Grain Belt Express HVDC

System Impact Study

Final Report for

Southwest Power Pool

Prepared by:
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0. Certification

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the Laws of the State of **Kansas**.

William Quaintance
Kansas License Number 20756

Excel Engineering, Inc.
Kansas Firm License Number 1611

1. Background and Scope

The ±600 kV Grain Belt Express (GBX) HVDC line is being developed by Clean Line Energy Partners LLC to transport renewable energy from SPP (near Clark County Substation, Kansas) to AMMO (Palmyra Tap Substation, Missouri) and AEP (Sullivan Substation, Indiana). Clean Line hired Siemens PTI to perform power flow and stability studies of the project's impact on the electric system. SPP hired Excel Engineering to review and repeat the results of the PTI stability study.

Excel analyzed system stability characteristics in the SPP footprint with the GBX HVDC line and renewable generation modeled in the system. The study was performed for select three phase and single line to ground faults at and near the converter stations in three seasonal cases: 2017 light load, 2017 summer peak, and 2022 summer peak. The three seasonal cases were provided by SPP with the HVDC line and wind generation already incorporated into the cases.

This study by Excel Engineering, Inc. consisted of analyzing system stability following faults in the area of the proposed HVDC project as well as providing comments on the project developer's report.

In August 2013, PTI provided new results based on a change in the Point of Interconnection. The new POI is 14 miles closer to Spearville than the previous POI at Clark Co. The new PTI stability results showed the same performance as the original POI. Analysis of the stability of the new POI is included in Section 4.2.2 of this report.

Study assumptions in general have been based on Excel's knowledge of the electric power system and on the specific information and data provided by SPP. The accuracy of the conclusions contained within this study is sensitive to the assumptions made with respect to generation additions and transmission improvements being contemplated. Changes in the assumptions of the timing of other generation additions or transmission improvements will affect this study's conclusions.

2. Executive Summary

The analysis performed by Excel Engineering confirms the results of the PTI stability report. The main conclusions of the report were as follows:

- The worst faults in SPP were N-1-1 and N-2 faults on the parallel 345 kV lines connected to Clark County substation. If one Clark Co – Thistle 345 kV line is out of service and there is a three-phase fault on the parallel line, the GBX wind generators may go unstable and trip off-line by over-frequency protection. The same behavior was seen if one Clark Co – Spearville 345 kV line is out of service and a three-phase fault occurs on the second line.

  The recommendation in the PTI study is to trip up to 877 MW of GBX wind generation after the fault occurs. This solution was confirmed for the original fault list. With an additional N-1-1 fault studied at the Thistle end, up to 1637 MW of wind generation will need to be tripped. However, SPP and the transmission owner will have to decide if a Special Protection System (SPS) such as this would be acceptable.

  An alternative is to reduce the GBX wind generation in a controlled fashion after the first outage occurs, to be prepared in case a fault occurs on the second circuit. Successful performance of this option was also confirmed. However, this option is not available if these double-circuit transmission lines share transmission towers for a significant distance and NERC Category C5 is considered.

  Similar results were found when the SPP POI was changed to a location 14 miles from Clark Co on the Clark Co-Spearville 345 kV lines.

  If neither the post-fault wind tripping SPS nor the pre-fault wind reduction is an acceptable solution, then a major transmission upgrade or reduction in the size of the GBX project will have to be considered.

- The worst faults in AEP were on the Rockport – Jefferson 765 kV line. Outage of this line leaves the 2600 MW Rockport plant feeding radially to Sullivan, the same place where the GBX HVDC converters are injecting 3000 MW. Following this fault, the Rockport generators go unstable and trip. In power flow, the solution diverges for this contingency.

  The recommendation in the PTI study is to trip one of the HVDC poles (1500 MW) after the fault occurs. This solution was confirmed. However, AEP and the transmission owner will have to decide if an SPS such as this would be acceptable.

  If the post-fault HVDC reduction SPS is not an acceptable solution, then a major transmission upgrade or reduction in the size of the GBX project will have to be considered.

- No stability problems were found for faults near the AMMO Palmyra station. The AMMO system is able to handle the additional 500 MW injection without a problem.

Outages of a single pole or both poles of the HVDC line were of particular interest for this study. The analysis confirms stable system response for the faults with loss of one or both poles. It should be noted that only a small portion of generation in the SPP Generator Interconnection Queue in the Spearville, Clark County, and Thistle areas were included in the analysis based on the information provided during the MDWG model development process.

In summary, the following mitigation options were confirmed to eliminate the unstable responses:

- A 900 Mvar Synchronous Condenser was assumed in all cases
- An SPS to reduce GBX wind generation following parallel circuit outages at Clark Co. Up to 1650 MW of wind generation tripping may be needed for certain double line outages.
- An SPS to reduce HVDC power by up to 1500 MW following outage of the Rockport-Jefferson 765 kV line.

It will be critical for the GBX project to maintain a balance in both its MW flow and its Mvar flow. The project is designed to have a normal power exchange with SPP of 0 MW and 0 Mvar. This target needs to be maintained during dynamic conditions as best as possible. Large imbalances can cause voltage violations and generator instability.

Additional considerations for futures studies of the GBX project include:

- Consideration of more breaker failure faults.
- Inclusion of other planned wind generation in the SPP footprint.
- Modeling the maximum 3500 MW HVDC injection at the AEP Sullivan end.
- If the SPS solutions are not acceptable, other solutions such as new transmission lines or reduced GBX project size will have to be found.

The results of this study depend on the assumed models for the HVDC equipment, wind generators, wind collector system, and the power systems in the area of the project. Some of these assumptions will surely change or come into better focus as the project moves forward. The stability analysis will need to be repeated when the assumptions are better defined.

3. Study Development and Assumptions

3.1 Simulation Tools

The Siemens PTI PSS/E power system simulation program Version 30.3.3 was used in this study. The time step used in all simulations was a quarter of a 60 Hz cycle (0.004167s). Simulation duration was as indicated in the fault definition table.

3.2 Models Used

SPP provided the power flow and dynamics models from PTI for 2017 Light Load, 2017 Summer Peak and 2022 Summer Peak conditions. There were also two connection options considered initially at Sullivan, 765 kV and 345 kV, giving a total of six (6) base cases. All other files used to run the original study, such as fault scripts, were also provided by PTI. They were reviewed for accuracy before use in the study.

Figure 3-1 and Figure 3-2 show power flow one-lines for the 2017 Summer Peak case with the 345 kV option at Sullivan and the GBX wind generation model, respectively. One-line diagrams of GBX and the full SPP 345 kV system for all three seasons are provided in Appendix E.

As in the PTI study, all faults in SPP, AMMO, and AEP were run on the cases with the 765 kV connection option at Sullivan. Only faults in AEP were tested with the 345 kV option at Sullivan. It is assumed that the faults in SPP and AMMO would not vary significantly between the two different connection options at AEP's Sullivan station.

Near the end of the study, Clean Line informed SPP that the 765 kV connection option at Sullivan should be dropped from consideration, and only the 345 kV option should be considered. However, most of the simulation work had already been completed. The results of the fault simulations in SPP and AMMO with the 765 kV option in AEP are still considered valid. For faults in AEP, results with the 765 kV option were set aside and only results with the 345 kV option are discussed in this report.

No changes were made to the provided models.

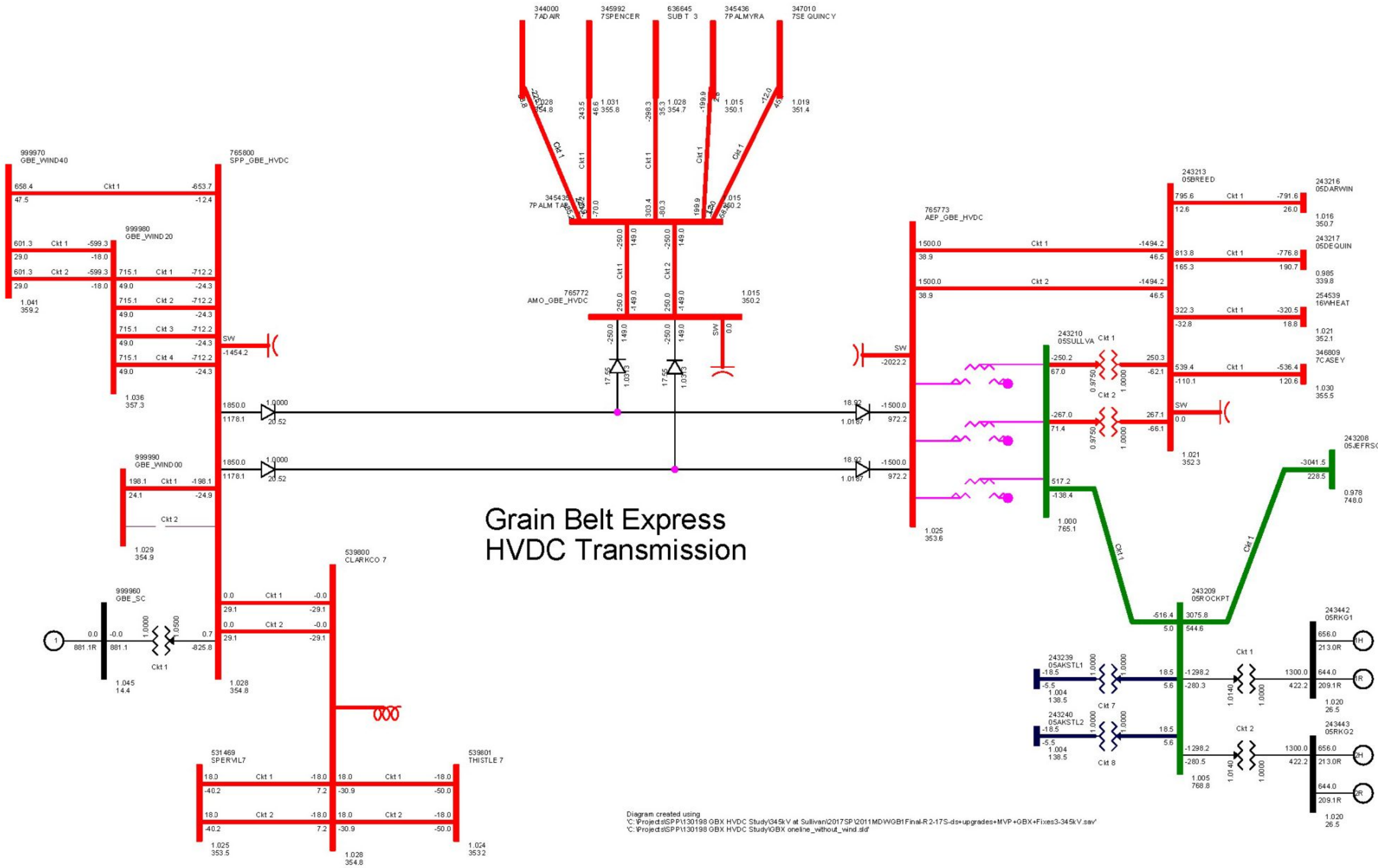


Figure 3-1. Power Flow One-line of GBX HVDC with 345 kV Option at Sullivan – 2017 Summer Peak

