System Impact Study

for the

Interconnection of a 150 MW

Wind Generation Facility

Xcel Energy Services, Inc
Transmission Planning
(#GEN-2002-006)

July 17, 2003

1 Executive Summary

>Omitted Text<, requested a System Impact Study under the Southwest Power Pool (SPP) Open Access Transmission Tariff (OATT) to interconnect a 150 MW wind farm to the transmission system of Southwestern Public Services (SPS). The wind-farm will be comprised of (100) 1.5 MW GE/Enron wind turbines. The planned in service date for the 150 MW wind-farm is by June 30, 2005.

The wind farm will be located approximately 3 miles east of Guymon, Oklahoma will connect to the SPS/Xcel Energy transmission system by a new 6.5 mile 115 kV transmission line. Figures 1 & 2 in Appendix A of this report illustrate the location and interconnection to the SPS/Xcel Energy transmission system .

The purpose of this study was to identify the SPS/Xcel Energy facilities adversely impacted by the interconnection and operation of the requester's 150 MW wind farm, and to determine the system improvements necessary to maintain transmission reliability and stability. Potential impacts due to transmission service requests are dealt with through separate studies. Transfer studies have not been performed because the requester has not made any request for firm transmission service.

There were no adverse impacts to the SPS/Xcel Energy transmission system identified through the power flow and single contingency studies, provided the proposed reactive power capabilities of the wind turbines perform as specified by the requester for this study.

Using the machine data provided by the requester, the stability studies indicate that the SPS/Xcel Energy system will remain stable when the 150 MW wind farm is connected to the transmission system. However, the preliminary layout of the wind turbines could greatly impact the wind farm's capability of riding through system faults. An undesirable tripping of individual wind turbines due to faults on the transmission system may occur depending on the length of the collection feeder from the interconnection substation to the wind turbine. The requester's final design of the wind farm collection feeders should address this issue.

The results of the short-circuit portion of this study indicate that there is adequate interrupting capability of the existing SPS/Xcel Energy breakers.

The wind farm will be connected to the Xcel Energy/SPS transmission system by constructing approximately 6.5 miles of 115 kV line tying the requester's interconnection substation to the 115 kV bus at Texas County Interchange. Figure A.3 of Appendix A is a simple one-line diagram illustrating the proposed interconnection of the requester's wind farm.

The total estimated cost of construction on the SPS/Xcel Energy system for this interconnection is **$ 1,533,272.** This estimated cost does not include the requester's interconnection substation.

2 Introduction

The requester proposes to build a 150 MW wind-farm to be located in Texas County, Oklahoma approximately 3 miles east of Guymon. The wind-farm will be comprised of (100) 1.5 MW GE/Enron wind turbines. Please see Figure A.1 of Appendix A, illustrating the location of the >Omitted Text< wind-farm. The planned in service date for the 150 MW wind-farm is by June 30, 2005.

The areas described in the interconnection request are two noncontiguous areas that are approximately 2.3 miles north, and 4.2 miles east of SPS/Xcel Energy's facility Texas County Interchange. There were two interconnection options considered in the feasibility study of this project. The requester has indicated their preference to interconnect the wind farm directly to Texas County Interchange by a single 6.5 mile 115 kV line.

The objectives of this study were to identify the adversely impacted SPS/Xcel Energy transmission facilities due to the interconnection of the proposed wind farm, determine the facility improvements necessary to maintain transmission reliability and stability, and estimate the costs associated with the necessary system improvements. Included in this report are the results of the comparative contingency analysis, the results of the transient stability analysis, and the results of the short circuit analysis.

The Steady-State analyses, or power flow studies were used to determine the thermal loading and voltage level impacts due to the interconnection of the new generation.

Stability analysis was used to determine what effects the new generation had on the SPS/Xcel Energy and SPP generation. This analysis examined the capability of the surrounding generation to recover from critical faults on the transmission system with and without the added generation of the wind farm.

A Short Circuit analysis was performed to determine if any equipment upgrades were required due to the interconnection of the new generation. The transmission reliability and coordination group at Xcel Energy performed the short circuit analysis.

This study does not include power transfers on or across the SPS/Xcel Energy transmission system above the current firm (contracted) transactions. These transfers are normally considered through transmission requests.

3 Steady State Analysis

3.1 Study Methodology

Power flow and contingency studies were performed using the Power System Analysis Program (PSS/E) developed by Power Technologies, Inc. This program has the capability of doing power flow simulations, short circuit studies, stability studies, and contingency studies.

SPP supplied models reflecting the 2005 summer and winter peaks, and 2006 spring loading conditions. Since the completion of the Frio Draw - Potter improvement project is not probable by the expected in-service date of the wind farm, the 2005 models were further modified to reflect the current transmission system without the Frio Draw - Potter improvements. These models included the expected generation and transfer requests covered by firm contracts, and became the basis by which this study's comparisons are made. Then each model was modified to include the data of the wind farm to create new case models to determine the system intact power flow changes to the SPS transmission system.

Power flow studies were performed with and without the 150 MW wind farm. System intact conditions of these power flow studies were compared to determine if the loading of any element exceeded 100% of the element's normal rating (Rate-A), or if voltage levels were outside their normal operating limits of 0.95 to 1.05 per unit due to the interconnection of the 150 MW wind farm. New overloads, or voltage problems due to the interconnection of the wind farm were noted for this report.

Next, single contingency studies were performed with and without the added generation from the 150 MW wind farm. With each contingency outage, transmission elements 69 kV and above were monitored for loading, which exceeds 100% of the elements emergency rating (Rate-B), or voltage levels outside their emergency limits of 0.90 to 1.05 per unit. If a transmission element overload or voltage problem is caused by the interconnection, the requester is responsible for the costs to mitigate the overload.

3.2 Results of Power Flow Analysis

The 150 MW wind farm was modeled as described by the requester with five 34.5 kV cabled feeders extending from the 115/34.5 kV interconnection substation. An equivalent plant of (20) twenty wind turbine generators was modeled at the end of each 34.5 kV feeder. Each equivalent plant was modeled with the reactive power generation comparable with the -0.90 to +0.95 power factor range of the GE/Enron wind turbine generators. The control mode for each equivalent plant was set to control the voltage at the 34.5 kV bus of the interconnection substation at 1.02 per unit.

The results of the power flow studies indicate that no new overloads, or voltage criteria violations were created due to the interconnection of the 150 MW wind farm. However, if the reactive power control from the wind turbine generators fails, the wind farm would experience voltages at or below 0.904 per unit. This does not cause voltage levels on the SPS/Xcel Energy system to fall below 0.95 per unit, but may prevent the continued operation of the wind farm.

3.3 Results of Single Contingency Analysis

Single contingency studies of each seasonal case with and without the 150 MW wind farm were done with the ACCC automatic contingency option, which allows a large number of contingencies to be studied with an AC power flow in a short period of time. In doing this analysis, Xcel Energy looked for outages that were significantly worse than in its base cases. Single transmission elements within the Xcel Energy system and ties to adjacent systems were outaged one at a time while monitoring the Xcel Energy transmission system for new overloads and low voltage conditions. There were no significant impacts observed from this comparative study. The comparative contingency studies are in Appendix C.

4 Short Circuit Analysis

The Short Circuit Analysis was performed internally by Xcel Energy Services to determine if the interrupting capability of the existing circuit breakers would be exceeded due to the addition of the 150 MW wind farm. Without specific impedance data, certain assumptions were made, whereby typical impedance values for the various wind farm equipment. were used. The results of this study indicate that the addition of the wind farm will not cause the available bus fault currents to increase past the interrupting capability of existing breakers.

5 Transient Stability Analysis

Power Technologies, Inc. (PTI) of Schenectady, New York performed the transient stability analysis to verify dynamic system responses to selected three-phase and single-phase faults on the SPS/Xcel Energy transmission. The stability studies were performed using the stability data from the 2005 summer peak model modified to include the 150 MW wind farm with data supplied by the requester. Included in this model was the dynamic setup of the HVDC units at Blackwater and Eddy County.

Selected 3ϕ and 1ϕ faults were simulated in the area surrounding the wind farm and across the SPS/Xcel Energy system with normal breaker clearing and re-closing times applied. All simulations were run for a minimum of 10 seconds to confirm proper machine damping.

The system remained stable for the faults simulated using the machine data supplied by the requester. However, an undesirable tripping of individual wind turbines, due to faults on the transmission system, may occur depending on the length of the collection feeder from the interconnection substation to the wind turbine. The requester's final design of the wind farm collection feeders should address this issue.

Please see Appendix D of this report for the simulation plots for the selected disturbances.

6 Interconnection Scope

To interconnect the requester's 150 MW wind farm, approximately 6.5 miles 115 kV line would be built from Texas County Interchange to the requester's 115/34.5 kV interconnection substation. The 115kV bus at Texas County Interchange would be expanded for the new 115 kV line terminal with breaker, metering, and protective relaying. This scope does not include the 115/34.5 kV interconnection substation, which is considered the requester's responsibility. Figure A.2 of appendix A, illustrates the line construction to the anticipated location of the interconnection substation.

