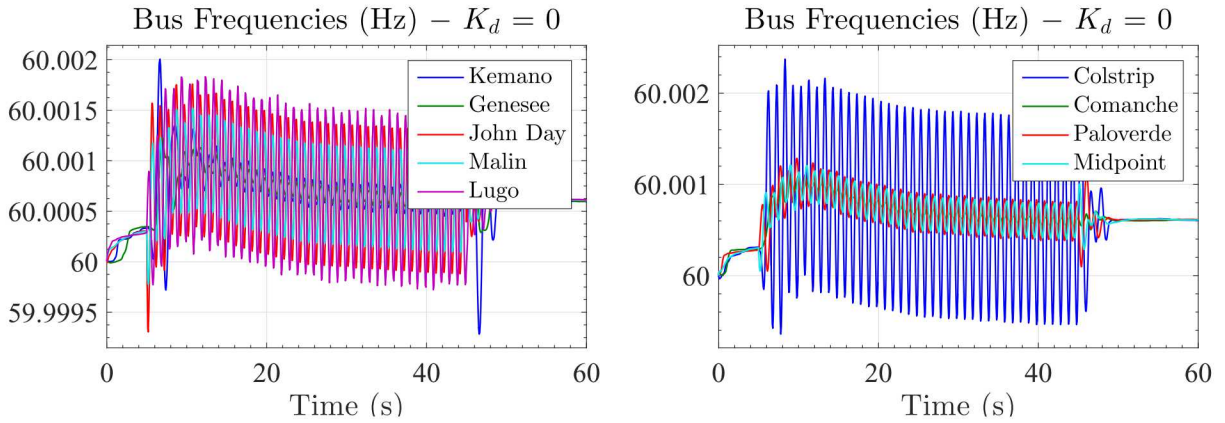


Figure 193. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

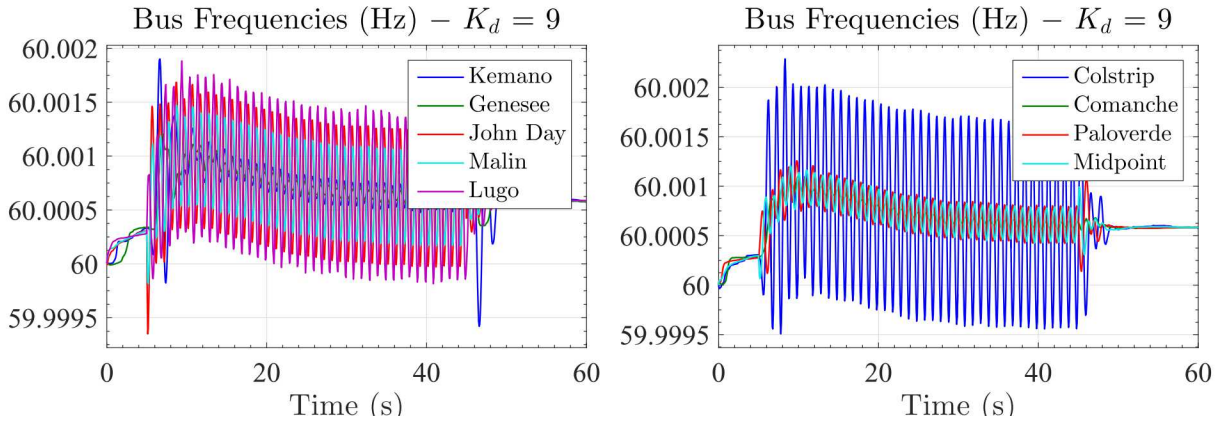


Figure 194. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

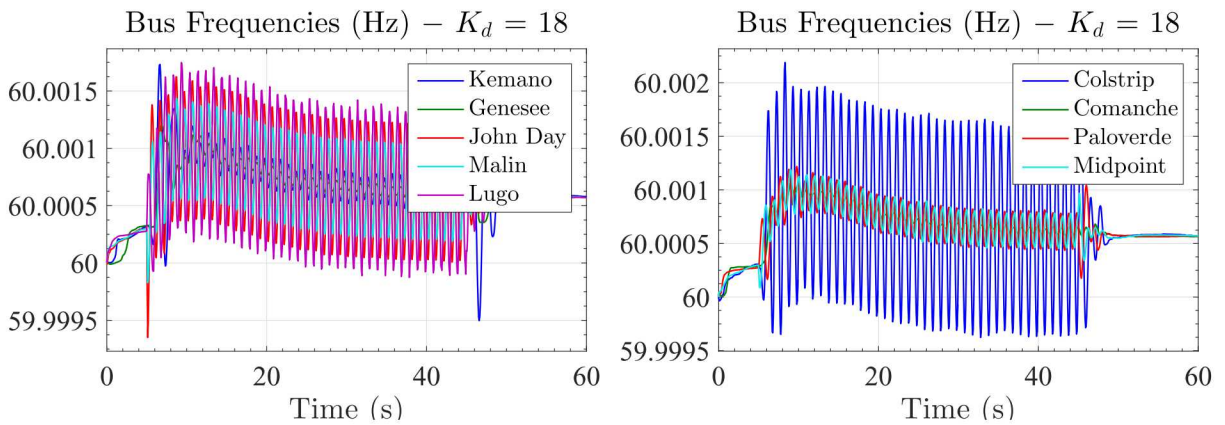


Figure 195. Bus frequencies. Event: PDCI probing. Test signal: 1 Hz Signal (30 MW)