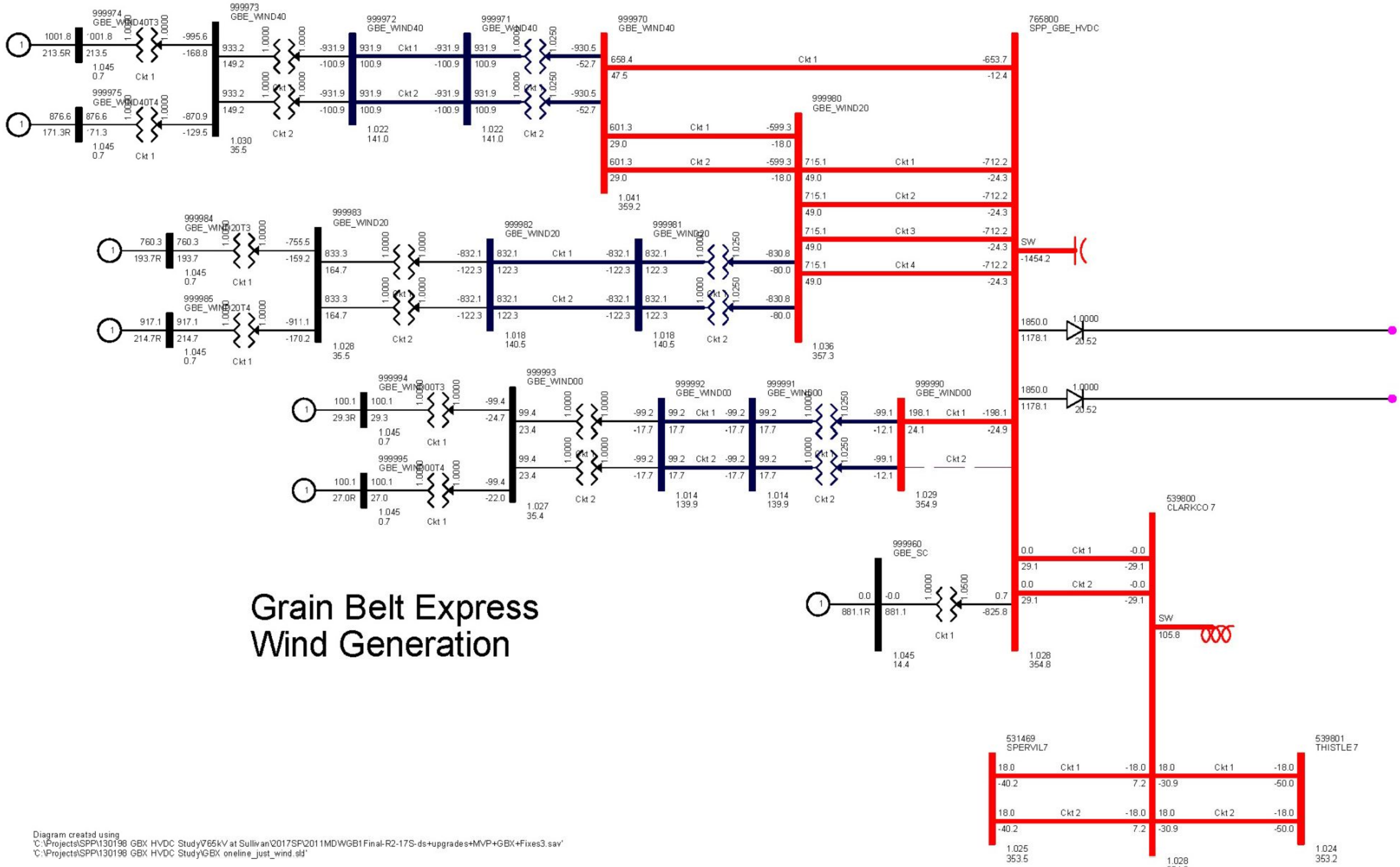


Figure 3-2. Power Flow One-line of GBX Wind Generation – 2017 Summer Peak

3.3 Monitored Facilities

Generators and transmission voltages were monitored in the following areas:

Table 3-1. Areas Monitored

AREA	NAME	AREA	NAME
523	GRDA	540	GMO
524	OKGE	541	KCPL
526	SPS	542	KACY
531	MIDW	640	NPPD
534	SUNC	330	AECI
536	WERE	351	EES

Additional generators were monitored near the AEP Sullivan and AMMO Palmyra rectifier stations, as listed in Table 3-2 and Table 3-3, respectively.

A selection of plots of voltage, frequency, rotor angle and speed from the HVDC project generation and across the SPP footprint were selected as the default plots provided in the appendices.

Table 3-2. Additional Generators Monitored Near Sullivan

Station	Buses	Area
Rockport	243442 - 243443	205 AEP
Petersburg	254811-254814	216 IPL
Gibson	251861-251865	208 DEM
Wheatland	251897-251900	208 DEM
Merom	248773	207 HE
Clifty Ck	248000	206 OVEC
Trimble Co	324034 - 324041	363 LGEE
Cayuga	251849 - 251850	208 DEM
Amos	242891 - 242893	205 AEP
Mountaineer	242894	205 AEP
Mitchel	243188 - 243189	205 AEP
Muskingum	242940	205 AEP
Lawrenceburg	243226	205 AEP
Tanner	243233	205 AEP
Cook	243440 - 243441	205 AEP
Conesville	243622	205 AEP
Big Sandy	243763 - 243764	205 AEP
Killen	253038	209 DAY
Stuart	253077	209 DAY

Table 3-3. Additional Generators Monitored Near Palmyra

Station	Buses	Area
Audrain	344061 - 344063	356 AMMO
Callaway	344225	356 AMMO
Kinmundy	344876	356 AMMO
Labody	344894 - 344895	356 AMMO
Meramad	345132 - 345156	356 AMMO
Osage	345400	356 AMMO
Peno Creek	345441	356 AMMO
Rush Island	345670	356 AMMO
Sioux	345756 - 345765	356 AMMO
Venice	345882	356 AMMO
Raccoon Ck	345994	356 AMMO
Goose Creek	345998	356 AMMO
Keokuk	344863	356 AMMO
Alsey	346516	357 AMIL
Avena	346573	357 AMIL
Coffeen	346897	357 AMIL
Gibson City	347112	357 AMIL
Grand Tower	347170	357 AMIL
Holland Energy	347231	357 AMIL
Hutsonville	347271	357 AMIL
RELU	347819	357 AMIL
Newton	347832	357 AMIL
Clinton	349101	357 AMIL
Vermilion	349109	357 AMIL
Wood River	349115	357 AMIL
Havana	349121	357 AMIL
Tilton	349122	357 AMIL
Baldwin	349126	357 AMIL
Prairie State	349129	357 AMIL
Edwards	349632	357 AMIL
Duck Ck	349633	357 AMIL
Railsplitter	349724	357 AMIL

3.4 Performance Evaluation Methods

The faults shown in Table 3-4 were simulated in this study. This list includes all faults from the PTI report plus some faults at 230 kV and lower voltage levels added at the request of transmission owner Sunflower Electric Power Corporation (SEPC).

Some N-1-1 and N-2 faults were also added to the list. Since both ends of the Clark Co – Spearville 345 kV lines were tested in the original study (FLT12A, FLT12B), a new FLT11B was added to the existing FLT11A so that the Clark Co – Thistle 345 kV lines received the same treatment. The solutions to these faults were tested as pre-fault wind reductions (FLT11C, FLT12C). N-2 faults (aka NERC Category C5) were added for these lines as well (FLT11D, FLT11E, FLT12D).

Simulation channels of voltages, frequencies, rotor angles, and speed deviation from areas covering the entire SPP footprint were selected as the default plot for each disturbance simulation.

All generators were reviewed for stability and tripping. Transmission bus voltages checked against the SPP requirement of 70% to 120% after fault clearing.

Table 3-4. Fault Definitions

No	Description	kV
	3-phase faults with normal clearing	
1	At Clark Co 765800, both poles are blocked	345
2	At Clark Co 765800, one pole is recovered	345
3	At Clark Co 765800, both poles are recovered	345
4	At Sullivan 765773, both poles are blocked	345
5	At Sullivan 765773, one pole is recovered	345
6	At Sullivan 765773, both poles are recovered	345
7	At Palmyra 765772, both poles are blocked	345
8	At Palmyra 765772, one pole is recovered	345
9	At Palmyra 765772, both poles are recovered	345
10	the Palmyra inverter of the recovered pole is still	345
11	Clark Co 539800 - Thistle 539801	345
12	Clark Co 539800 - Spearville 531469	345
13	Thistle 539801 - Wichita 532796	345
14	Thistle 539801 - Woodward 515375	345
15	Woodward 515375 - Tatonga 515407	345
16	Spearville 531469 - Holcomb 531449	345
17	Spearville 531469 - Post Rock 530583	345
18	Spearville 345/230 kV TF (531469 - 539695)	345/230

No	Description	kV
19	Spearville 539695 - Mullergren 539679	230
20	Post Rock 530583 - Axtell 640065	345
21	Holcomb 531449 - Finney 523853	345
22	Holcomb 531449 - Setab 531465	345
23	Finney 523853 - Hitchland 523080	345
24	Finney 523853 - Lamar 599950	345
25	Setab 531465 - Mingo 531451	345
26	Mingo 531451 - Red Willow 640325	345
27	Sullivan 3wnd TF (243210-765773-999920)	765/345
28	Sullivan 765/345 kV TF (243210 - 243213)	765/345
29	Sullivan 243210 - Rockport 243209	765
30	Breed 243213 - Casey 346809	345
31	Breed 243213 - Darwin 243216	345
32	Breed 243213 - Dequine 243217	345
33	Breed 243213 - Wheat 254539	345
34	Rockport 243209 - Jefferson 243208	765
35	Palmyra 765772 - Palmyra tap 345435	345
36	Palmyra Tap 345435 - Sub T 636645	345
37	Palmyra Tap 345435 - Palmyra 345436	345
38	Palmyra Tap 345435 - Adair 344000	345
39	Palmyra Tap 345435 - Spencer 345992	345
40	Palmyra Tap 345435 - Se Quincy 347010	345
	SLG faults with protection failure	
41	Clark Co 539800 - Thistle 539801	345
42	Clark Co 539800 - Spearville 531469	345
43	Thistle 539801 - Wichita 532796	345
44	Thistle 539801 - Woodward 515375	345
45	Woodward 515375 - Tatonga 515407	345
46	Spearville 531469 - Holcomb 531449	345
47	Spearville 531469 - Post Rock 530583	345
48	Spearville 345/230 kV TF (531469 - 539695)	345/230
49	Spearville 539695 - Mullergren 539679	230
50	Post Rock 530583 - Axtell 640065	345
51	Holcomb 531449 - Finney 523853	345
52	Holcomb 531449 - Setab 531465	345
53	Finney 523853 - Hitchland 523080	345
54	Finney 523853 - Lamar 599950	345
55	Setab 531465 - Mingo 531451	345