7 Interconnection Cost

Listed below are the directly assigned costs associated with interconnecting the 150 MW wind farm to the SPS/Xcel Energy transmission system. Table 2 on the following page illustrates the cost summary with construction scope to tie the requester's interconnection substation to SPS/Xcel Energy's Texas County Interchange 115 kV bus, and the 115 kV line construction. These costs do not include the costs of the requester's 115/34.5kV interconnection substation.

Table 1: Directly Assigned Estimated Costs

Estimated Costs of Interconnecting the 180 MW Wind Farm	COST
Extend 115 kV bus at Texas County Interchange, and add 115 kV GCB and metering with SCADA reporting.	482,522
Construct approximately 6.5 miles of 397.5 MCM ACSR 115 kV line from Wind Farms interconnection substation to Texas County Interchange.	950,000
115 kV line & Facility Right of Way	100,750
TOTAL	**$ 1,533,272**

8 Estimated Construction Schedule

The estimated construction schedule for this project is approximately 10.5 months after an interconnection agreement is signed. Appendix E illustrates the estimated construction schedule.

9 Conclusions

The results of this study indicate that the interconnection of the 150 MW wind farm will not adversely impact the SPS/Xcel Energy transmission system, provided the wind farm operates as described by the requester. Any deviation from these operations could cause low voltages and possible contingency overloads. Costs to correct these potential problems will be attributed to the requester. Since this study only modeled the operation of the wind farm as stated by the requester and lacked sufficient information to do otherwise, this study does not include cost estimates to mitigate any potential adverse impacts. All estimated costs are for interconnection only.

The results of the transient stability study indicate that the system would remain stable for the selected 3ϕ and 1ϕ faults across the transmission system provided there was proper operation of the reactive power control of the wind turbines. However, an undesirable tripping of individual wind turbines, due to faults on the transmission system, may occur depending on the length of the collection feeder from the interconnection substation to the wind turbine. The requester's final design of the wind farm collection feeders should address this issue. The voltages at the end of the 34 kV feeders were abnormally high, causing substantial concern. Either the voltage control philosophy applied to the wind turbines should be reviewed for changes or a stable voltage source (Static Var Compensator) used by the requester should this problem arise in operation.

The short circuit analysis evaluated the available fault currents of selected faults placed on the SPS system in the area surrounding the interconnection of the wind farm. The results of this analysis indicate the interrupting capability of existing breakers will be adequate and no SPS/Xcel Energy breakers will need to be replaced.

To interconnect the 150 MW wind farm, the 115 kV bus at Texas County Interchange will have to be expanded for a new 6.5 mile 115 kV line from Texas County Interchange to the requester's 115/34.5kV interconnection substation. The estimated cost to interconnect the requester's wind farm is approximately $ 1,533,272.

The estimated construction schedule for this project is approximately 10.5 months after an interconnection agreement is signed. Appendix E illustrates the estimated construction schedule.