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

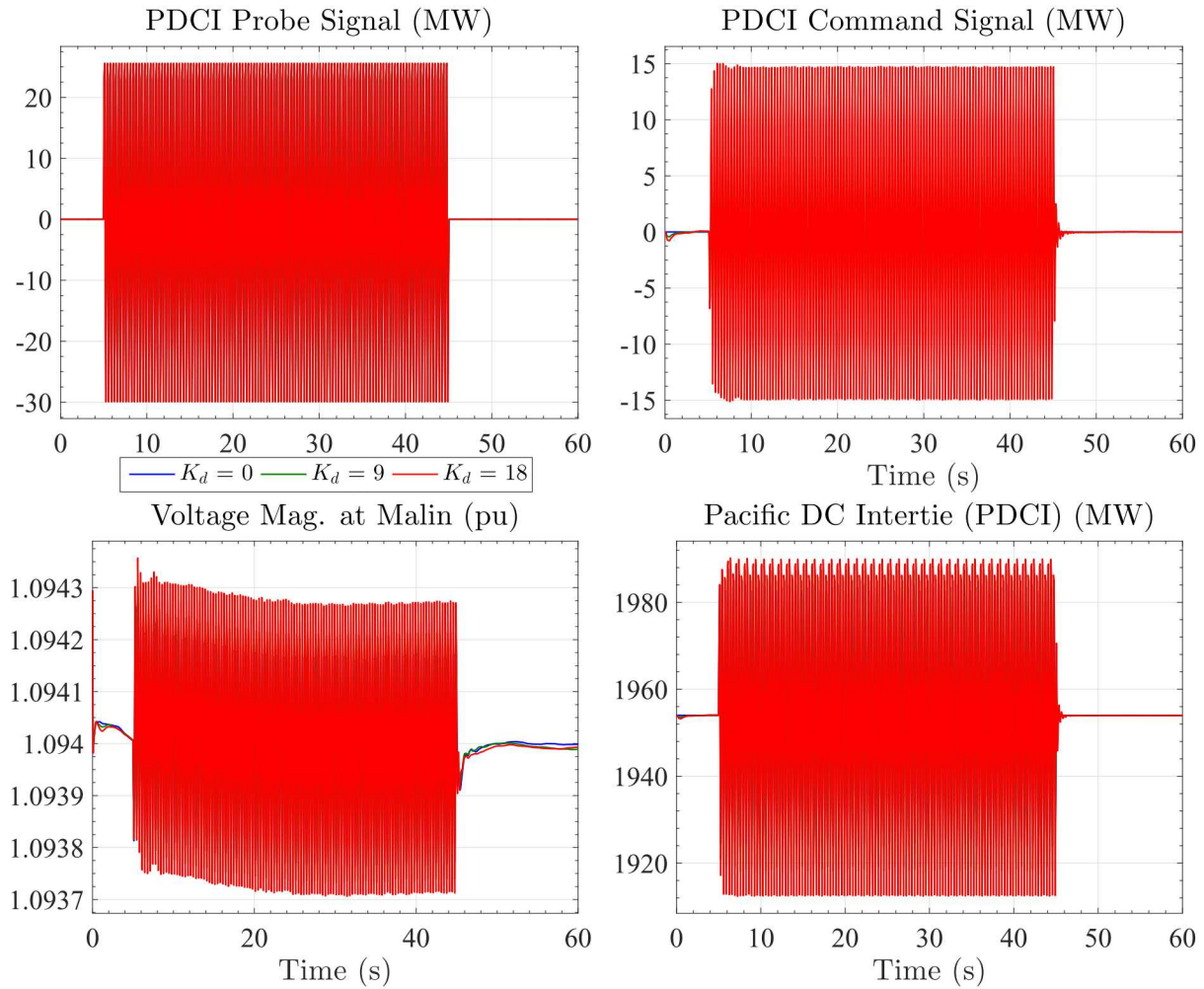


Figure 196. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

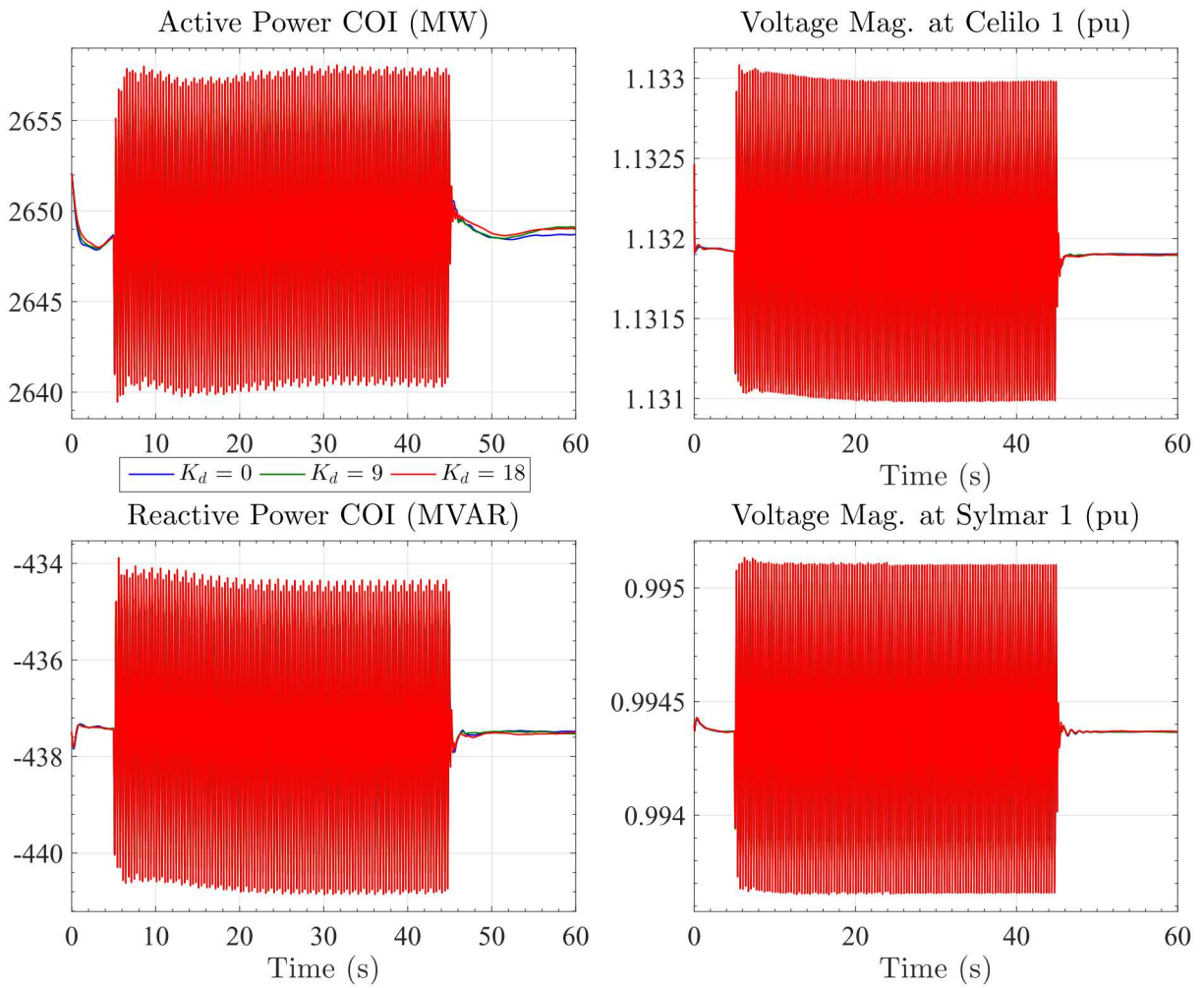


Figure 197. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

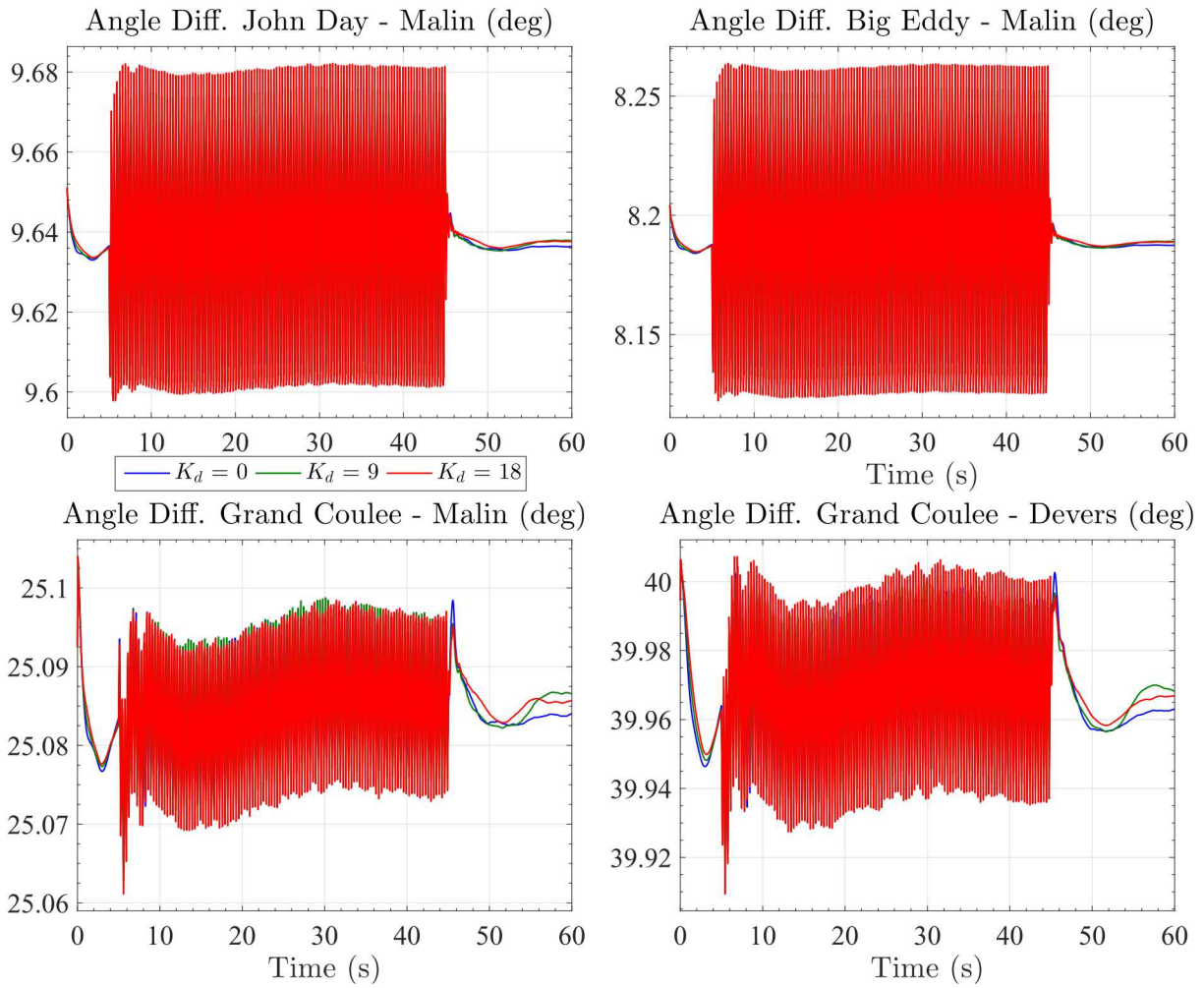