No	Description	kV
56	Mingo 531451 - Red Willow 640325	345
57	Sullivan 3wnd TF (243210-765773-999920)	765/345
58	Sullivan 765/345 kV TF (243210 - 243213)	765/345
59	Sullivan 243210 - Rockport 243209	765
60	Breed 243213 - Casey 346809	345
61	Breed 243213 - Darwin 243216	345
62	Breed 243213 - Dequine 243217	345
63	Breed 243213 - Wheat 254539	345
64	Rockport 243209 - Jefferson 243208	765
65	Palmyra 765772 - Palmyra tap 345435	345
66	Palmyra Tap 345435 - Sub T 636645	345
67	Palmyra Tap 345435 - Palmyra 345436	345
68	Palmyra Tap 345435 - Adair 344000	345
69	Palmyra Tap 345435 - Spencer 345992	345
70	Palmyra Tap 345435 - Se Quincy 347010	345
	SLG faults with stuck breaker	
71	Fault at Rectifier, block the pole and trip line to collector system	345
72	Fault at Sullivan, trip 3wnd and 2wnd transformers	765/345
73	Fault at Palmyra Tap, trip lines to inverter station and to Palmyra	345
	Faults Added by Sunflower	
74	Mullergren 539679 - Circle 532871, 3-phase	230
75	Mullergren 539679 - Circle 532871, 1-phase delayed	230
76	Pile 531432 - Dobson 531419, 3-phase	115
77	Pile 531432 - Dobson 531419, 1-phase delayed	115
78	Holcomb transformer 531449-531448, 3-phase	345/115
79	Holcomb transformer 531449-531448, 1- phase delayed	345/115
80	Harper 539668 - Milan Tap 539675 - Clearwater 533036, 3-phase	138
81	Harper 539668 - Milan Tap 539675 - Clearwater 533036, 1- phase delayed	138
	N-1-1 and N-2, 3 phase fault with normal clearing	
11A	Prior outage of Clark Co - Thistle #1, fault on #2	345
11B	Prior outage of Thistle - Clark Co #1, fault on #2	345
11C	Prior outage of some GBX wind generation and Clark Co - Thistle #1, fault on #2	345
11D	Clark Co 539800 - Thistle 539801 double circuit	345
11E	Thistle 539801 - Clark Co 539800 double circuit	345
12A	Prior outage of Spearville - Clark Co #1, fault on #2	345

No	Description	kV
12B	Prior outage of Clark Co - Spearville #1, fault on #2	345
12C	Prior outage of some GBX wind generation and Clark Co - Spearville #1, fault on #2	345
12D	Clark Co 539800 - Spearville 531469 double circuit	345
17A	Prior outage of Spearville - Holcomb, fault on Spearville - Post Rock	345

4. Results and Observations

4.1 Stability Analysis Results

Table 4-1 summarizes the results of the initial simulations. Discussion of specific results follows the table.

Table 4-1. Summary of Stability Results

No	Description	2017 LL	2017 SP	2022 SP
	3-phase faults with normal clearing			
1	At Clark Co 765800, both poles are blocked	ok	ok	ok
2	At Clark Co 765800, one pole is recovered	ok	ok	ok
3	At Clark Co 765800, both poles are recovered	ok	ok	ok
4	At Sullivan 765773, both poles are blocked	ok	ok	ok
5	At Sullivan 765773, one pole is recovered	ok	ok	ok
6	At Sullivan 765773, both poles are recovered	ok	ok	ok
7	At Palmyra 765772, both poles are blocked	ok	ok	ok
8	At Palmyra 765772, one pole is recovered	ok	ok	ok
9	At Palmyra 765772, both poles are recovered	ok	ok	ok
10	the Palmyra inverter of the recovered pole is still	ok	ok	ok
11	Clark Co 539800 - Thistle 539801	ok	ok	ok
12	Clark Co 539800 - Spearville 531469	ok	ok	ok
13	Thistle 539801 - Wichita 532796	ok	ok	ok
14	Thistle 539801 - Woodward 515375	ok	ok	ok
15	Woodward 515375 - Tatonga 515407	ok	ok	ok
16	Spearville 531469 - Holcomb 531449	ok	ok	ok
17	Spearville 531469 - Post Rock 530583	ok	ok	ok
18	Spearville 345/230 kV TF (531469 - 539695)	ok	ok	ok
19	Spearville 539695 - Mullergren 539679	ok	ok	ok
20	Post Rock 530583 - Axtell 640065	ok	ok	ok
21	Holcomb 531449 - Finney 523853	ok	ok	ok
22	Holcomb 531449 - Setab 531465	ok	ok	ok
23	Finney 523853 - Hitchland 523080	ok	ok	ok
24	Finney 523853 - Lamar 599950	ok	ok	ok
25	Setab 531465 - Mingo 531451	ok	ok	ok
26	Mingo 531451 - Red Willow 640325	ok	ok	ok
27	Sullivan 3wnd TF (243210-765773-999920)	ok	ok	ok
28	Sullivan 765/345 kV TF (243210 - 243213)	ok	ok	ok

No	Description	2017 LL	2017 SP	2022 SP
29	Sullivan 243210 - Rockport 243209	ok	ok	ok
30	Breed 243213 - Casey 346809	ok	ok	ok
31	Breed 243213 - Darwin 243216	ok	ok	ok
32	Breed 243213 - Dequine 243217	ok	ok	ok
33	Breed 243213 - Wheat 254539	ok	ok	ok
34	Rockport 243209 - Jefferson 243208	ok	ok	ok
35	Palmyra 765772 - Palmyra tap 345435	ok	ok	ok
36	Palmyra Tap 345435 - Sub T 636645	ok	ok	ok
37	Palmyra Tap 345435 - Palmyra 345436	ok	ok	ok
38	Palmyra Tap 345435 - Adair 344000	ok	ok	ok
39	Palmyra Tap 345435 - Spencer 345992	ok	ok	ok
40	Palmyra Tap 345435 - Se Quincy 347010	ok	ok	ok
	SLG faults with protection failure			
41	Clark Co 539800 - Thistle 539801	ok	ok	ok
42	Clark Co 539800 - Spearville 531469	ok	ok	ok
43	Thistle 539801 - Wichita 532796	ok	ok	ok
44	Thistle 539801 - Woodward 515375	ok	ok	ok
45	Woodward 515375 - Tatonga 515407	ok	ok	ok
46	Spearville 531469 - Holcomb 531449	ok	ok	ok
47	Spearville 531469 - Post Rock 530583	ok	ok	ok
48	Spearville 345/230 kV TF (531469 - 539695)	ok	ok	ok
49	Spearville 539695 - Mullergren 539679	ok	ok	ok
50	Post Rock 530583 - Axtell 640065	ok	ok	ok
51	Holcomb 531449 - Finney 523853	ok	ok	ok
52	Holcomb 531449 - Setab 531465	ok	ok	ok
53	Finney 523853 - Hitchland 523080	ok	ok	ok
54	Finney 523853 - Lamar 599950	ok	ok	ok
55	Setab 531465 - Mingo 531451	ok	ok	ok
56	Mingo 531451 - Red Willow 640325	ok	ok	ok
57	Sullivan 3wnd TF (243210-765773-999920)	ok	ok	ok
58	Sullivan 765/345 kV TF (243210 - 243213)	ok	ok	ok
59	Sullivan 243210 - Rockport 243209	ok	ok	ok
60	Breed 243213 - Casey 346809	ok	ok	ok
61	Breed 243213 - Darwin 243216	ok	ok	ok
62	Breed 243213 - Dequine 243217	ok	ok	ok
63	Breed 243213 - Wheat 254539	ok	ok	ok
64	Rockport 243209 - Jefferson 243208	ok	ok	ok

No	Description	2017 LL	2017 SP	2022 SP
65	Palmyra 765772 - Palmyra tap 345435	ok	ok	ok
66	Palmyra Tap 345435 - Sub T 636645	ok	ok	ok
67	Palmyra Tap 345435 - Palmyra 345436	ok	ok	ok
68	Palmyra Tap 345435 - Adair 344000	ok	ok	ok
69	Palmyra Tap 345435 - Spencer 345992	ok	ok	ok
70	Palmyra Tap 345435 - Se Quincy 347010	ok	ok	ok
	SLG faults with stuck breaker			
71	Fault at Rectifier, block the pole and trip line to collector system	ok	ok	ok
72	Fault at Sullivan, trip 3wnd and 2wnd transformers	ok	ok	ok
73	Fault at Palmyra Tap, trip lines to inverter station and to Palmyra	ok	ok	ok
	Faults Added by Sunflower			
74	Mullergren - Circle, 3-phase	ok	ok	ok
75	Mullergren - Circle, 1-phase delayed	ok	ok	ok
76	Pile - Dobson, 3-phase	ok	ok	ok
77	Pile - Dobson, 1-phase delayed	ok	ok	ok
78	Holcomb transformer, 3-phase	ok	ok	ok
79	Holcomb transformer, 1- phase delayed	ok	ok	ok
80	Harper - Milan Tap - Clearwater, 3-phase	ok	ok	ok
81	Harper - Milan Tap - Clearwater, 1- phase delayed	ok	ok	ok
	N-1-1 and N-2, 3 phase fault with normal clearing			
11A	Prior outage of Clark Co - Thistle #1, fault on #2	**unstable**	**unstable**	**unstable**
11A _voltcont	Prior outage of Clark Co - Thistle #1, fault on #2 Trip some wind generation	**Ok if trip 877 MW**	**Ok if trip 760 MW**	**Ok if trip 760 MW**
11B	Prior outage of Thistle - Clark Co #1, fault on #2	**unstable**	**unstable**	**unstable**
11B _voltcont	Prior outage of Thistle - Clark Co #1, fault on #2 Trip some wind generation	**Ok if trip 1637 MW**	**Ok if trip 1637 MW**	**Ok if trip 1637 MW**
11C	Prior outage of some GBX wind generation and Clark Co - Thistle #1, fault on #2	**Ok if trip 877 MW**	**Ok if trip 877 MW**	**Ok if trip 877 MW**
11D	Clark Co - Thistle double circuit	**unstable**	**unstable**	**unstable**
11D _voltcont	Clark Co - Thistle double circuit Trip some wind generation	**Ok if trip 877 MW**	**Ok if trip 877 MW**	**Ok if trip 877 MW**
11E	Thistle - Clark Co double circuit	**unstable**	**unstable**	**unstable**
11E _voltcont	Thistle - Clark Co double circuit Trip some wind generation	**Ok if trip 1637 MW**	**Ok if trip 1637 MW**	**Ok if trip 1637 MW**
12A	Prior outage of Spearville - Clark Co #1, fault on #2	ok	ok	ok

No	Description	2017 LL	2017 SP	2022 SP
12B	Prior outage of Clark Co - Spearville #1, fault on #2	**unstable**	**unstable**	**unstable**
12B _voltcont	Prior outage of Clark Co - Spearville #1, fault on #2 Trip some wind generation	**Ok if trip 877 MW**	**Ok if trip 877 MW**	**Ok if trip 877 MW**
12C	Prior outage of some GBX wind generation and Clark Co - Spearville #1, fault on #2	**Ok if trip 877 MW**	**Ok if trip 877 MW**	**Ok if trip 877 MW**
12D	Clark Co - Spearville double circuit	**unstable**	**unstable**	**unstable**
12D _voltcont	Clark Co - Spearville double circuit Trip some wind generation	**Ok if trip 877 MW**	**Ok if trip 877 MW**	**Ok if trip 877 MW**
17A	Prior outage of Spearville - Holcomb, fault on Spearville - Post Rock	ok	ok	ok

4.2 Discussion of Notable Results

4.2.1 Faults near SPP Clark County 345 kV Station

All of the NERC Category B faults in SPP were stable. Some of the NERC Category C faults were unstable, including the N-1-1 (aka NERC Category C3) faults on the Clark Co. – Spearville 345 kV lines (FLT12A, FLT12B) and the Clark Co. – Thistle 345 kV lines (FLT11A, FLT11B). If one of the lines is out of service and the parallel line has a fault, the GBX wind generators trip on over-frequency (see plot of FLT11A in Figure 4-1). To fix this problem, the PTI report proposes tripping some of the wind generation (760-877 MW) at the same time as the faulted line. This solution is confirmed to work and allows the remaining GBX wind generation to stay on-line and stable (Figure 4-2). However, generation tripping will require a Special Protection System (SPS) that may not be acceptable to SPP or the transmission owner.