10 APPENDIX A *Interconnection Location and Facility One-line Diagram*

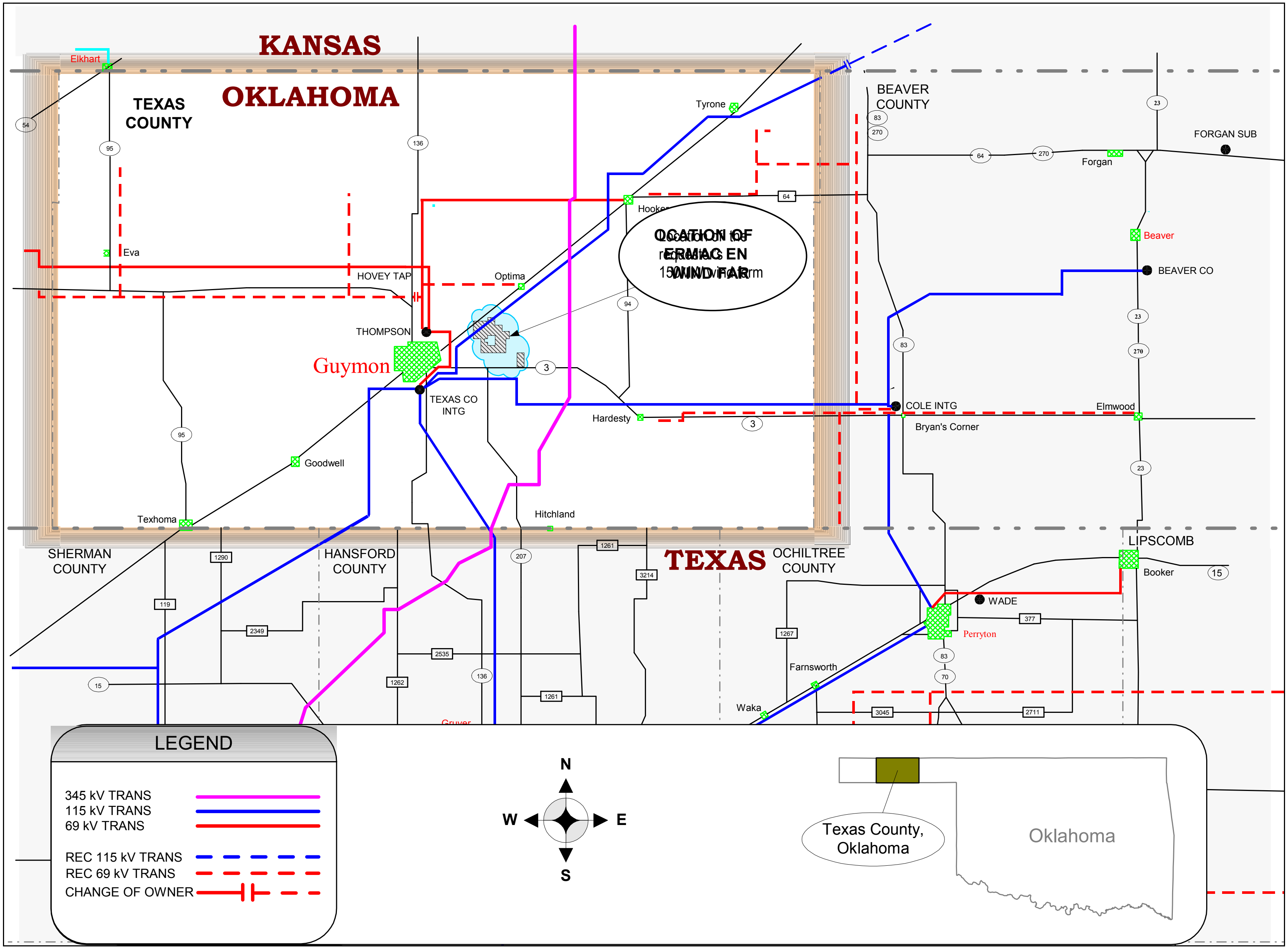


Figure A. 1: Location of Requester's 150MW Wind-Farm

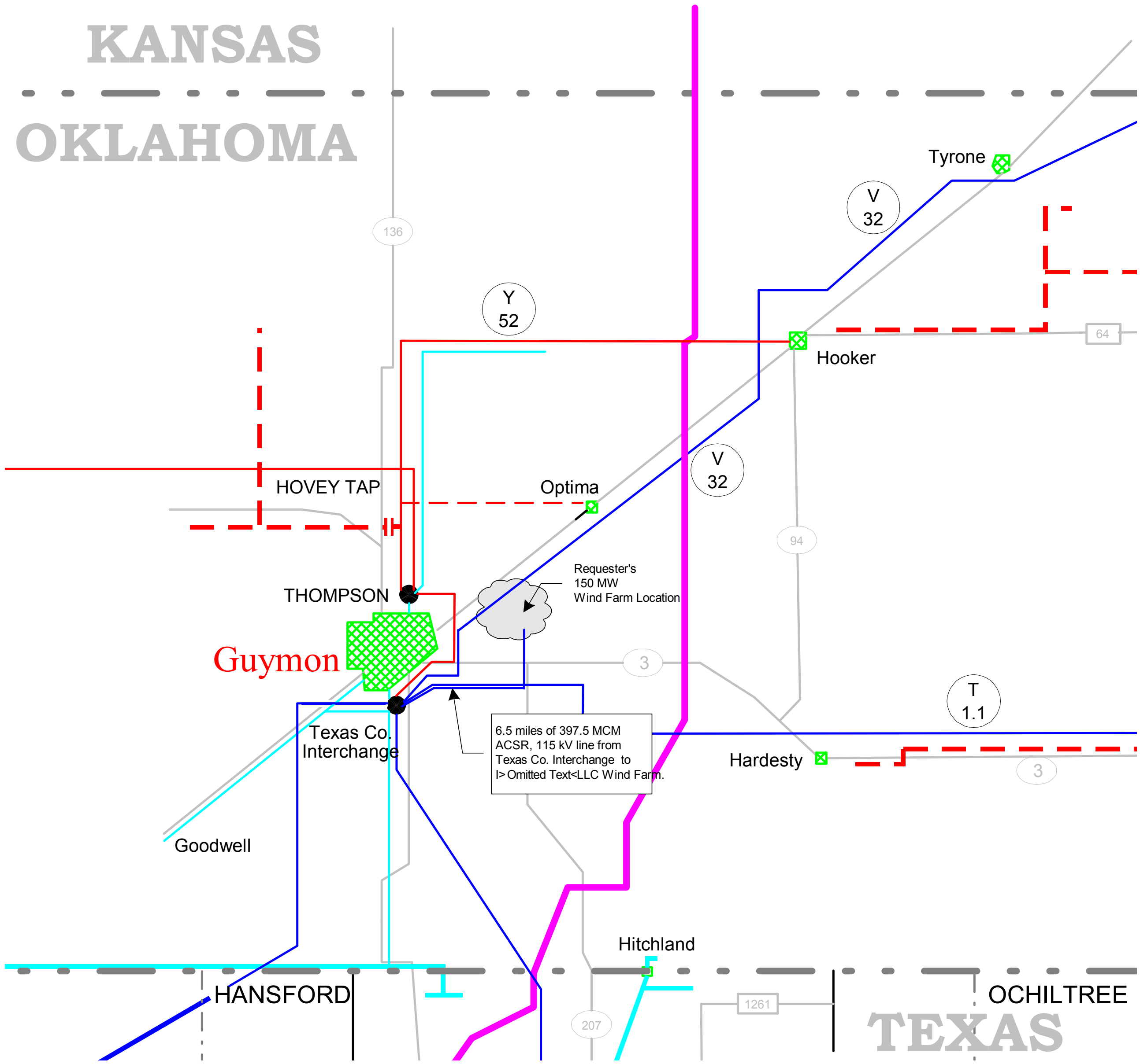


Figure A. 2: Illustration of proposed 115kV line construction to Requester's Interconnection Substation

WIND FARM INTERCONNECTION

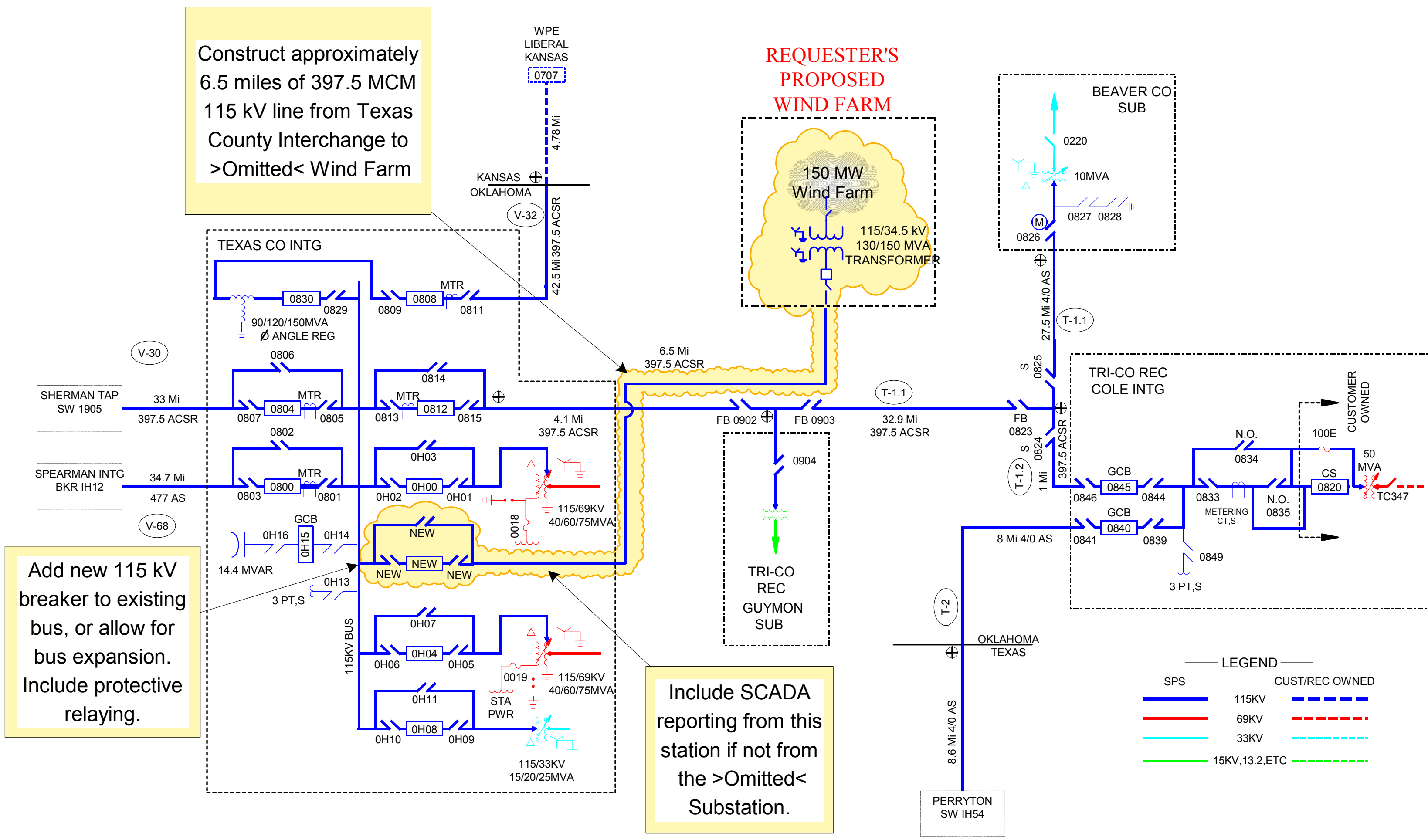
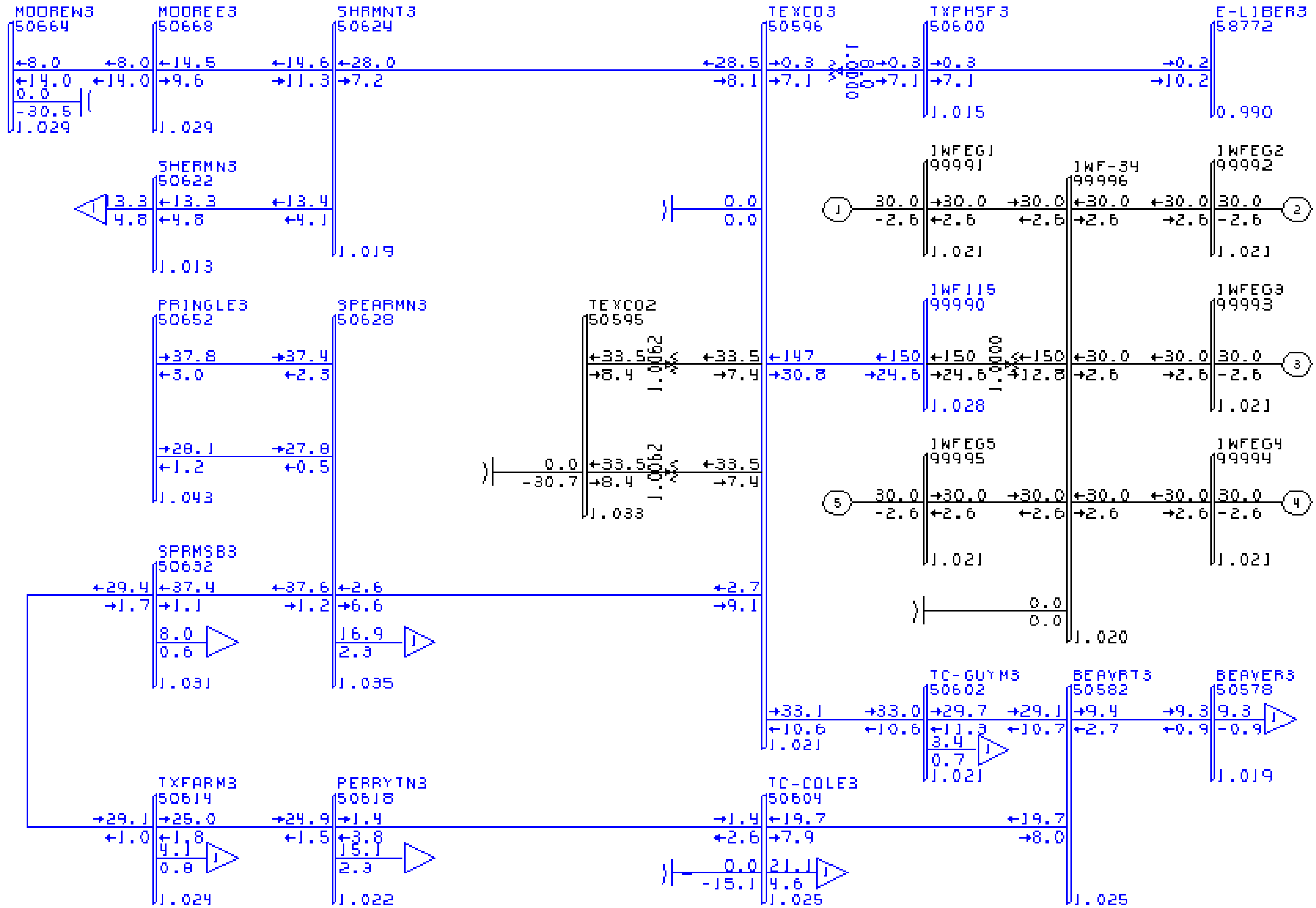


Figure A. 3: 115 kV Line Construction from Texas County Interchange to the Requester's Interconnection Substation.