Figure 198. Angle differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

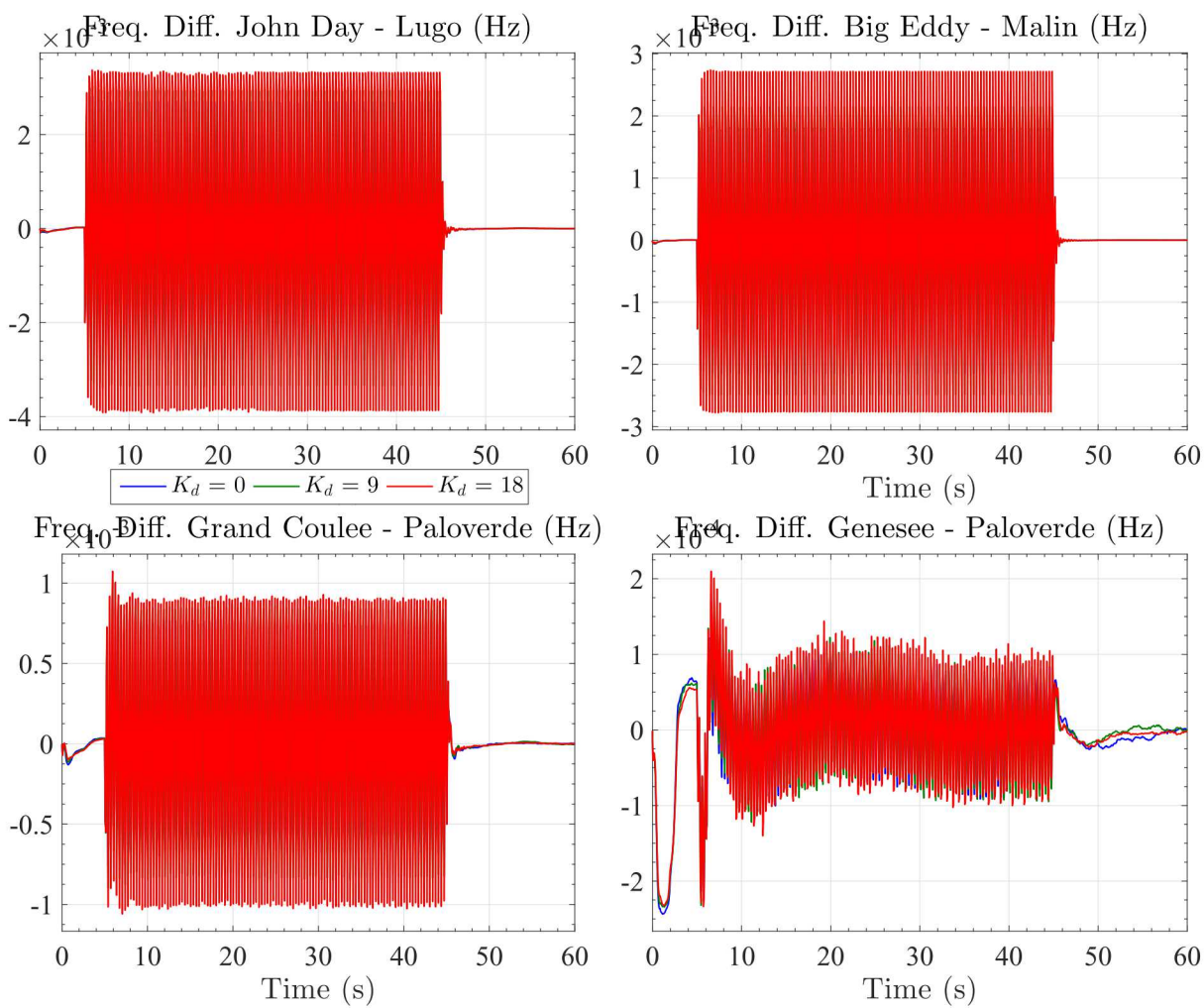


Figure 199. Frequency differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

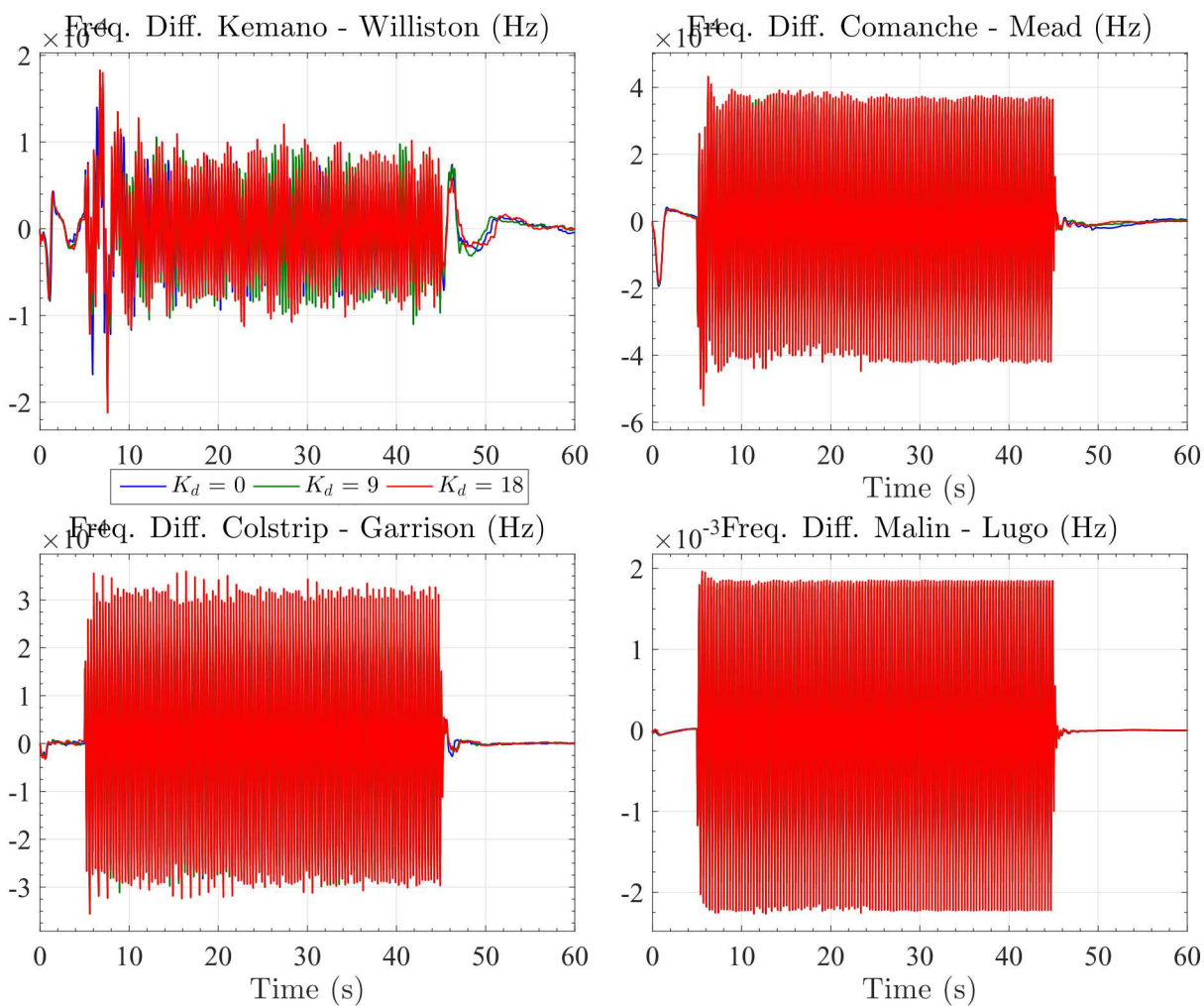


Figure 200. Frequency differences. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