Another option is to reduce wind generation after the first contingency occurs but before the second contingency. This option was tested in PSS/E as FLT11C and FLT12C, and the results were stable but without the need for an SPS (Figure 4-3).

If the parallel Clark Co. – Spearville 345 kV lines share towers, or if the parallel Clark Co. – Thistle 345 kV lines share towers, then NERC Category C5 will have to be considered as well. In this case, there is no option to reduce wind generation and HVDC schedule between the two line trips. Consideration of Category C5 would bring back the need for post-fault generation tripping. Simulations were run (FLT11D, FLT11E, and FLT12D) that demonstrated the generation tripping solution works for the N-2 contingencies just as well as for the N-1-1 contingencies. However, if an SPS is not acceptable to SPP, then a new transmission line or other major upgrade may be needed.

The original study did not simulate the fault at Thistle for the N-1-1 outage of the Clark Co. – Thistle 345 kV lines. When that fault was tested in this study (FLT11B), more generation tripping was required than for the other faults – 1637 MW. Since a fault can occur anywhere along a line, the largest amount of tripping found while testing faults at both ends will need to be used.

In the original simulations, the HVDC power schedule did not always follow the over-frequency tripping of GBX wind generation. In the actual equipment, HVDC power will need to follow the wind power, at least in the steady state, if not faster. One possibility is for the HVDC control system to continually adjust its power schedule to maintain zero flow on the lines connecting to SPP. This could include active power flow, reactive power flow, or both. The speed of this control will have to be agreed to by Clean Line, SPP, and the local transmission utility. A faster control will reduce inadvertent flows and impacts on the SPP system.

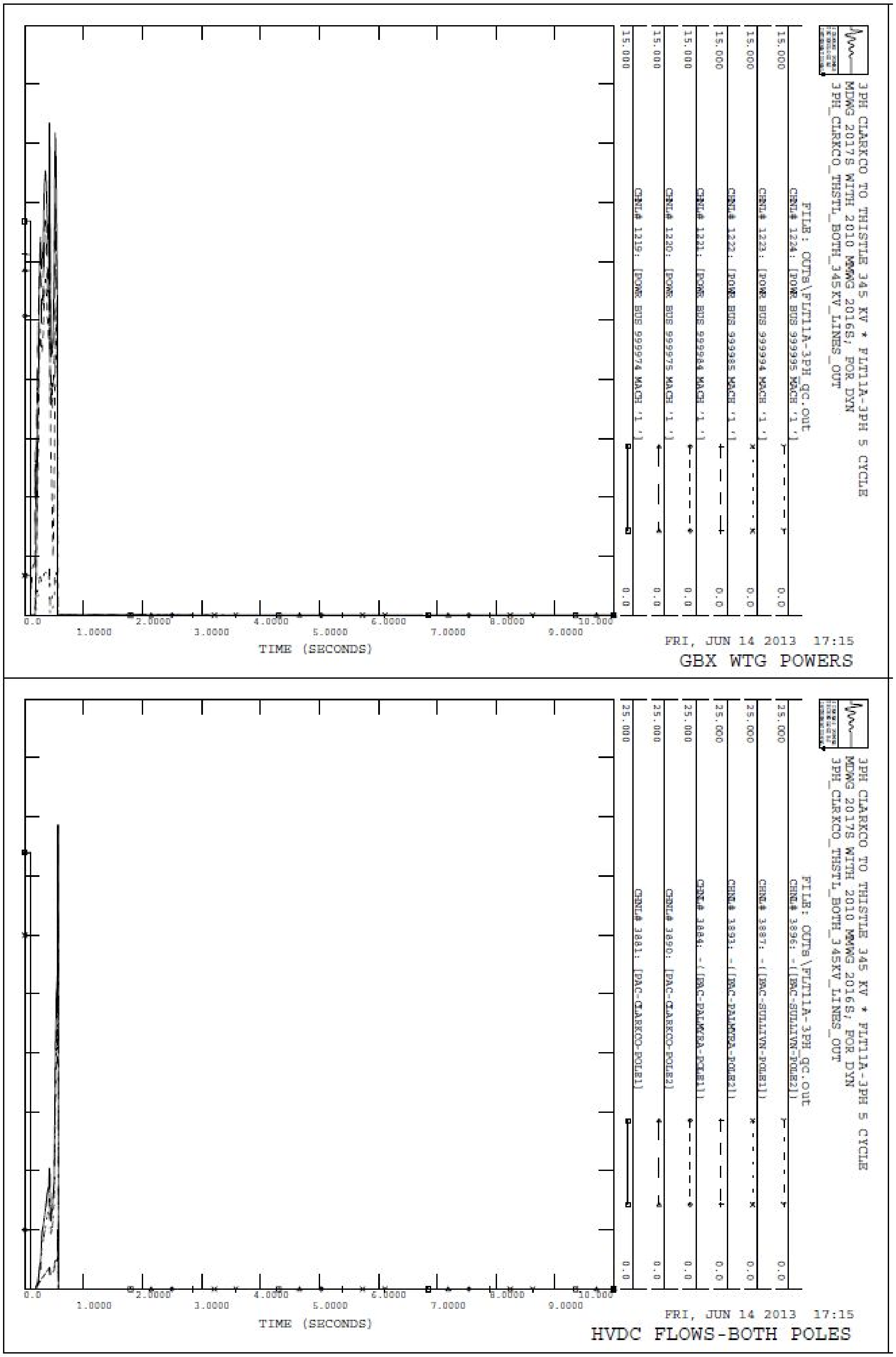


Figure 4-1. Wind and HVDC Powers for FLT11A, 3ph fault on Clark Co – Thistle 345 #1 with prior outage of #2

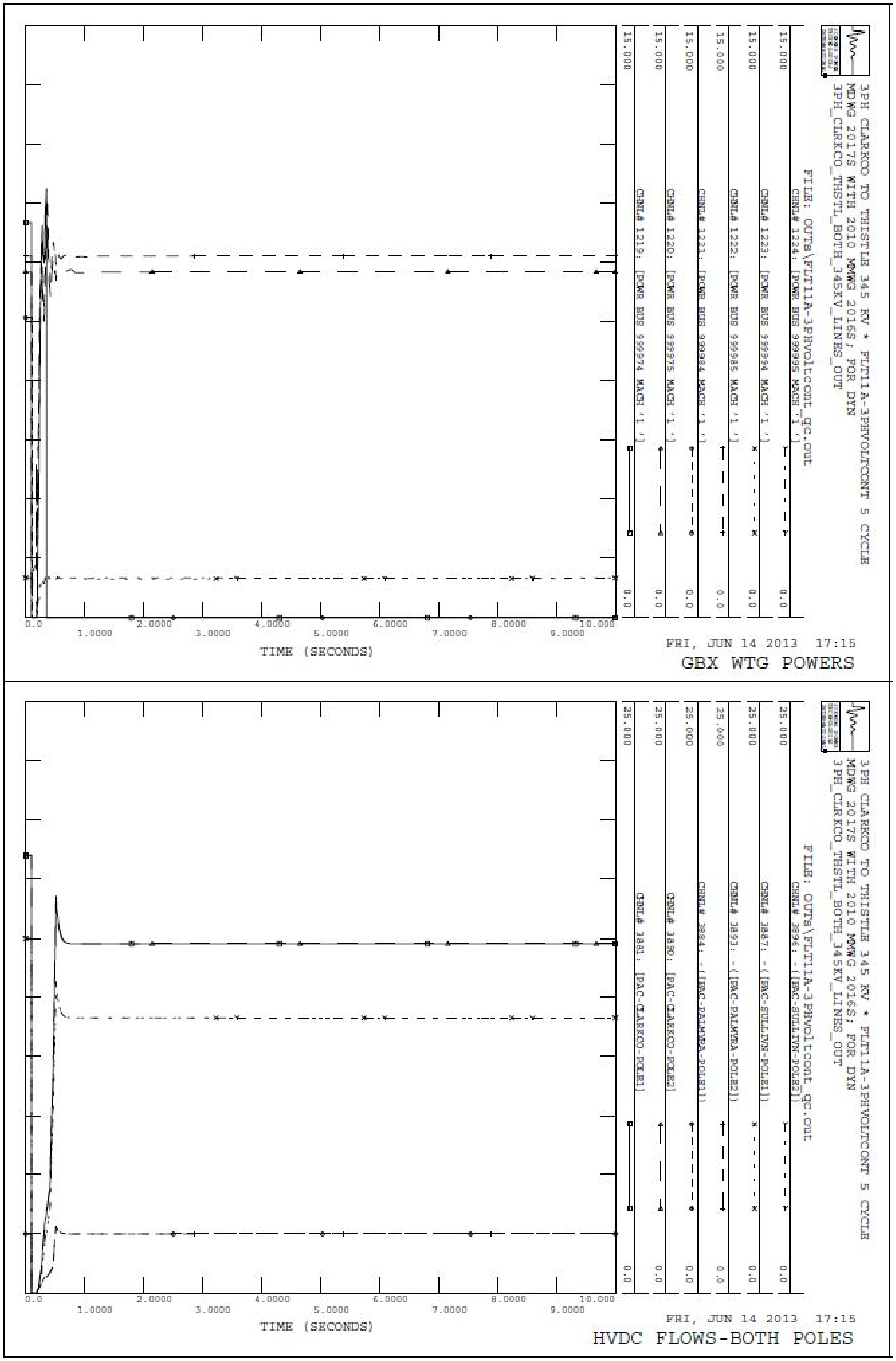


Figure 4-2. Wind and HVDC Powers for FLT11A_voltcont, 3ph fault on Clark Co – Thistle 345 #1 with prior outage of #2, trip some wind generation post-fault