11 APPENDIX B *One-line Diagrams with Power Flow reports*

2005 Summer Peak Case

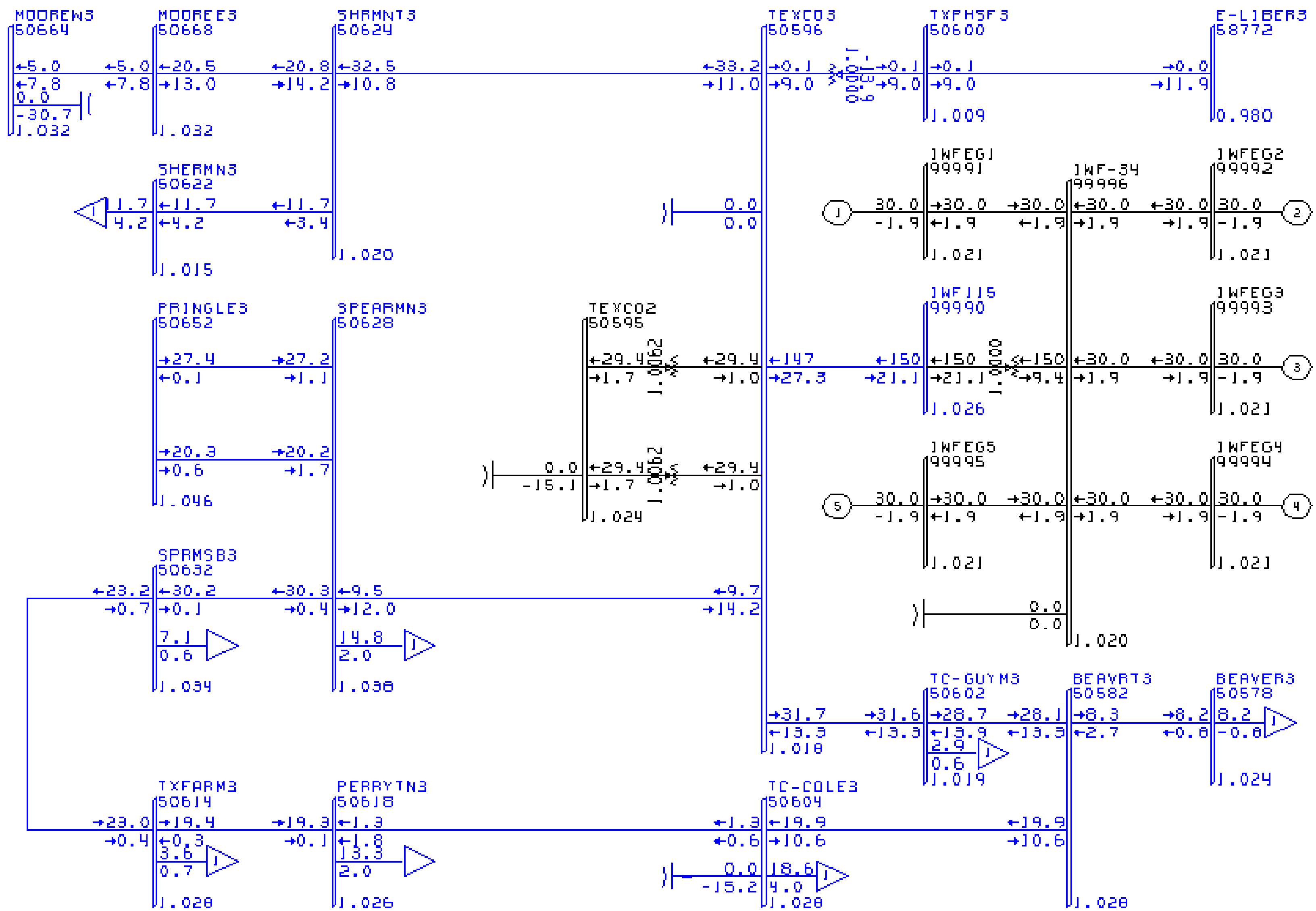


INVENERGY 150 MW WIND (SPP-GEN-2002-006) 05SP-30310-001
2005 SUMMER PEAK CASE WITH IWF-150 MW 4/10/03
MON. JUN 23 2003 15:03

100% RATEB
0.900UV 1.050OV
KV: ≤69 , ≤115 , ≤230

BUS - VOLTAGE (PU)
BRANCH - MW/MVAR
EQUIPMENT - MW/MVAR

2005 Winter Peak Case

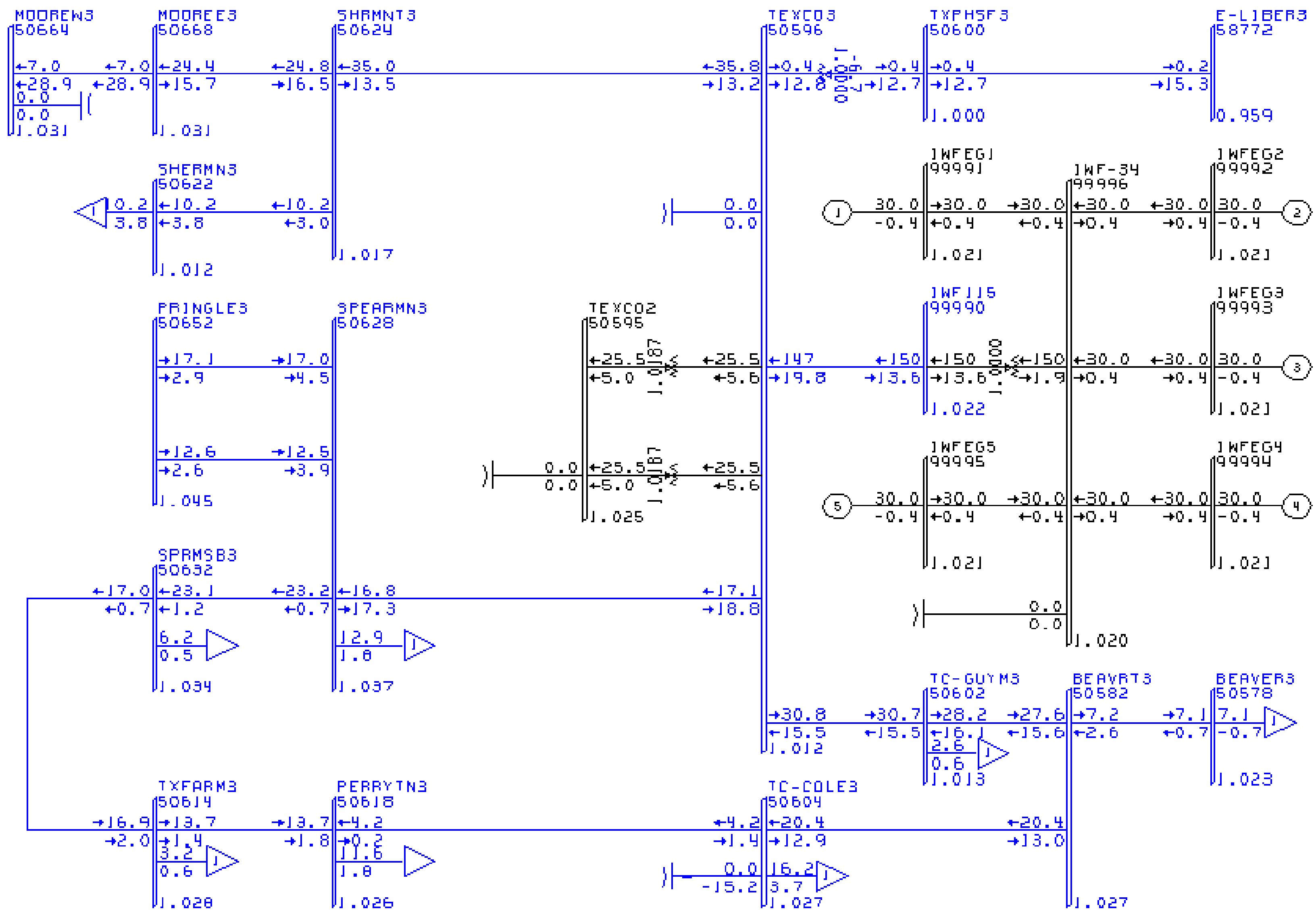


INVENERGY 150 MW WIND (SPP-GEN-2002-006) 05WP-30310-001
2005 WINTER PEAK BASE CASE. IWF-150 4/11/03
MON. JUN 23 2003 15:19