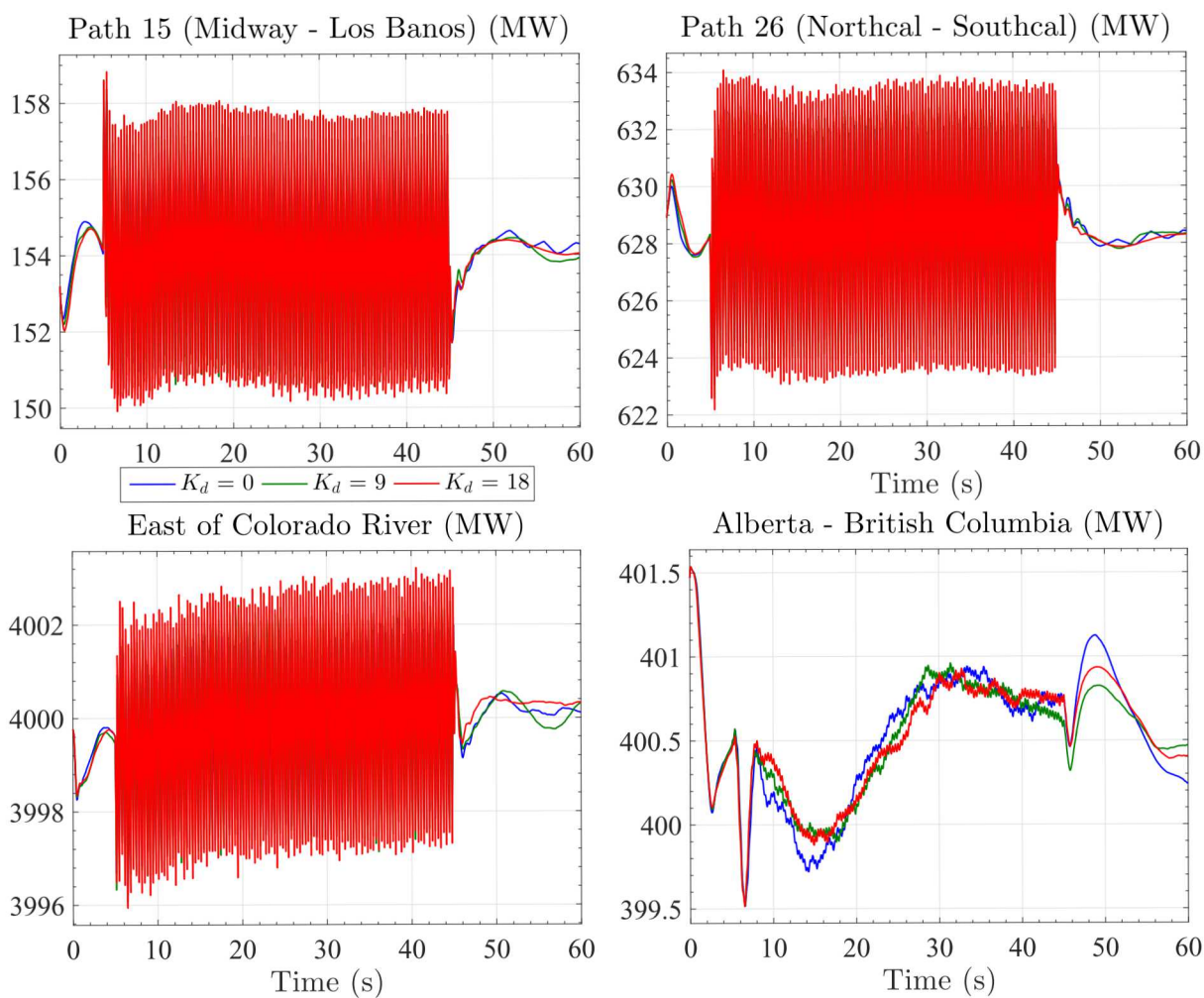


Figure 201. Active power flows. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

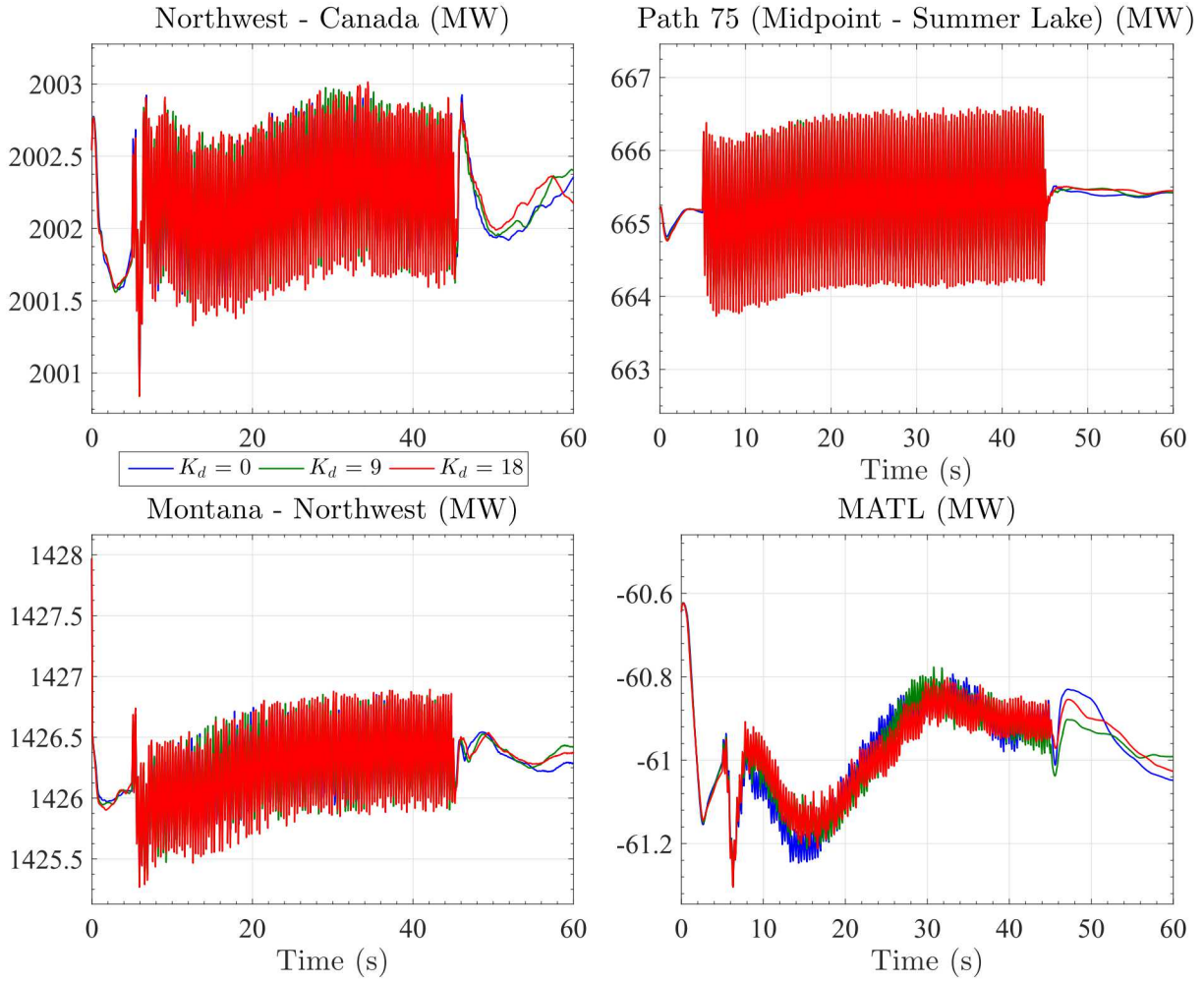


Figure 202. Active power flows. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