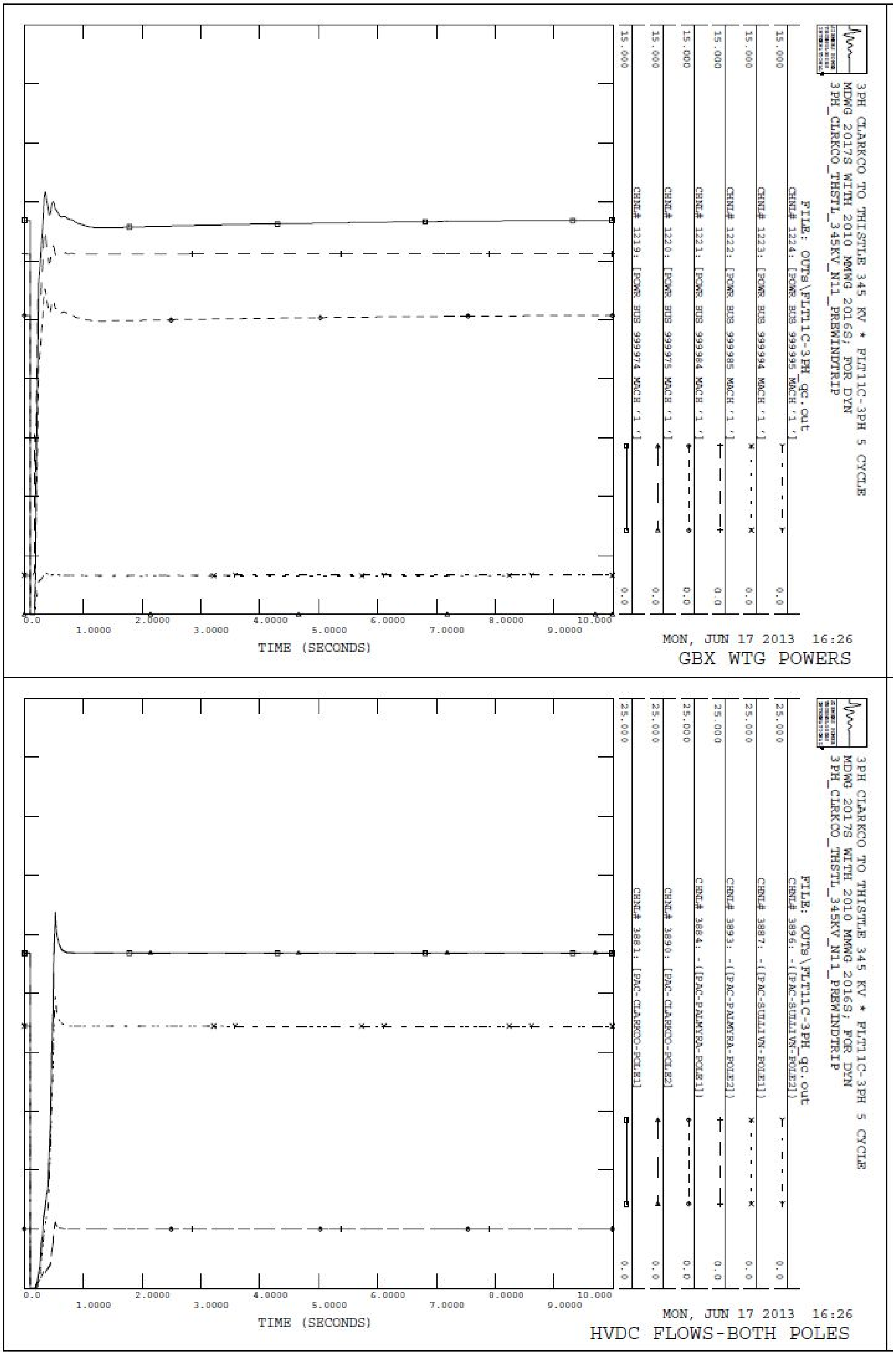


Figure 4-3. Wind and HVDC Powers for FLT11C, 3ph fault on Clark Co – Thistle 345 #1 with prior outage of #2, trip some wind generation PRE-fault

4.2.2 Faults near SPP Clark County 345 kV Station – New POI

The GBX project developer notified SPP of a desire to change the POI to a point 14 miles from Clark Co on the 345 kV lines to Spearville. Section 4.2.1 showed that the critical faults in SPP are the N-1-1 and N-2 faults around the POI. The critical faults were updated and repeated for the new POI location. Faults that were previously simulated at Clark Co, which was the POI for the initial analysis, were moved to the new GBX POI. Faults at Spearville and Thistle were left at those buses. Results are summarized in Table 4-2.

Most of the results are the same as with the previous POI. The most notable difference is that faults 11A and 11D are stable **in the 2017SP case** with the new POI (but still unstable in the 2017LL and 2022SP cases). Losing the lines toward Thistle may not be quite as severe now that the POI is closer to Spearville. However, while the fault 11A and 11D results are officially stable in the 2017SP case, they are not acceptable. After fault clearing, transmission voltage dips as low as 45% at the Post Rock 345 kV bus (Figure 4-4). The solution to trip up to 877 MW of wind generation following faults 11A and 11D continues to work for the new POI, providing both stability and keeping post-fault voltages above 70% (Figure 4-5).

These results match the results shown in PTI's August 13-14 power point slides, for the same faults. As with the original POI, PTI's slides do not discuss faults at the Thistle end of the Clark Co – Thistle 345 kV lines. In this study, these Thistle faults are shown to require the largest amounts of GBX wind tripping.

Table 4-2. Summary of Stability Results for new POI

No	Description	2017 LL	2017 SP	2022 SP
	N-1-1 and N-2, 3 phase fault with normal clearing			
11A	Prior outage of GBX POI - Clark Co #1, fault on #2	unstable	severe voltage dip	unstable
11A _voltcont	Prior outage of GBX POI - Clark Co #1, fault on #2 Trip some wind generation	Ok if trip 877 MW	Ok if trip 760 MW	Ok if trip 760 MW
11B	Prior outage of Thistle - Clark Co #1, fault on #2	unstable	unstable	unstable
11B _voltcont	Prior outage of Thistle - Clark Co #1, fault on #2 Trip some wind generation	Ok if trip 1637 MW	Ok if trip 1637 MW	Ok if trip 1637 MW
11C	Prior outage of some GBX wind generation and GBX POI - Clark Co #1, fault on #2	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
11D	GBX POI - Clark Co double circuit	unstable	severe voltage dip	unstable
11D _voltcont	GBX POI - Clark Co double circuit Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
11E	Thistle - Clark Co double circuit	unstable	unstable	unstable
11E _voltcont	Thistle - Clark Co double circuit Trip some wind generation	Ok if trip 1637 MW	Ok if trip 1637 MW	Ok if trip 1637 MW
12A	Prior outage of Spearville - GBX POI #1, fault on #2	ok	ok	ok
12B	Prior outage of GBX POI - Spearville #1, fault on #2	unstable	unstable	unstable
12B _voltcont	Prior outage of GBX POI - Spearville #1, fault on #2 Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
12C	Prior outage of some GBX wind generation and GBX POI - Spearville #1, fault on #2	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
12D	GBX POI - Spearville double circuit	unstable	unstable	unstable
12D _voltcont	GBX POI - Spearville double circuit Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
17A	Prior outage of Spearville - Holcomb, fault on Spearville - Post Rock	ok	ok	ok

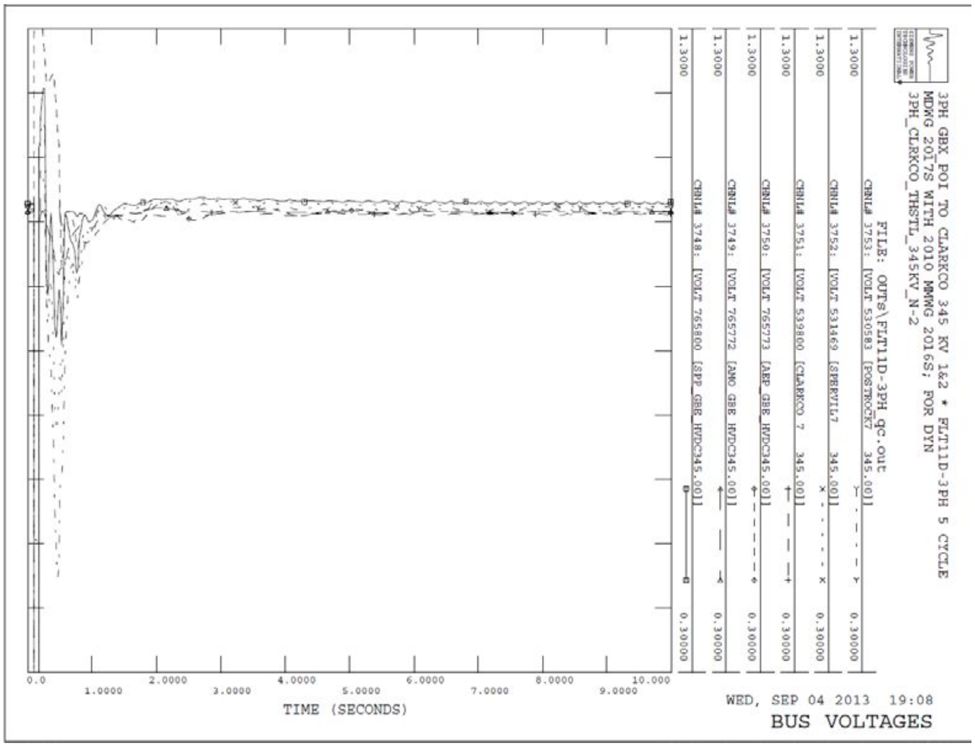


Figure 4-4. Transmission Voltages for FLT11D, 3ph fault on GBX POI – Clark Co 345 #1 and #2 double circuit

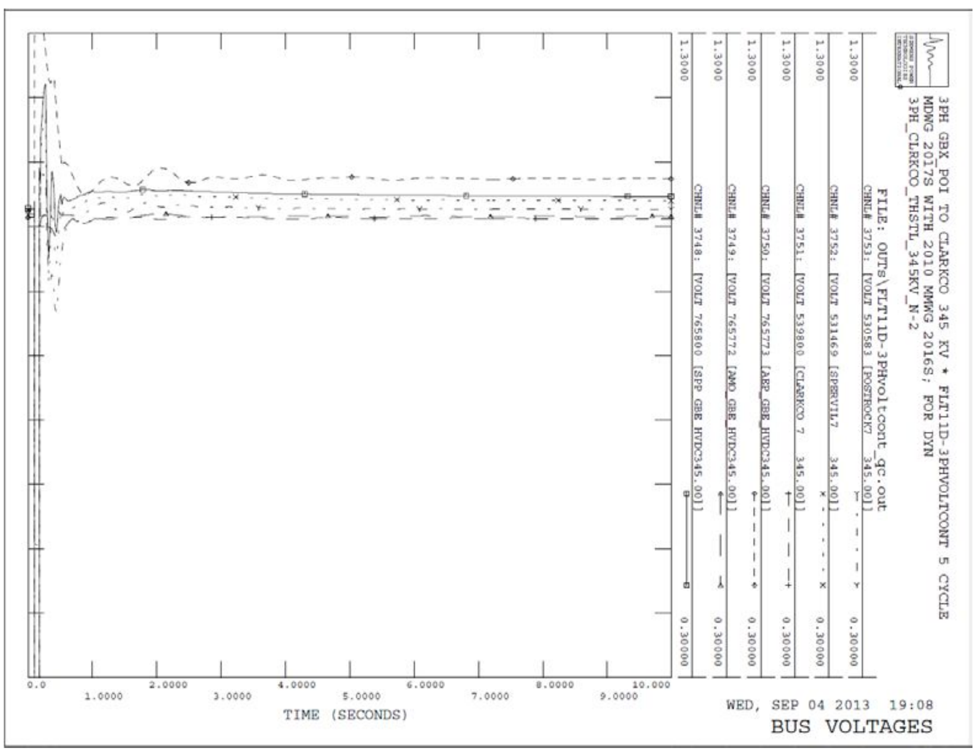


Figure 4-5. Transmission Voltages for FLT11D, 3ph fault on GBX POI – Clark Co 345 #1 and #2 double circuit, trip some wind generation post-fault

4.2.3 Faults near AEP Sullivan 765/345 kV Station

After most of this study work was complete, Clean Line notified SPP that the 765 kV connection option at the AEP Sullivan station should no longer be considered. The 345 kV connection at Sullivan is now the only option considered at the AEP end of the HVDC line. The following discussion applies to the Sullivan 345 kV connection.

The most severe fault near Sullivan was on the Rockport – Jefferson 765 kV line. Loss of this line results in all 2600 MW from the Rockport plant feeding into Sullivan 765 and Breed 345 stations, the same place where 3000 MW is injected from the GBX project. The Rockport generators go unstable and trip off-line in the 2017SP (Figure 4-6) and 2022SP cases. This problem did not show up in the 2017LL case because Rockport was dispatched at a lower level of 1760 MW.