100% RATEB
0.900UV 1.050OV
KV: ≤69 .≤115 .≤230

BUS - VOLTAGE (PU)
BRANCH - MW/MVAR
EQUIPMENT - MW/MVAR

2006 Spring Case



INVENERGY 150 MW WIND (SPP-GEN-2002-006) 06G-30310-001 2006 SPRING CASE. IWF - 150 MW 4/11/03 MON. JUN 23 2003 15:21	100% RATEB 0.900 UV 1.050 OV KV: ≤69 , ≤115 , ≤230	BUS - VOLTAGE (PU) BRANCH - MW/MVAR EQUIPMENT - MW/MVAR

12 APPENDIX C *Comparative Contingency Study Results*

13 APPENDIX D *Stability Study*

14 APPENDIX E *Estimated Construction Schedule*

ID	Task Name	Year 1 (months 1–12)
1	**Substation Project**	
2	Signed Agreement	1/1
3	Preliminary Engineering & material commitment	1/28
4	Material Delivery	7/1
5	Foundation design complete	2/11
6	Final Engineering - Drawing Revisions - Drafting	4/8
7	Manifest Construction Drawings	4/15
8	Foundation work	7/7 – 8/1
9	Complete steel, bus work & wiring	8/4 – 9/26
10	Construction completion, station testing and inspection	9/29 – 10/3
11	Completion of Substation	10/6
12		
13	**Transmission Line Project**	
14	Preliminary Engineering	1/28
15	Design Line	2/25
16	Order Material	3/3 – 7/18
17	Material Delivery	7/21
18	Final Engineering	3/25
19	Manifest Construction Drawings	3/17 – 6/9
20	Complete Survey	3/31 – 4/11
21	Foundations Completed	7/23 – 8/5
22	Structures installed	8/11 – 9/5
23	Wire work	9/8 – 9/26
24	Completion of Transmission Work	10/3

Estimated Construction Schedule

Final Report No. R23-03

Stability Studies of the Proposed >Omitted Text< Wind Farm Project

Prepared for
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July 17, 2003

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Section
1

Introduction

PTI was contracted by Xcel Energy to perform a specified set of stability studies in order to evaluate the impact of a proposed >Omitted Text< Wind Farm Project near Guymon, Oklahoma. This report summarizes results of the study.

The proposed plant is located near Guymon in Xcel Energy's transmission system. This wind farm has a nominal output of 150 MW and is interconnected to Xcel Energy's 115 kV network. The wind farm is using GE 1.5 MW wind turbines units rated 1.5 MW each.

The setup for load flow and dynamic simulation was based on SPP stability database of year 2005. Three load flow base cases were prepared following Xcel Energy's instructions: two cases with the >Omitted Text< Wind Farm Project and one case without. DC lines PNM and EPE are modeled in all cases. The modeling data of the DC lines was retrieved from the Duke Plant study, which was conducted for Xcel Energy in March 2002. The data was then updated following Xcel's instructions for the >Omitted Text< study. The dynamic model for GE 1.5 MW unit wind turbines was developed by PTI.

A set of stability studies was performed to evaluate the wind farm using PTI's power system simulation program PSS/E, revision 29.

Section

2

Data Preparation

The plant is located near Guymon, Oklahoma, 6.5 miles from Texas County Interchange 115 kV substation.

2.1 Load Flow Data

Three load flow cases were created for the stability study of the >Omitted Text< Wind Farm Project: without >Omitted Text< Wind Farm Project (referred to as "WO_IWF case") and two cases with >Omitted Text< Wind Farm Project (referred to as "WI_IWF case" and “WI_IWF_102 case”).

2.1.1 Setup of Base Load Flow Cases

The 2005 load flow case received from Xcel Energy was used to create the load flow cases for the study. The following updates were made to the load flow case:

- Blackwater DC line model is added. Blackwater DC line transfers 200 MW out of SPP from the interconnection point at Roosevelt 230 kV substation. The load flow set up of the DC line was retrieved from the study for the Duke Project with the interconnection point changed from Clovis 230 kV to Roosevelt 230 kV. To help distinguish the difference between two studies, buses were given different bus numbers from the Duke study.

- Eddy County DC line model is added. The Eddy County DC line transfers 54 MW out of SPP from the interconnection point at Eddy County 230 kV substation. The load flow setup was also retrieved from the Duke study with just the bus numbers changed.

- The buses 59995 PNM-DC6 and 59996 EPTNP-D6 in the original 2005 load flow case were simplified representations of the two DC lines. Both buses are deleted from the case since detailed models are now in place.

- Due to the addition of two DC ties, an additional 200 MW of generation is needed. This 200MW was picked up by the swing generator at bus 18137 N3BFN.

Figure 2-1 is the one-line diagram of the Blackwater and Eddy County DC lines. Figure 2-2 is the one-line diagram of the area of the Xcel Energy’s system before the >Omitted Text< Project is added in the case. Color-coding was used for different voltage levels: blue for above 115 kV, black for between 115 kV and 34.5 kV, red for below 34.5 kV.