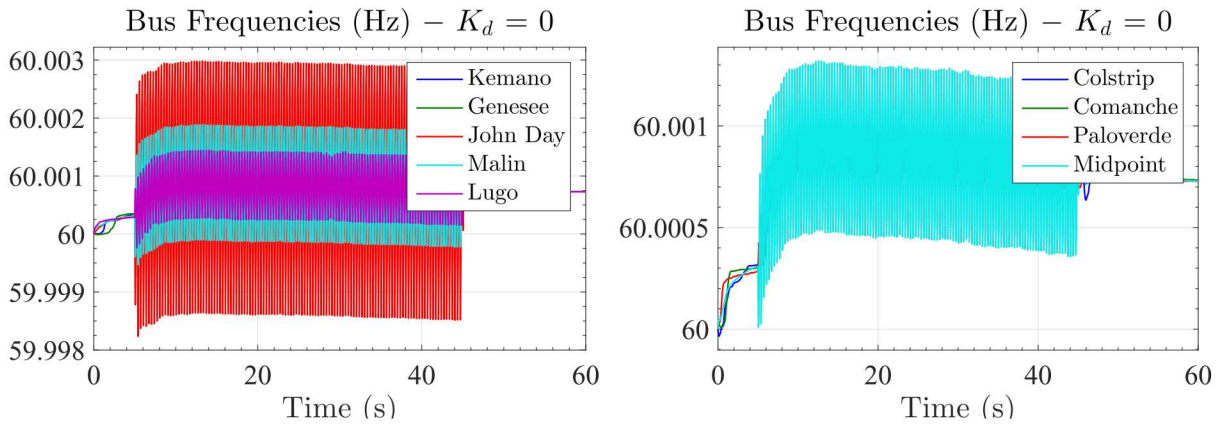


Figure 203. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

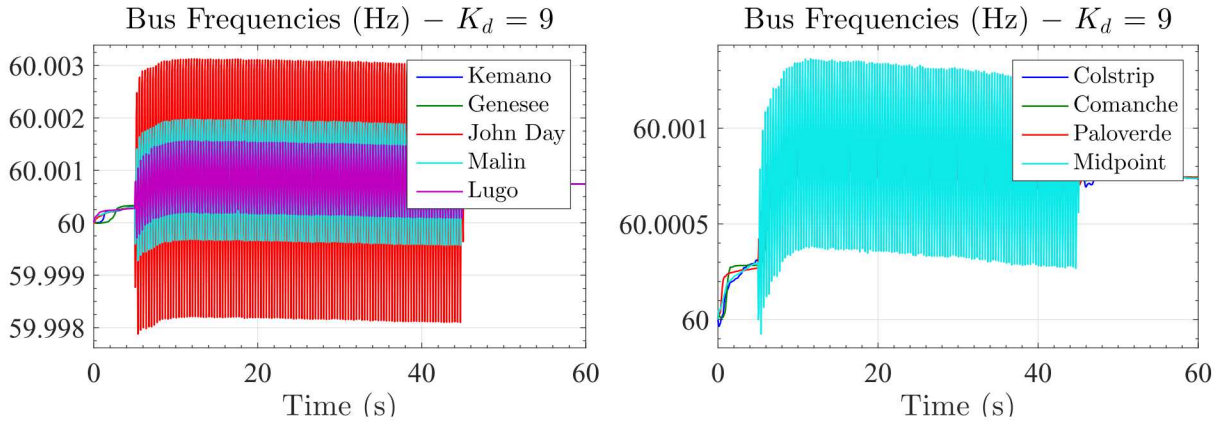


Figure 204. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

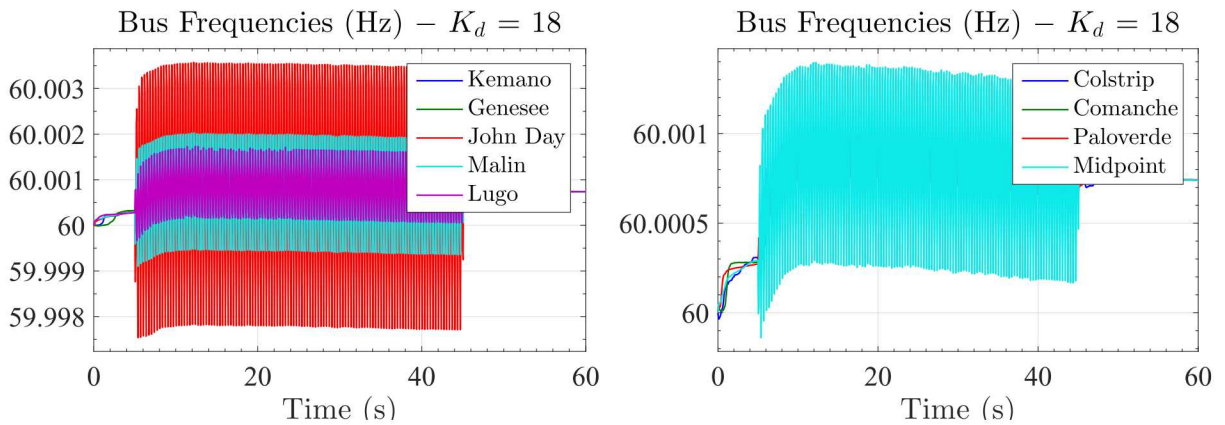


Figure 205. Bus frequencies. Event: PDCI probing. Test signal: 3 Hz Signal (30 MW)

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

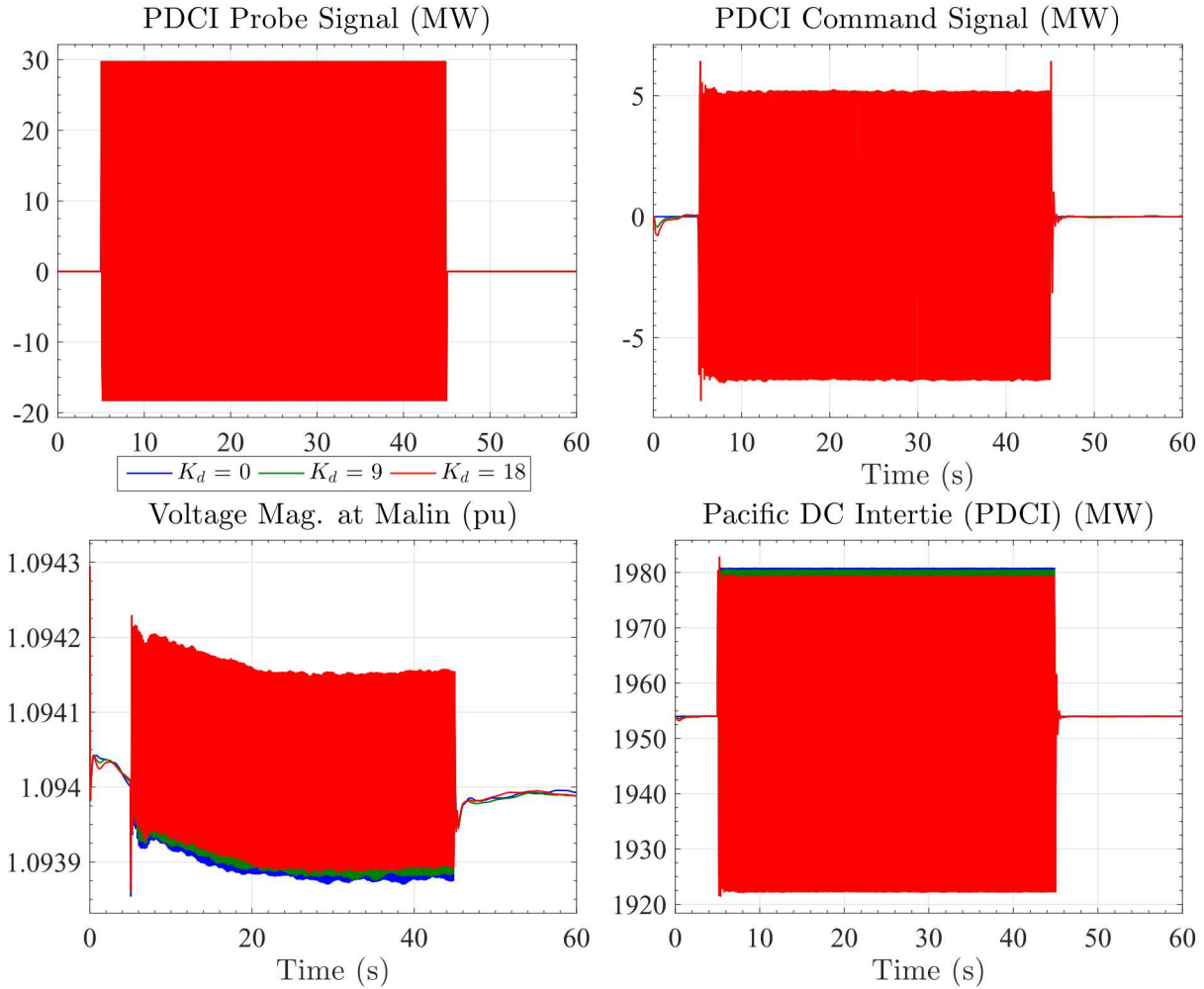


Figure 206. PDCI probe signal and controller command input. Voltage magnitude at Malin and PDCI power flow. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

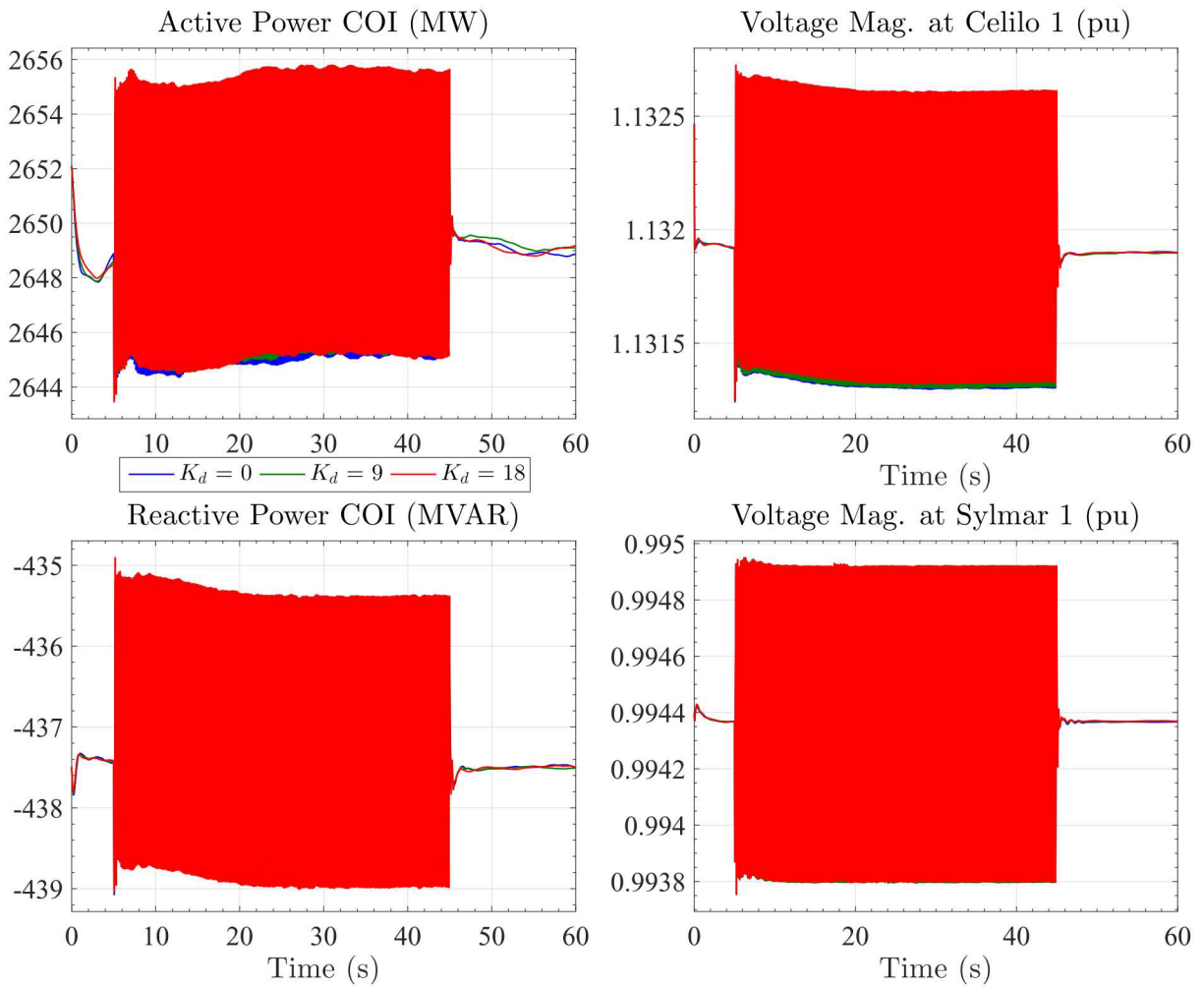


Figure 207. Active and reactive power at the COI. Voltage at Celilo and Sylmar. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