When this contingency was tested in AC power flow on the 2017SP and 2022SP cases, the Newton solution algorithm diverged. Looking at the pre-contingency 2017SP base case with the GBX project, the Rockport – Jefferson 765 kV line is loaded to 3076 MW, beyond its surge impedance loading of 2270 MW. The line is consuming a total of 773 Mvar of reactive power (including 300 Mvar of line shunt reactors) and the Rockport generators are running at a high reactive power output.

The PTI report showed that reducing HVDC power injection at Sullivan to 1500 MW by tripping one pole following the Rockport – Jefferson 765 kV fault allowed the Rockport units to remain stable. This solution was confirmed in dynamics (Figure 4-7) and was also stable in power flow. However, this solution would require an SPS that may not be allowed by AEP. If an SPS is not acceptable, then a major transmission upgrade, such as a new line, may be needed near Sullivan or Rockport, or the project size may need to be reduced.

The 3500 MW injection option at Sullivan was not studied. This scenario will need to be addressed if the project moves forward with its current design.

4.2.4 Faults near AMMO Palmyra Tap 345 kV Station

All faults near the AMMO Palmyra Tap station were stable. The GBX HVDC project only injects 500 MW at this 345 kV station that includes five (5) 345 kV transmission lines. Figure 4-8 shows example plots for a three-phase fault on the Palmyra Tap – Sub T 345 kV transmission line. Voltages are stable and the HVDC recovers to pre-contingency power flows.

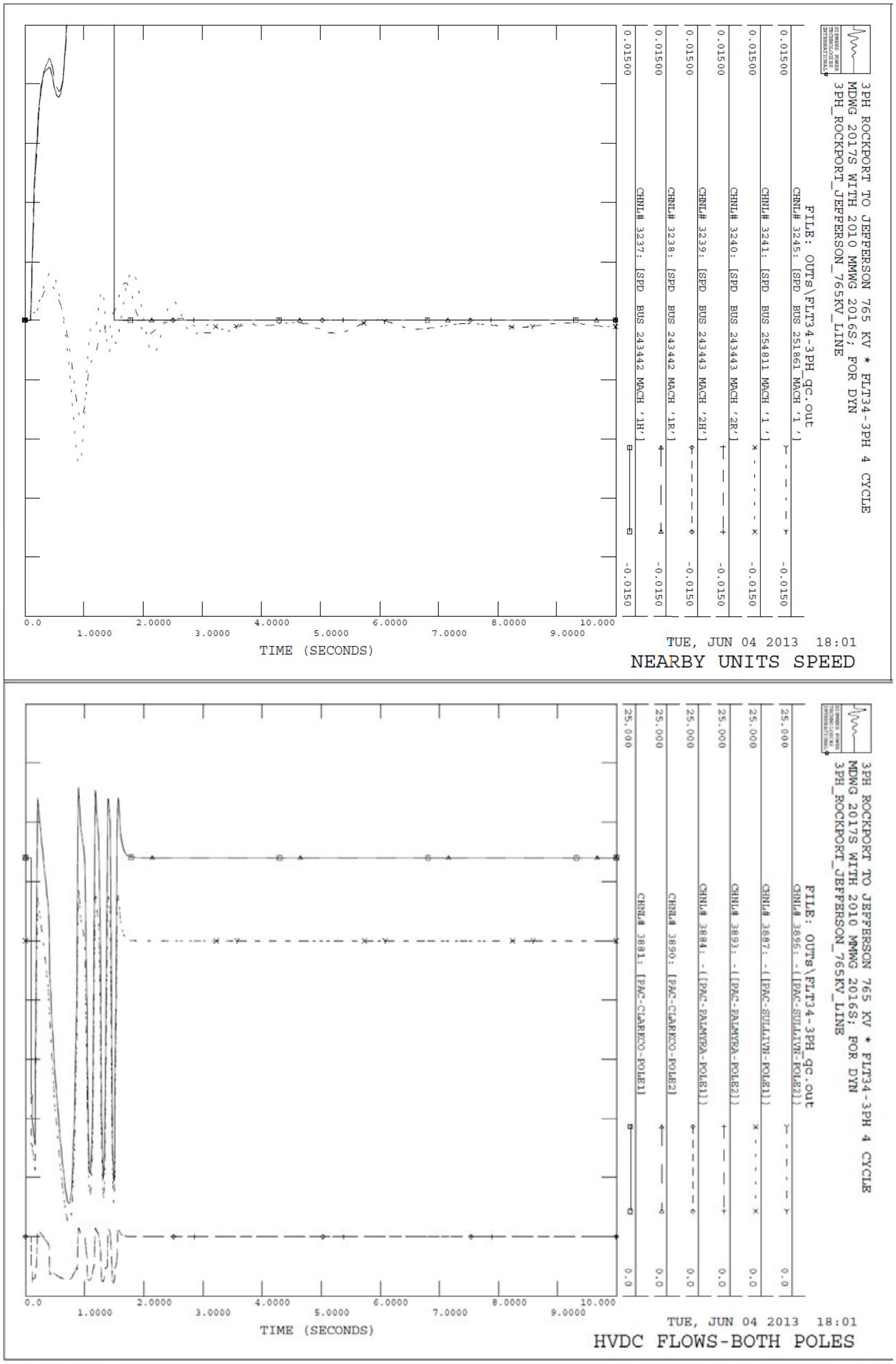


Figure 4-6. Rockport Speeds and HVDC Powers for FLT34, 3ph fault on Rockport – Jefferson 765

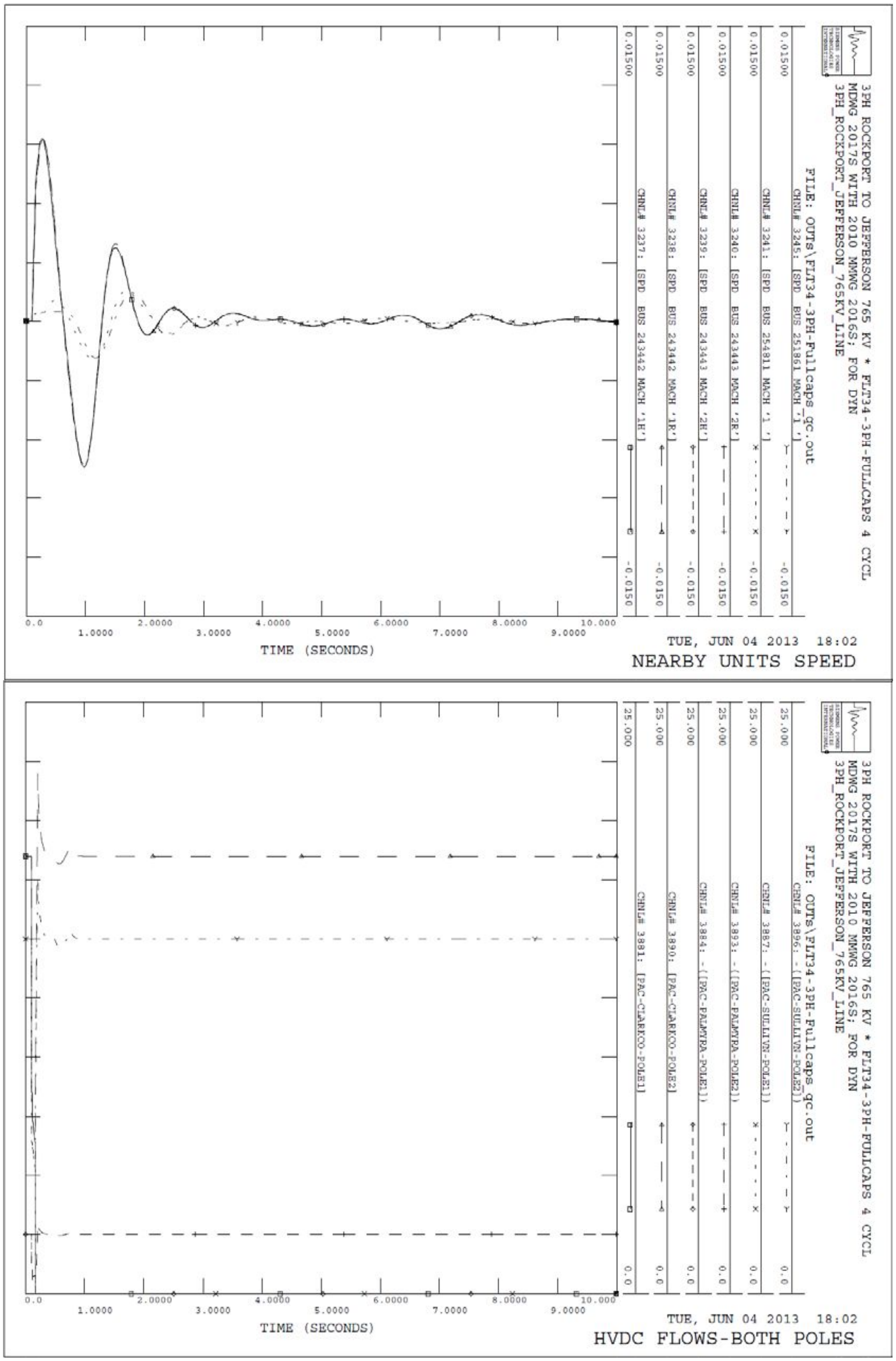
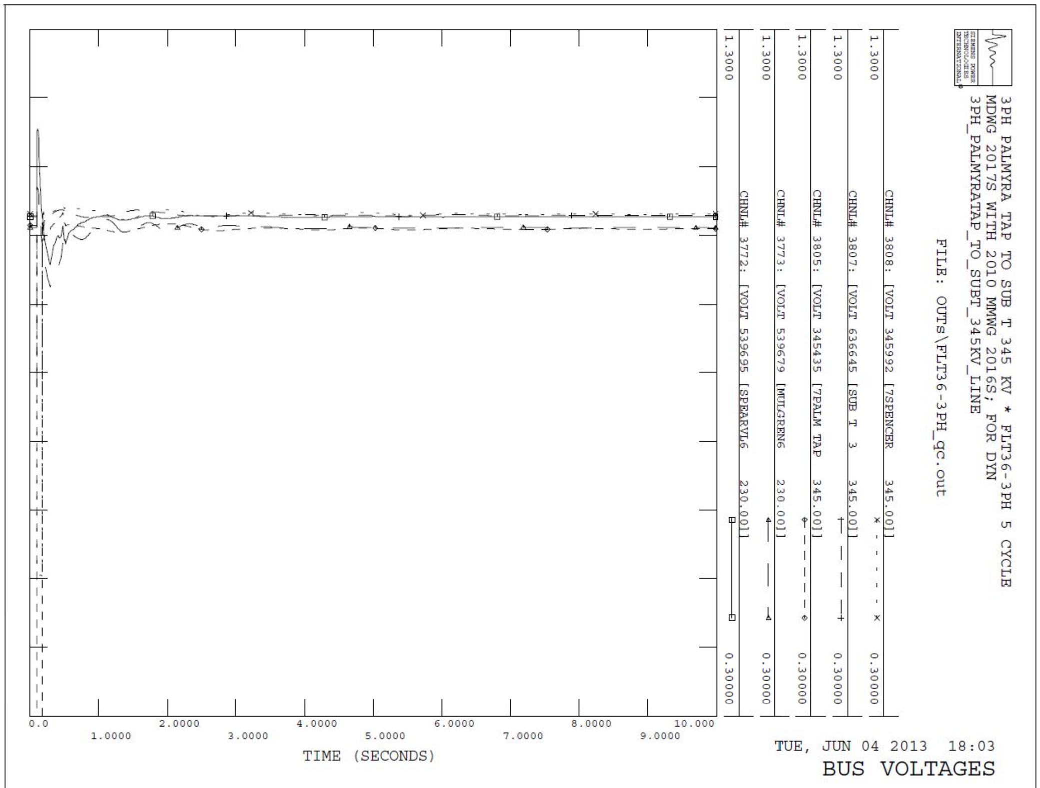