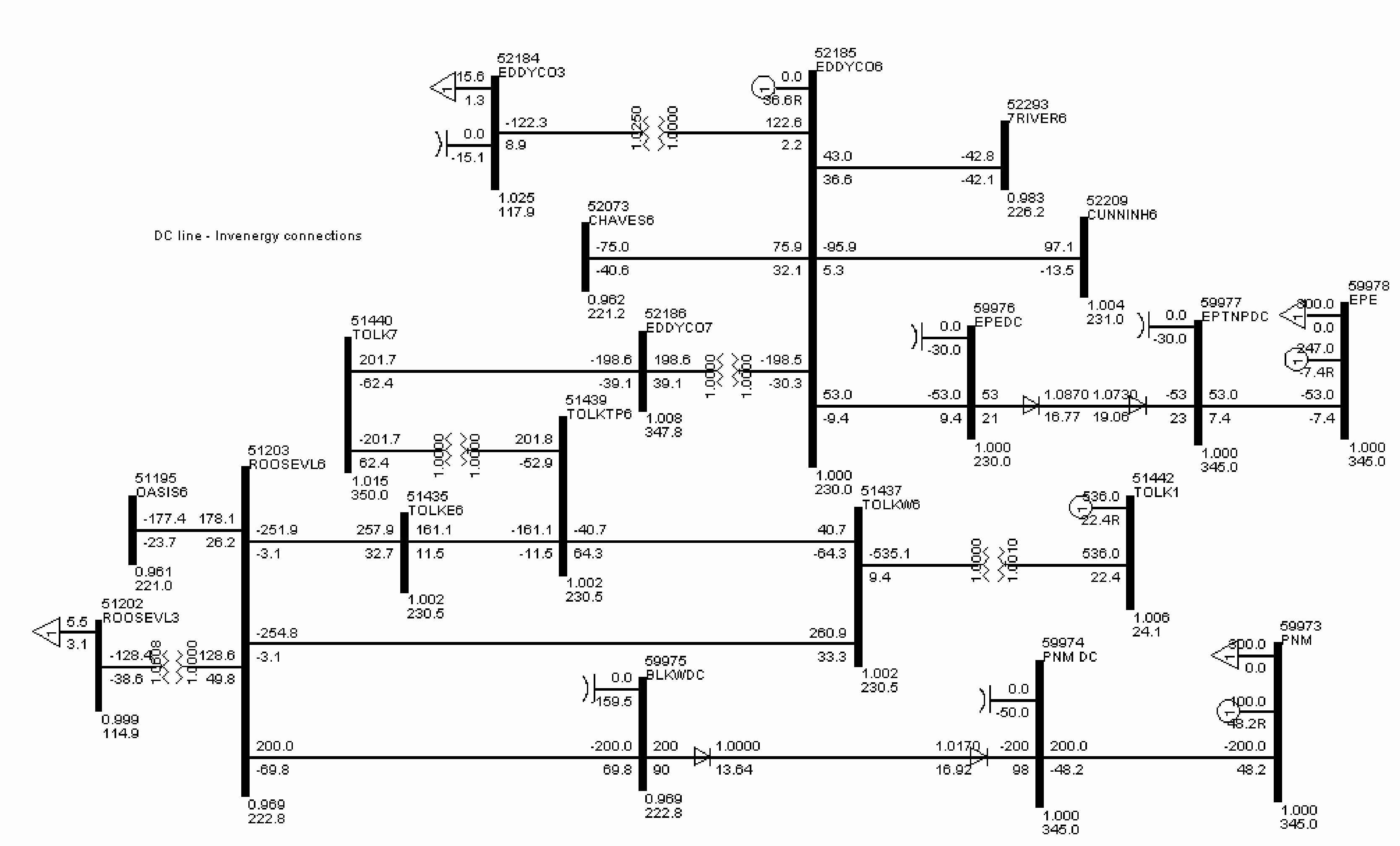


Figure 2-1: Load Flow Model of the Blackwater and Eddy County DC lines

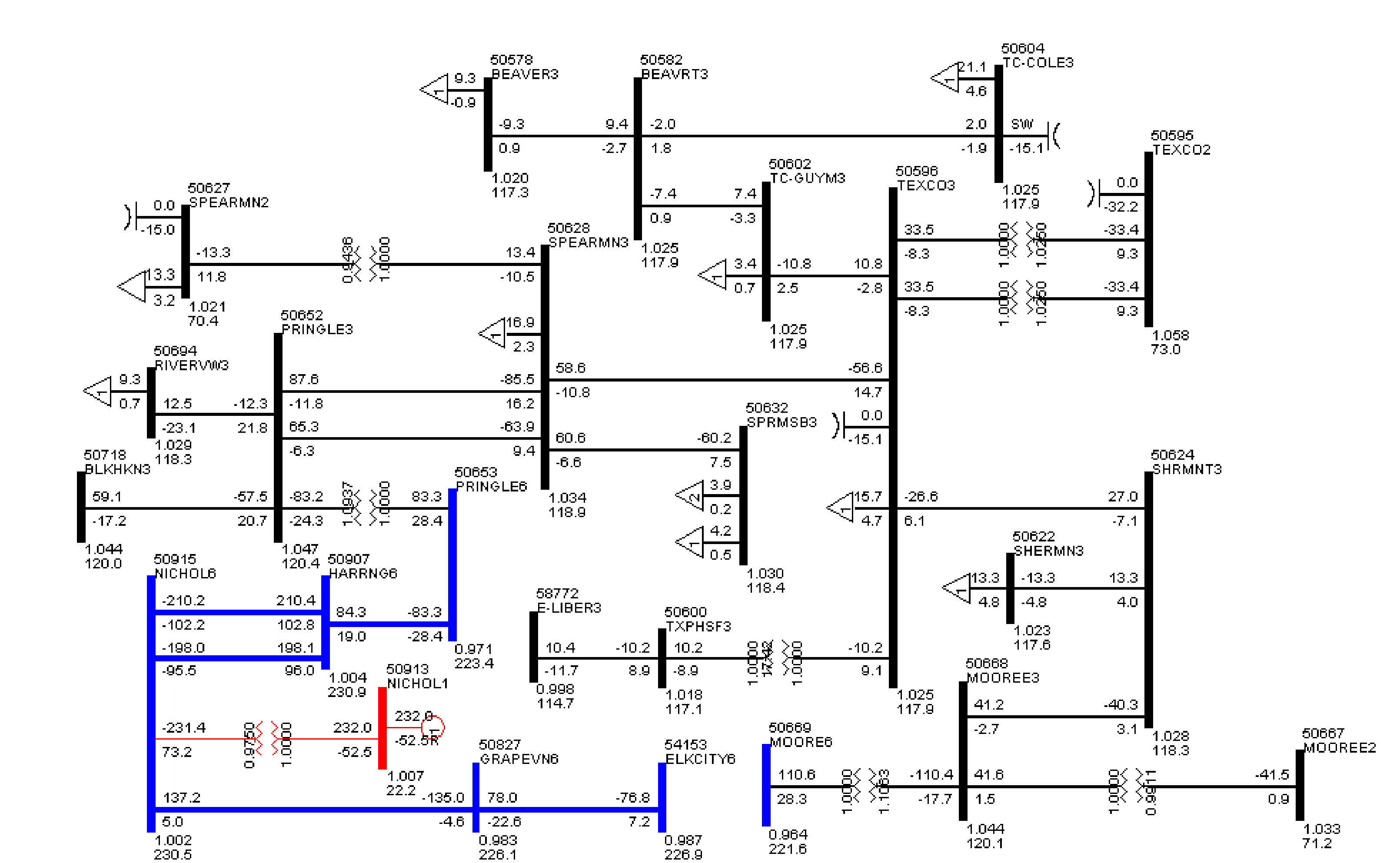


Figure 2-2: One-Line Diagram of Xcel Energy's Network near Guymon, OK without the >Omitted Text< Project

2.1.2 Modeling of the >Omitted Text< Wind Farm

The rated output of the >Omitted Text< plant is 150 MW, comprised of one hundred (100) GE 1.5 MW unit units. The base voltage of a GE wind turbine generator is 570 V, and a generator-step-up (GSU) transformer of 1.85 MVA connects each unit to the high side of 34.5 kV. The rated power output of is 1.5 MW for each unit, while the actual power output depends on the wind.

For the load flow case with >Omitted Text< Wind Farm in service, a dispatch scenario was defined by Xcel Energy to accommodate the increase of 150 MW generation from I>Omitted Text<Wind Farm:

- MRG31 off-line (bus 50663, original Pgen = 48 MW)
- RVRV1 off-line (bus 50696, original Pgen = 25 MW)
- Tolk1 increased generation to 535.8 MW (bus 51441, original Pgen = 457.38 MW)
- Tolk2 increased generation to 536.0 MW (bus 51442, original Pgen = 500.0 MW)
- Tolk3 decreased generation to 64.0 MW (bus 51443, original Pgen = 250 MW)

Figure 2-3 illustrates the interconnection of the >Omitted Text< Wind Farm. Observing Figure 2-4, there are 5 major feeders connecting 100 wind turbine units. Five 34.5 kV collector feeders were thus established with 20 wind turbines connected in series along each collector line in the load flow. Figure 2-5 shows how the 20 units are connected in series on one 34.5 kV collection system. Figure 2-3, Figure 2-4, and Figure 2-5 were supplied by I>Omitted Text<.

Each wind turbine is located approximately 1000 feet apart from other turbines. To demonstrate the effect of equivalent generators, three different levels of model detail were used:

- cluster all 20 units at the end of 34.5 kV line of 20,000 feet, resulting in 1 equivalent generator.
- cluster units at end of each section of different cable sizes, resulting in 5 equivalent generators.
- model all 20 units separately, resulting in 20 units; no equivalent was made.

The actual parameters (R, X and B) of the 34.5 kV collector circuits are calculated based on the instruction from Xcel. Type MV-90 35 kV shielded 100% insulated aluminum cable with 345 mils EPR insulation and Class B stranding was used.

- Resistance R: 90 degree aluminum single conductor (Table 7-4 from Chapter 7 Electrical Characteristics in Anixter catalog)
- Reactance X: 8-inch spacing copper conductor in separate conduits (Table 7-5 from Chapter 7 Electrical Characteristics in Anixter catalog)
- Charging B: not modeled

Cable size (kcmil)	Aluminum	Copper
	R (90 degree), Ohm/1000 feet	X (25 degree), Ohm/1000 feet
750	0.03020	0.0694
500	0.04480	0.074
350	0.06380	0.078
4/0	0.10600	0.084
1/0	0.21100	0.0918

To simulate the worse case scenario, all wind turbine generators are located at the end of its own section of the collector cable. The bus number for the equivalent generator is 90000 + collector bus number. The machine ID is set to 1. The following is the details of the calculation of the parameters of the collector cables and generators:

1. Cluster all 20 units as one equivalent generator at feeder 1 (referred to as “Equivalent 1”)

- Bus number: collector bus 111, generator bus 90111
- Pgen = 1.5 MW*20 = 30 MW
- Cable parameters: R = 0.15293 pu, X = 0.14179 pu.(series equivalent of cables)

2. Cluster generators at each section of different cables at feeders 2, 3 and 4 (referred to as “Equivalent 2”)

- Bus number: collector bus 121-125, 131-135, 141-145. Corresponding equivalent generator buses are 90121-90125, 90131-90135, and 90141-90145.
- 2 units at collector generator 90121, 90131 and 90141. Collector cable 3500 ft of size 750 kcmil. Pgen = 3.0 MW.
- 3 units at collector generator 90122, 90132 and 90142. Collector cable 3000 ft of size 500 kcmil. Pgen = 4.5 MW.
- 5 units at collector generator 90123, 90133 and 90143. Collector cable 5000 ft of size 350 kcmil. Pgen = 7.5 MW.
- 4 units at collector generator 90124, 90134 and 90144. Collector cable 4000 ft of size 4/0 kcmil. Pgen = 6.0 MW
- 6 units at collector generator 90125, 90135 and 90145. Collector cable 6000 ft of size 1/0. Pgen = 9.0 MW.

3. Model all 20 units separately at feeder 5 (referred to as “Equivalent 0”)

- Bus number: twenty collector buses: 150-170. Twenty equivalent generator buses: 90151 - 90170.
- Pgen = 1.5 MW
- Cable parameters: each unit is 1000 feet apart. R and X of the collector cable for each section correspond to each cable size.