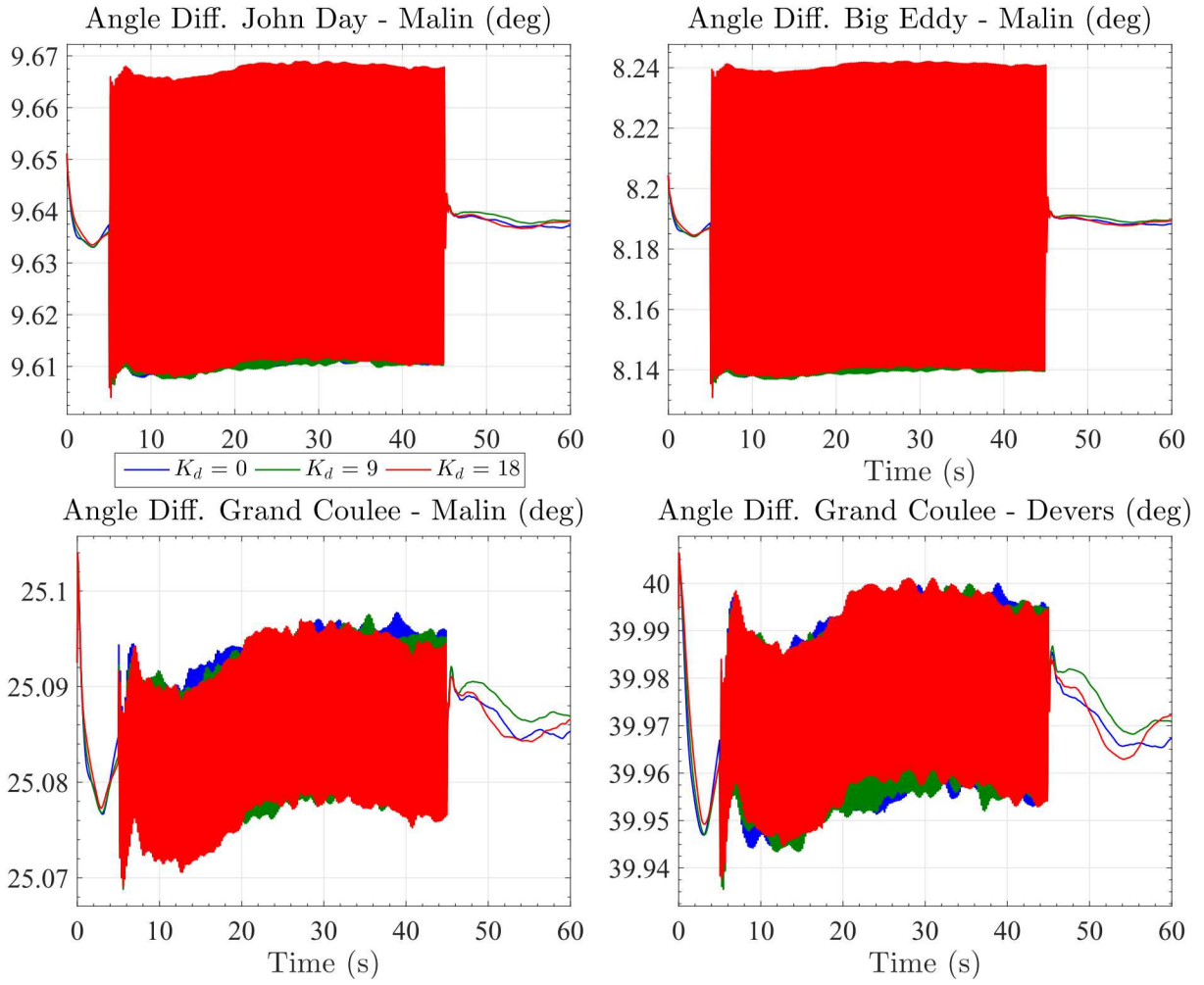


Figure 208. Angle differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

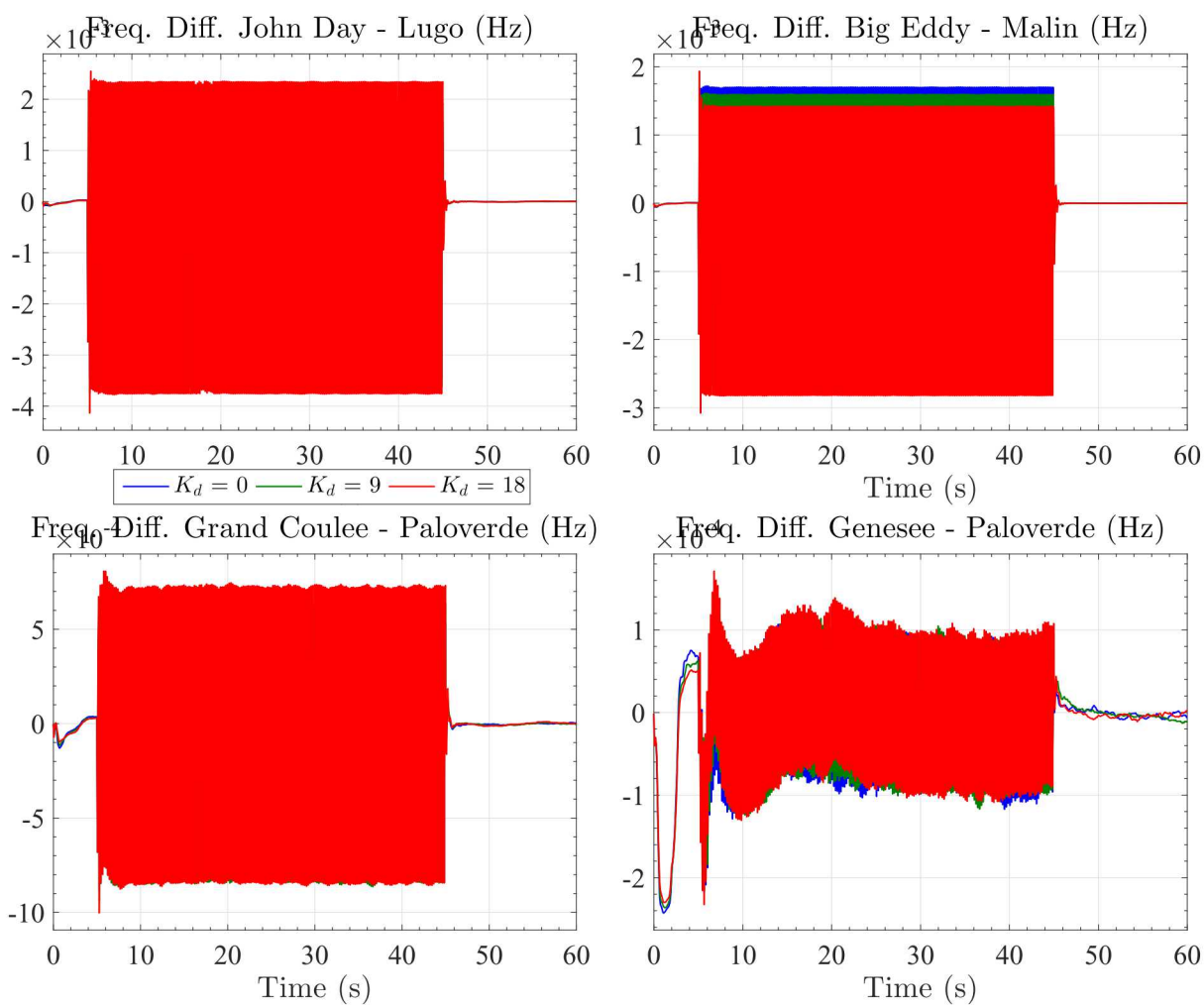


Figure 209. Frequency differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