Figure 4-7. Rockport Speeds and HVDC Powers for FLT34, 3ph fault on Rockport – Jefferson 765, tripping one GBX HVDC pole post-fault



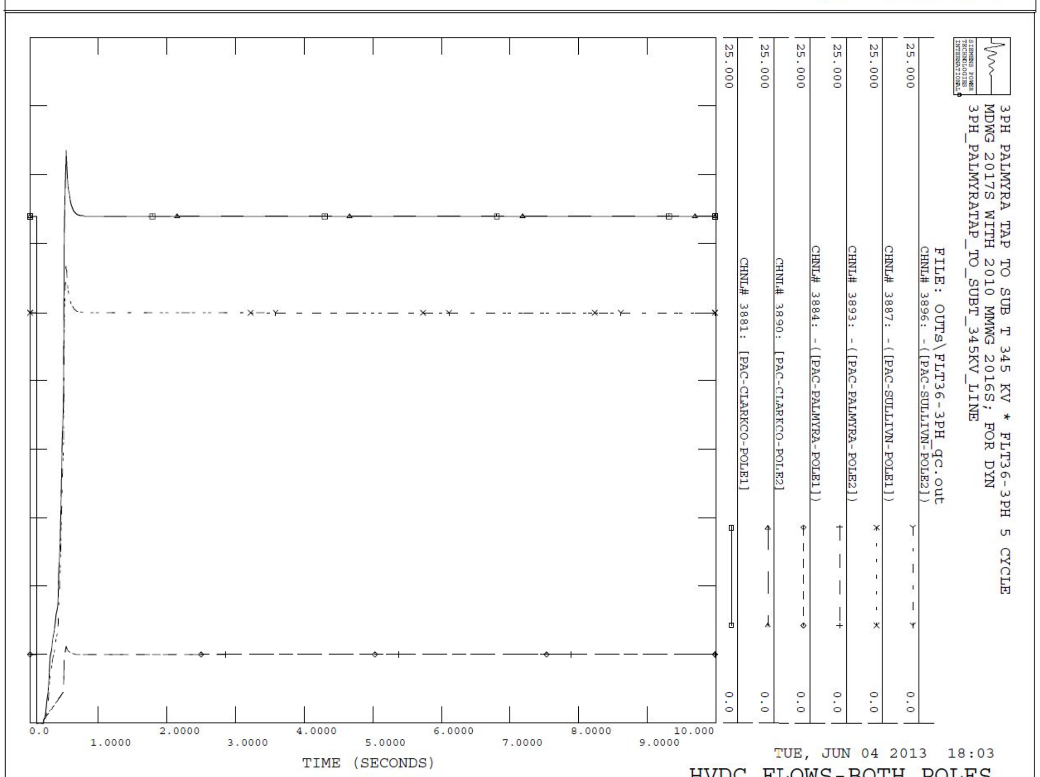


Figure 4-8. Bus Voltages and HVDC Powers for FLT36, 3ph fault on Palmyra Tap – Sub T 345

4.2.5 Both HVDC Poles Blocked

Of particular interest to the existing AC transmission owners and operators is what happens when both HVDC poles are lost. On the SPP side, this results in all GBX wind generation flowing into the SPP AC grid rather than the HVDC lines. The power then flows over the rest of the Eastern Interconnection AC grid to the MISO and PJM loads. The simulations show stable operation following loss of both HVDC poles (Figure 4-9). There is certainly significant power flow onto the SPP transmission network, but the AC grid is able to handle the flow in the short term. The GBX project will still need a control scheme that matches GBX wind generation and HVDC flow as quickly as feasible after an imbalance occurs.

Note however that most wind generation from the SPP interconnection queue is NOT present in the study cases. The current SPP queue contains hundreds of MW of wind plants that plan to connect at or near Clark Co, Spearville, and Thistle 345 kV stations. Stability results could change for the worse if SPP queue generation were included in the analysis.

For faults at the AEP Sullivan and AMMO Palmyra converters resulting in loss of both HVDC poles, simulation results were also stable (Figure 4-10, Figure 4-11).

4.2.6 Transient Voltage Review

After fault clearing, transmission voltages were checked to determine if they fell outside the SPP criteria of 70% to 120%. The previously-discussed unstable faults had many transient voltage violations and are not discussed further in this section.

For stable faults, there were frequent excursions above 120% in the time from fault clearing until the HVDC poles were ramped back up to full power. During this time, the HVDC capacitors were on line but the converters were consuming little to no reactive power. Among the initial fault runs, the highest voltage found was 134.5% at the AEP HVDC converter bus following a fault on the Sullivan-Rockport 765 kV line. The highest voltage seen at an existing bus was 128.7% at Breed 345 for the same fault. During the generation-tripping solutions for some of the N-1-1 faults, up to 136% voltage was seen near the AEP HVDC converter and up to 125.5% near the SPP converter bus.

The GBX project will need to control its reactive power sources and sinks to ensure acceptable voltages. For example, the capacitors can be taken off-line during severe faults that shut down the HVDC converters, and the capacitors can be brought back on in steps as HVDC power is ramped back up.

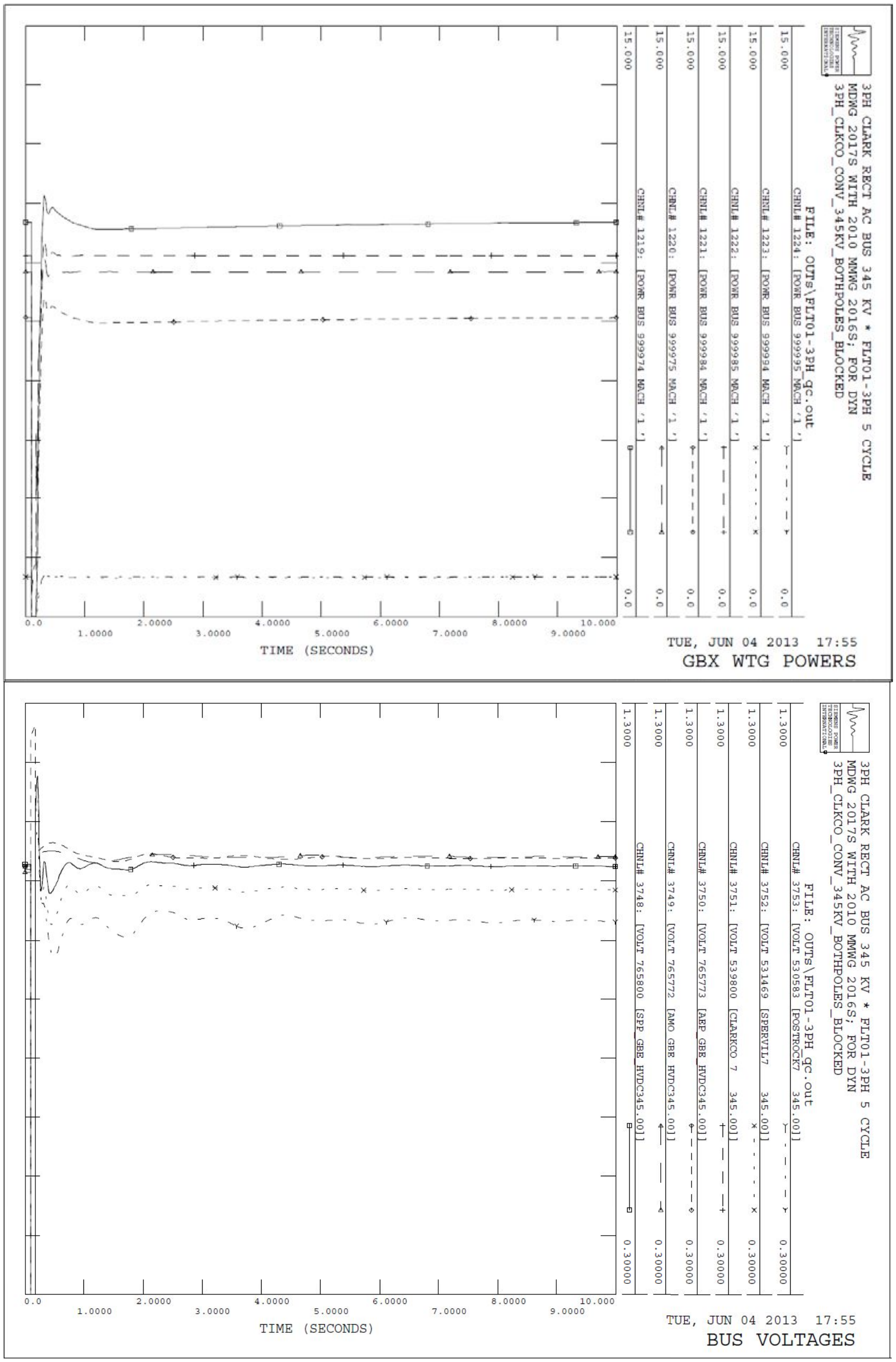


Figure 4-9. GBX Wind Power and Bus Voltages for FLT01, 3ph fault at GBX SPP converter AC bus, tripping both GBX HVDC poles