The purpose of modeling the wind farm with three different levels of detail is to demonstrate the effect of the model representation on the calculations. This has several advantages: it allows for better comparisons to previous studies using more simplified models, demonstrates the significance of model parameters and assumptions, and gives insight to future modeling practice needed.

Equivalent 0 has generators modeled “as is” with as many details as available at the time of study. The results from load flow and dynamics study of Equivalent 1 and 2 can be compared with Equivalent 0 to investigate the effect of the level of model detail. The generator Equivalent 1 approximates locating the generator at the end of 3.8-mile line. Equivalent 2 has generators distributed along the feeder, albeit lumped at five locations. Results of Equivalent 0 and 2 are similar. Equivalent 1 exaggerates the worst case scenario in both load flow and dynamic simulations.

Eight user-written models (details included in the summary for dynamics setup) and an IPLAN program were developed by PTI and are collectively referred to as the “GE wind turbine package”. The IPLAN program adds equivalent wind turbine generators (WTG), along with their step-up transformers, to a number of collector buses that exist in the load flow case. Equivalent wind turbine generators will be dispatched based on the given wind speed and control mode. There is also an option of dispatching units uniformly with the given percentage of the rated power. The corresponding curve of the power output versus the wind speed and the generator speed is embedded in the code.

In this study, >Omitted Text< wind farm is dispatched at 100% of rated output. All wind turbine generators have their terminal voltage scheduled to result in 1.0 pu at bus 99991 (34.5 kV collector bus) in the load flow. The reactive power generation is scheduled so that all units have the same power factor.

The following table lists the resulting load flow equivalent of the I>Omitted Text<Wind Farm.

Model Equivalent	Generator bus number	# of 1.5 MW units	Pgen (MW)	Qgen (MVAR)
Equivalent 0	90111	20	30.0	-4.93
Equivalent 1	90151 - 90170	1	1.5	-0.25
Equivalent 2	90121, 90131, 90141	2	3.0	-0.49
	90122, 90132, 90142	3	4.5	-0.74
	90123, 90133, 90143	5	7.5	-1.23
	90124, 90134, 90144	4	6.0	-0.99
	90125, 90135, 90145	6	9.0	-1.48

The power flow model indicates that at the 115 kV interconnection point (bus 99990), the wind farm would be supplying 145.4 MW while consuming 47.7 MVAR, a power factor of 0.95. Following Xcel Energy's instruction, a load flow case with a higher power factor was created. The following modifications were applied to the case:

- Set scheduled voltage of the remote 34.5 kV bus 99991 to be 1.02 per unit
- Turning off the 14.4 MVAR cap bank at Texas County Interchange (Bus # 50596).

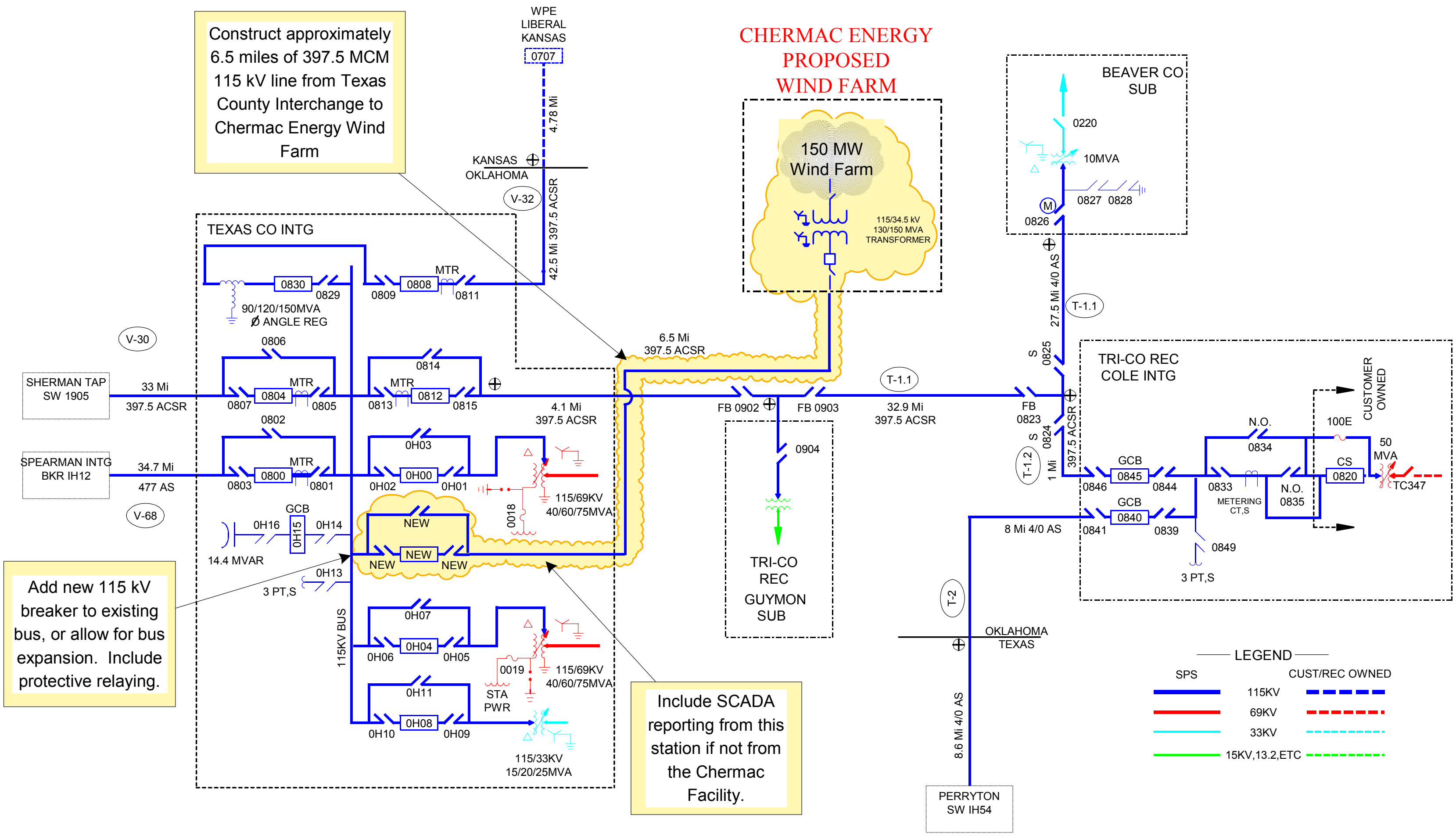
The resulting power flow indicates the wind farm now supplies 145.4 MW while it consumes 30.0 MVAR, a power factor of 0.98. Table 2-1 summarizes the setup and output of the two different load flow cases.

Table 2-1: Summary of Load Flow Cases with Different Power Factor

Case name	Scheduled Volt	MW	MVAR	PF	Cap at Texas Co.
WI_IWF.SAV	1.0	145.4	-47.7	0.95 leading	14.4 MVAR
WI_IWF_102.SAV	1.02	145.4	-30.0	0.98 leading	0