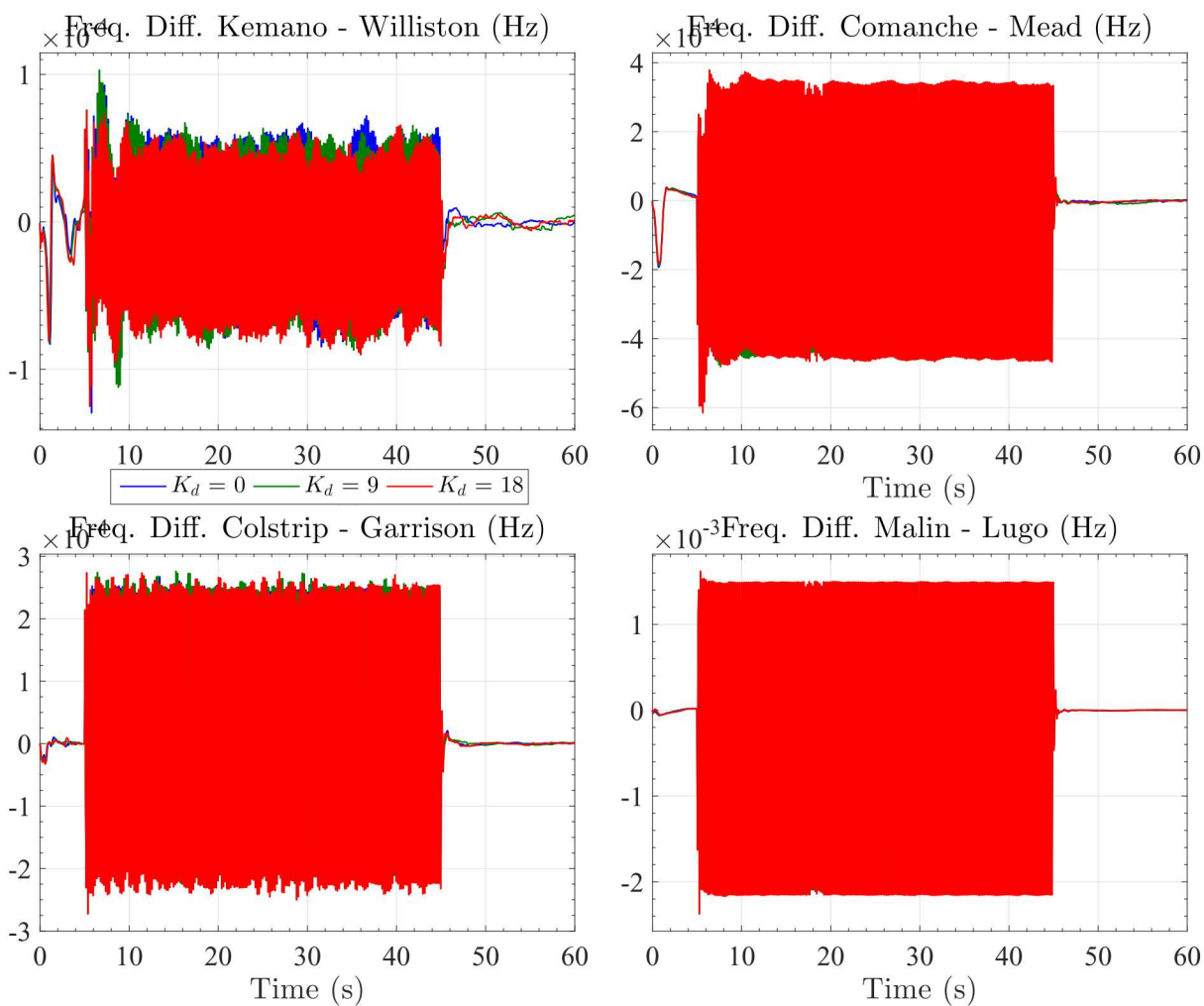


Figure 210. Frequency differences. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

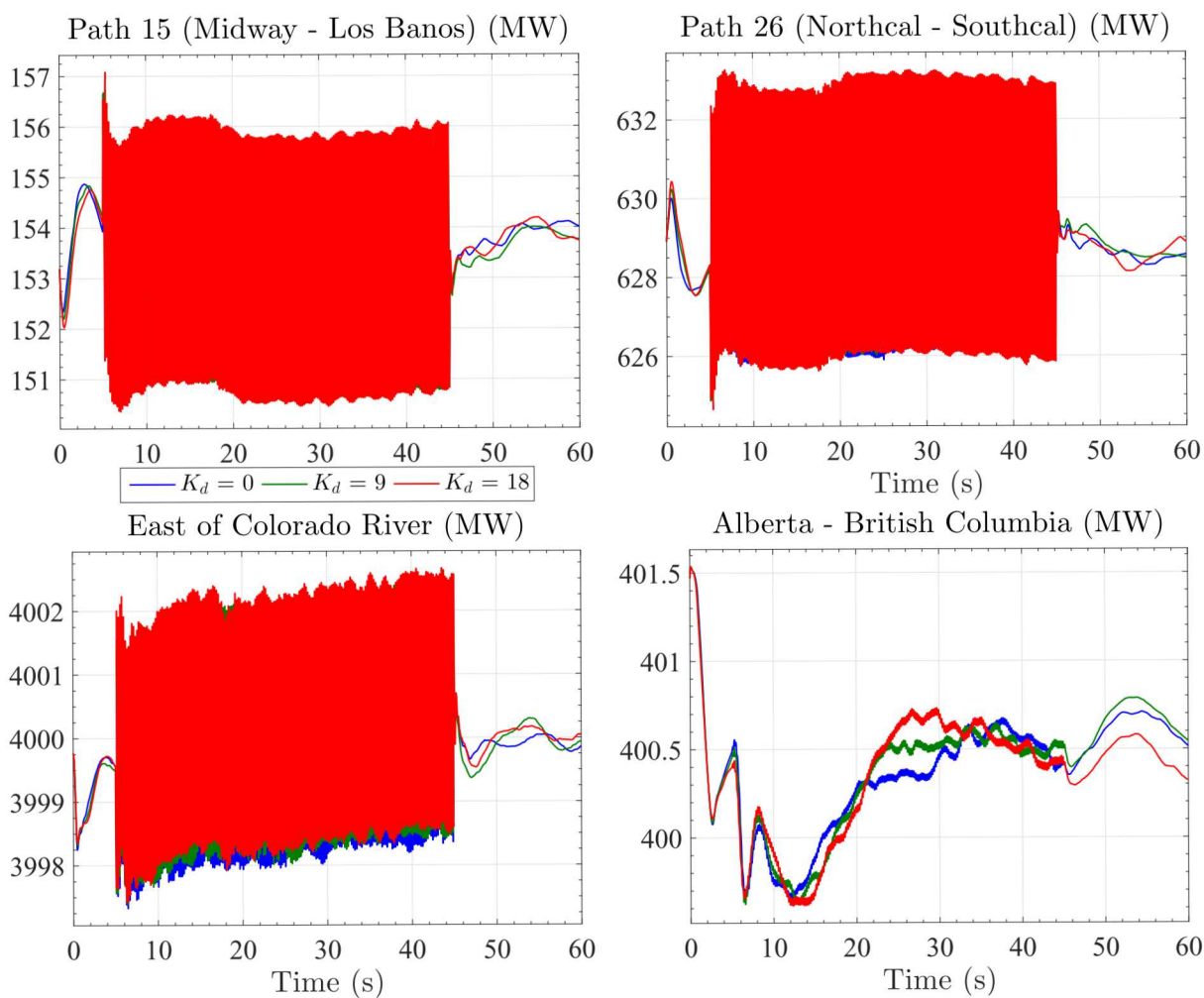


Figure 211. Active power flows. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