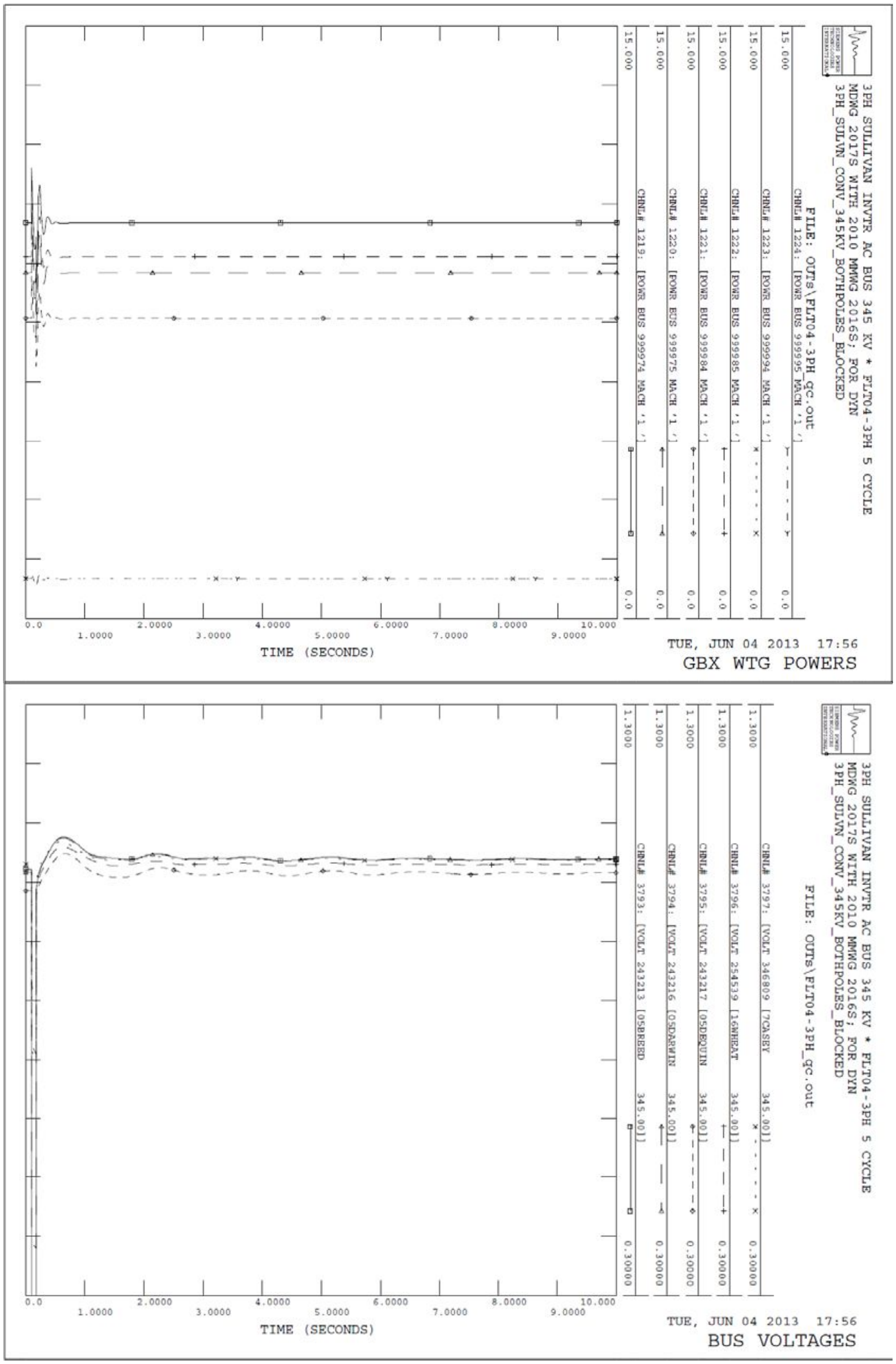
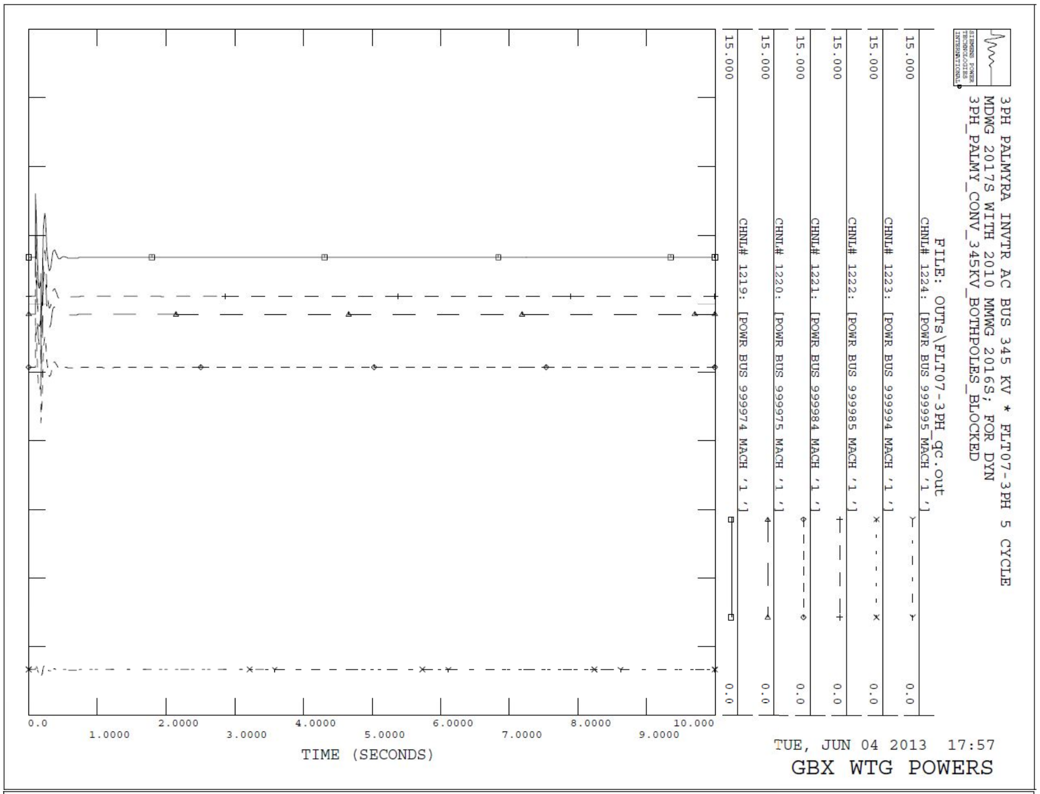


Figure 4-10. GBX Wind Power and Bus Voltages for FLT04, 3ph fault at GBX AEP converter AC bus, tripping both GBX HVDC poles



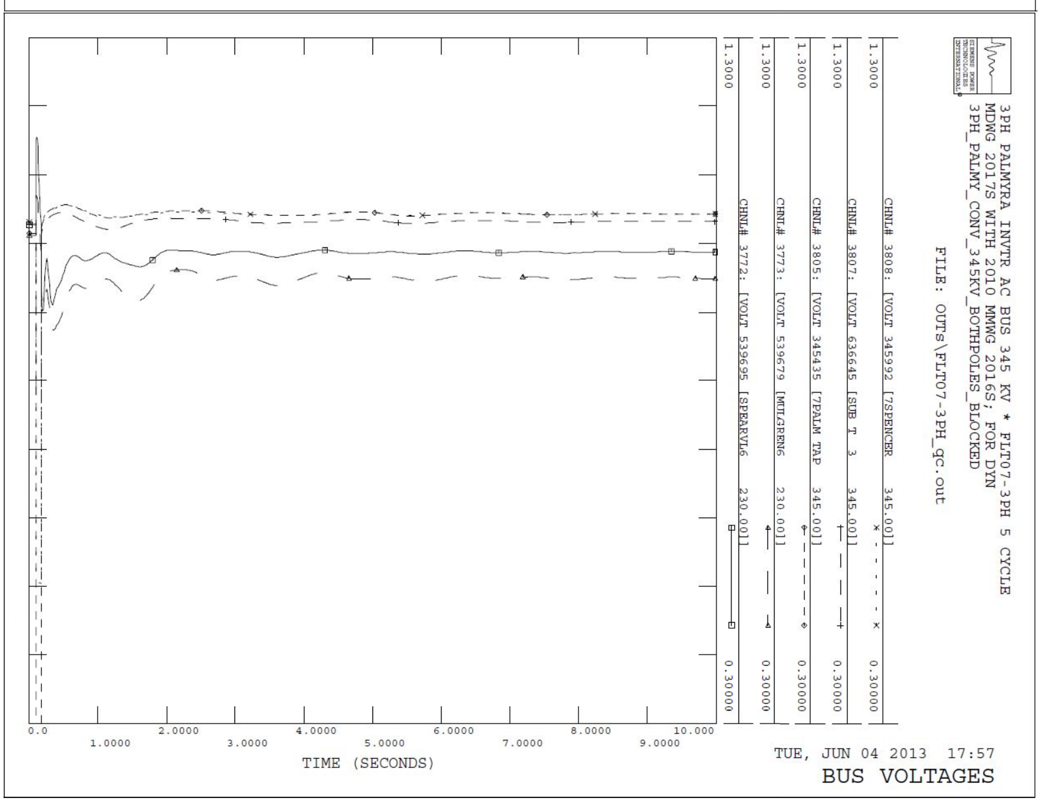


Figure 4-11. GBX Wind Power and Bus Voltages for FLT07, 3ph fault at GBX Palmyra converter AC bus, tripping both GBX HVDC poles

4.3 General Review of the Previous Report

Part of the scope of this project was to review the report created by the developer's consultant. The March 2013 report from Siemens PTI is well-written and describes the problems found and proposed solutions to fix those problems. A few comments on that report and study are as follows:

Conditions Analyzed

The analysis included three-phase faults with normal clearing and single-line-to-ground faults with delayed clearing. Most of the delayed clearing faults assumed protection system failure, so the fault took longer to clear but no additional branches were tripped. Only a few faults were analyzed with delayed clearing due to breaker failure. Future studies should examine more single-line-to-ground faults with breaker failure. Clark Co 345 would be especially interesting. Breaker configurations will need to be known or assumed.

The interconnection request states that 3500 MW may be injected at the AEP Sullivan converter, with the AMMO Palmyra Tap converter running at 0 MW. This operating state will need to be examined in a future study. It will certainly add further stress to the AEP transmission system near Sullivan.

Solutions Proposed

For the stability problems seen at the SPP and AEP ends of the project, the primary solutions involved tripping parts of the GBX project – wind generation and/or HVDC flow – following certain faults. These types of solutions are generally considered Special Protection Systems (SPS) and are not favored by some utilities. SPS's add more complexity and modes of failure to an already complex electric grid. Passive solutions such as new transmission lines or reduced project size may also need to be considered. The PTI report included a sensitivity test of reducing the project size by half. This option showed stable results without an SPS.

Wind Farm Design

The PTI report shows that tripping some of the wind generation can eliminate instability following some NERC Category C faults. While this amount was shown to work for the studied base cases, the project should be designed to be able to adjust this tripping amount easily as system conditions change. An alternative may be to state the maximum MW that can remain on-line following specific contingencies. Because wind generation is variable, this method may be easier to implement and could result in less tripping of wind generation.

Such a large amount wind generation (3700 MW) added to the power system needs to support grid frequency the same as any other large plant such as nuclear or coal-fired. Two important controls that are now available for wind turbines allow both inertia- and governor-like response from wind turbines. For the inertia response, the wind turbine controls take energy out of the spinning blades, slowing their speed, and inject that energy into the electric grid. This is similar to the inertia response from synchronous generators, except that the wind turbine response is actively implemented by controls, as opposed to the natural response of synchronous generators.

For a governor-like control, the wind farm may not be able to ramp up power in response to low frequency (except for the short-term inertia response just discussed) because a wind farm typically runs at its maximum available output all the time. However, with the right controls, wind turbines can respond to high frequency by reducing power output. For a wind farm development as large as this project, it is especially important that the latest advanced controls be included to help support the electric power grid.

5. Conclusions

The results of the PTI report on the Grain Belt Express project have been confirmed by this study. The following mitigation options were confirmed to eliminate the unstable responses:

- A 900 Mvar Synchronous Condenser was assumed in all cases
- An SPS to reduce GBX wind generation following parallel circuit outages at Clark Co. Up to 1650 MW of wind generation tripping may be needed for certain double line outages.
- An SPS to reduce HVDC power following outage of the Rockport-Jefferson 765 kV line.

It will be critical for the GBX project to maintain a balance in both its MW flow and its Mvar flow. The project is designed to have a normal power exchange with SPP of 0 MW and 0 Mvar. This target also needs to be maintained during dynamic conditions as best as possible.

Additional considerations for futures studies of the GBX project include:

- Consideration of more breaker failure faults.
- Inclusion of other planned wind generation in the SPP footprint.
- Modeling the maximum 3500 MW HVDC injection at the AEP Sullivan end.
- If the SPS solutions are not acceptable, other solutions such as new transmission lines or reduced GBX project size will have to be found.

The results of this study depend on the assumed models for the HVDC equipment, wind generators, wind collector system, and the power systems in the area of the project. Some of these assumptions will surely change or come into better focus as the project moves forward. The stability analysis will need to be repeated when the assumptions are better defined.