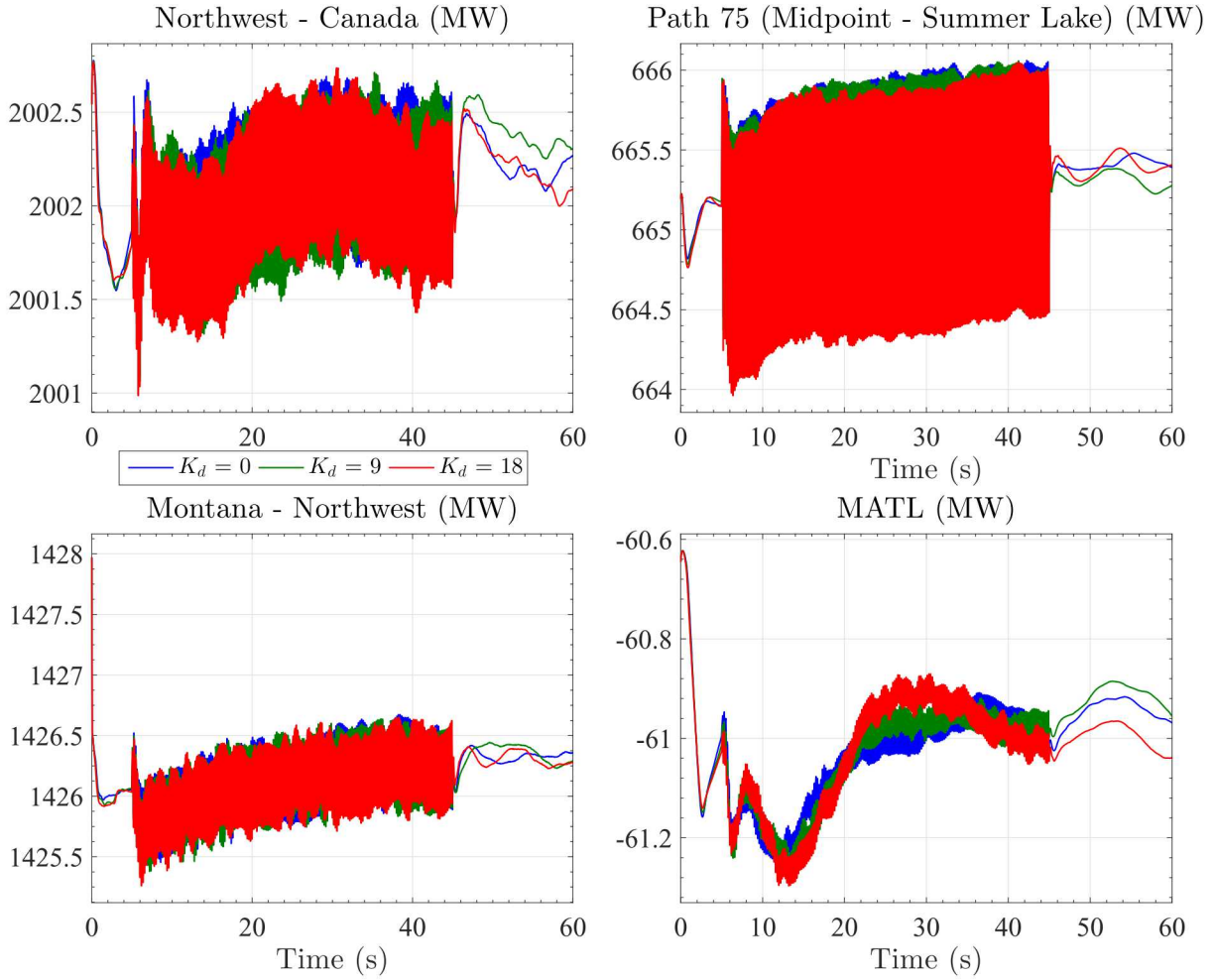


Figure 212. Active power flows. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

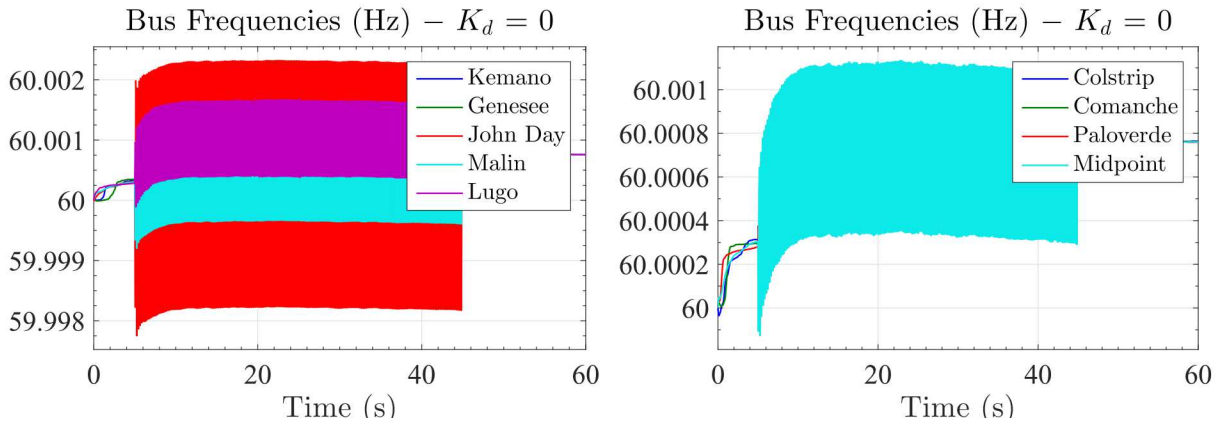


Figure 213. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

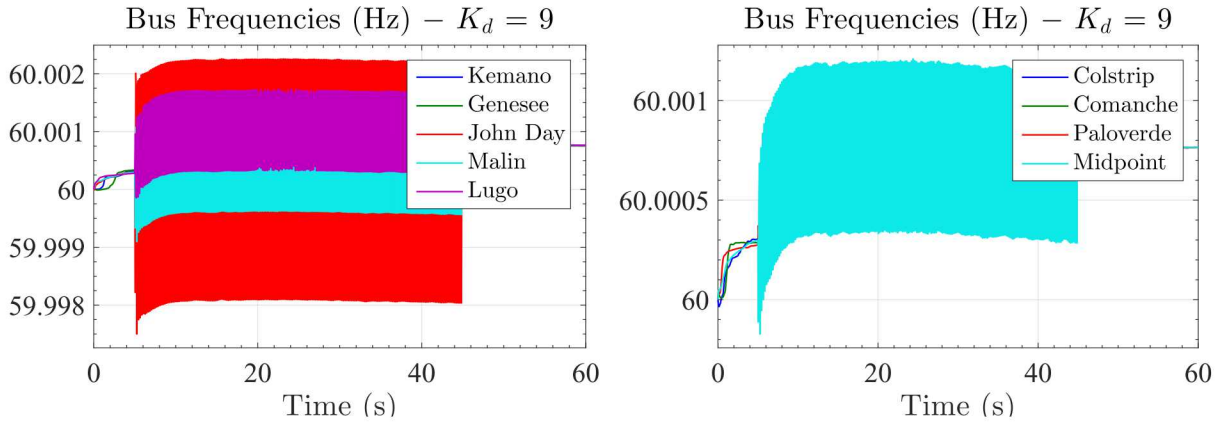


Figure 214. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

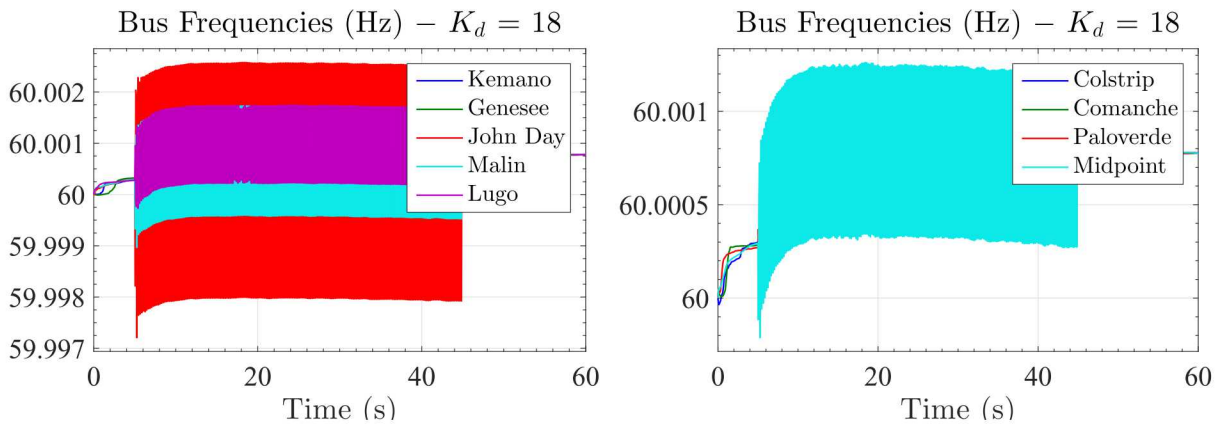


Figure 215. Bus frequencies. Event: PDCI probing. Test signal: 5 Hz Signal (30 MW)

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.

DISTRIBUTION

- 1 Dr. Dmitry Kosterev
Bonneville Power Administration
P.O. Box 3621
Portland, OR 97208-3621
dnkosterev@bpa.gov
- 1 Jisun Kim
Bonneville Power Administration
Portland, OR 97232
jxkim@bpa.gov
- 1 Jeffrey Johnson
Bonneville Power Administration
Vancouver, WA 98663
jnjohanson@bpa.gov
- 1 Jeff Barton
Bonneville Power Administration
Vancouver, WA 98663
jgbarton@bpa.gov
- 1 Gordon Matthews
Bonneville Power Administration
Portland, OR 97232
ghmatthews@bpa.gov
- 1 Phil Overholt
Office of Electricity Delivery and Energy Reliability
U.S. Dept. of Energy
Washington, DC 20585
Philip.Overholt@hq.doe.gov
- 1 Dr. Dan Trudnowski
Montana Tech University
Electrical Engineering Department
1300 W. Park Street
Butte, MT 59701
dtrudnowski@mtech.edu
- 1 Dr. Matt Donnelly
Montana Tech University
Electrical Engineering Department
1300 W. Park Street
Butte, MT 59701
mdonnelly@mtech.edu

1	MS1033	Abraham Ellis	06112
1	MS1104	Charles J. Hanley	06110
1	MS1108	Raymond H. Byrne	06111
1	MS1108	Babu Chalamala	06111
1	MS1108	David Copp	06111
1	MS1140	Ryan T. Elliott	06113
1	MS1140	Ian Gravagne	06113
1	MS1140	Ross Guttromson	06113
1	MS1140	Brian J. Pierre	06113
1	MS1140	Sharon A. Ruiz	06113
1	MS1140	David A. Schoenwald	06113
1	MS1140	Felipe Wilches-Bernal	06113
1	MS1152	Steven F. Glover	01353
1	MS1152	Jason C. Neely	01353
1	MS0899	RIM-Reports Management	09532
1	MS0899	Technical Library	09536