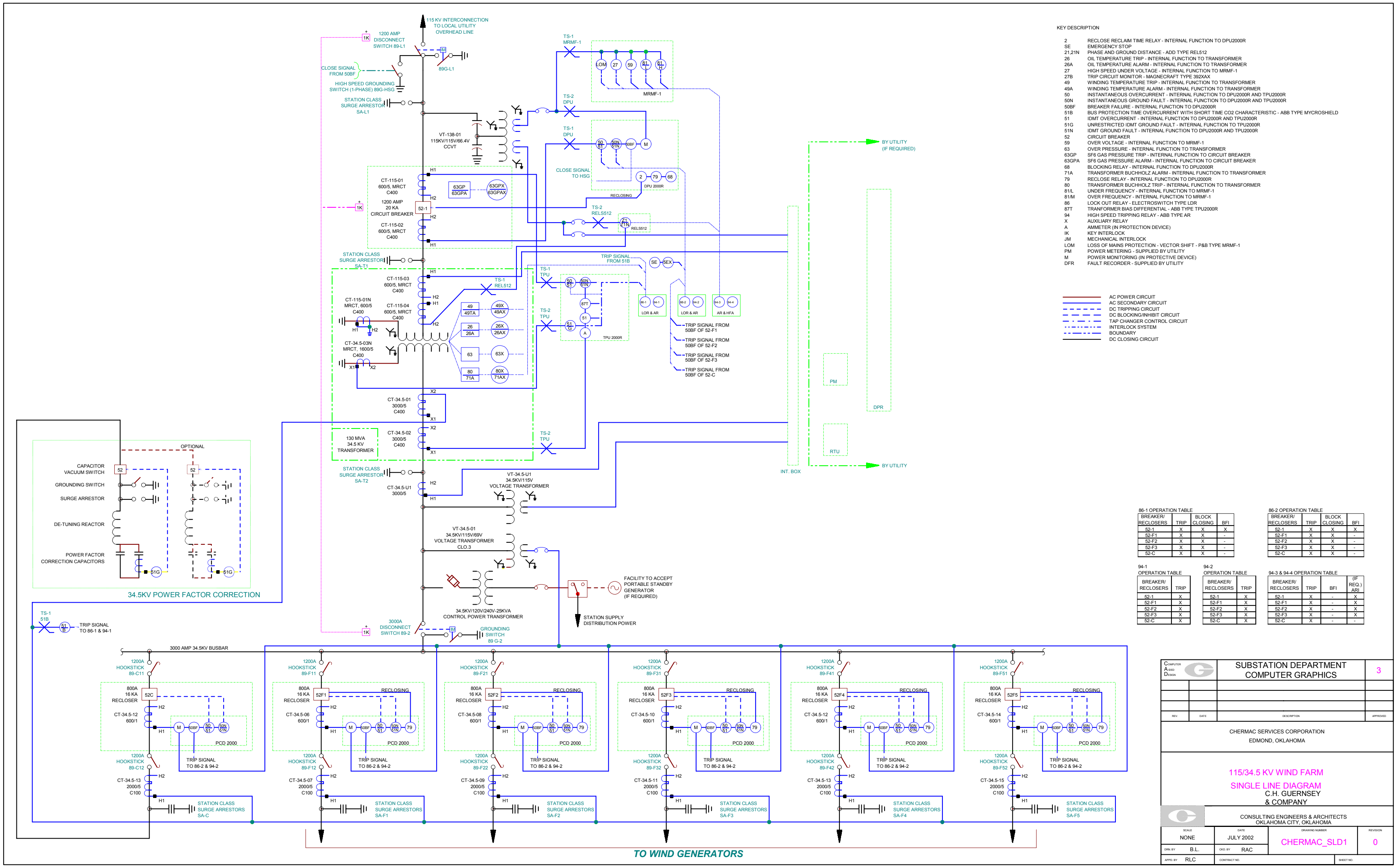
Figure 2-6 is the one-line diagram of >Omitted Text< Wind Farm of the case WI_IWF, showing the load flow results. Collector buses 130-135 and 140-145 are not shown on the diagram since the modeling detail is identical to that of buses 120-125. Figure 2-7 is the one-line diagram of the nearby Xcel Energy's network with the >Omitted Text< Project on-line. Figure 2-8 and Figure 2-9 are the one-line diagrams of the case WI_IWF_102.

INTERCONNECTION OPTION-1



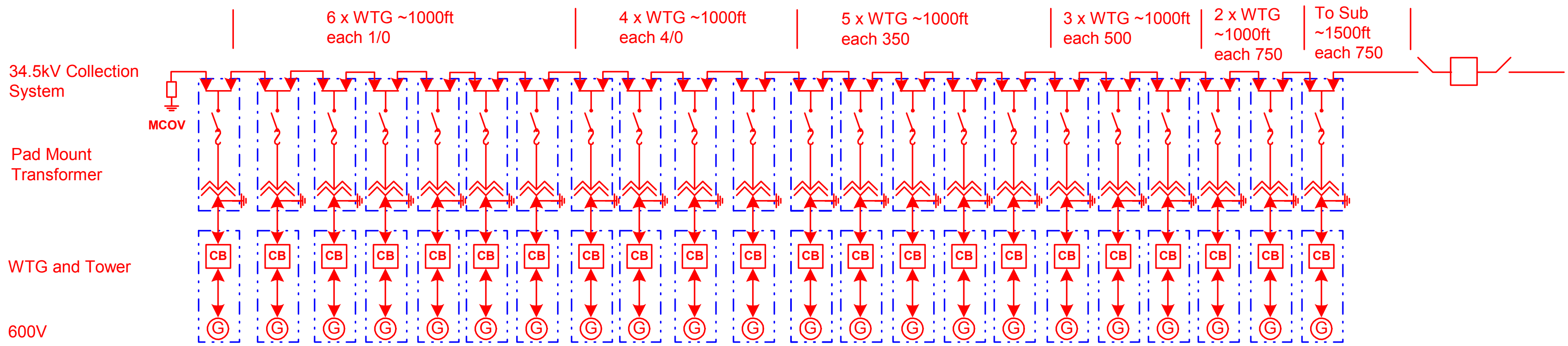
*Received from >Omitted Text< LLC 2/25/03

Figure 2-3: Interconnection of >Omitted Text< Wind Farm Project



***Received from >Omitted Text<LLC 2/25/03**

Figure 2-4: Detailed Interconnection Diagram of >Omitted Text< Wind Farm Project



Typical 20 WTG collection system assuming no laterals and 1.5MW units
3 separate single phase XLPE or ERP cables to be direct buried as per NEC minimums ie 7.5" apart

***Received from In>Omitted Text<LC 2/25/03**

Figure 2-5: Typical 34.5 kV Collector Feeder

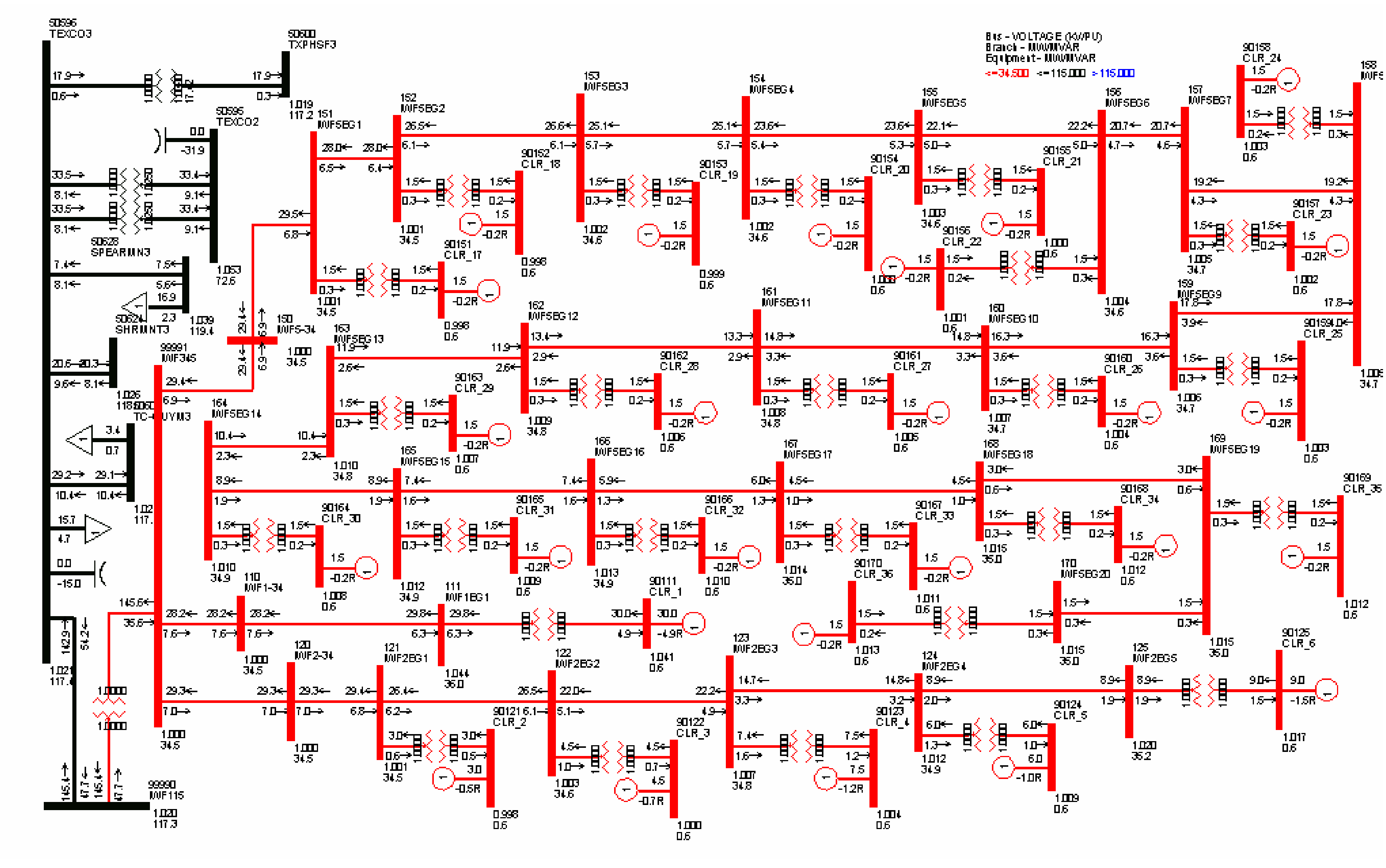


Figure 2-6: Load Flow Model of the >Omitted Text< Wind Farm Project, PF = 0.95 leading

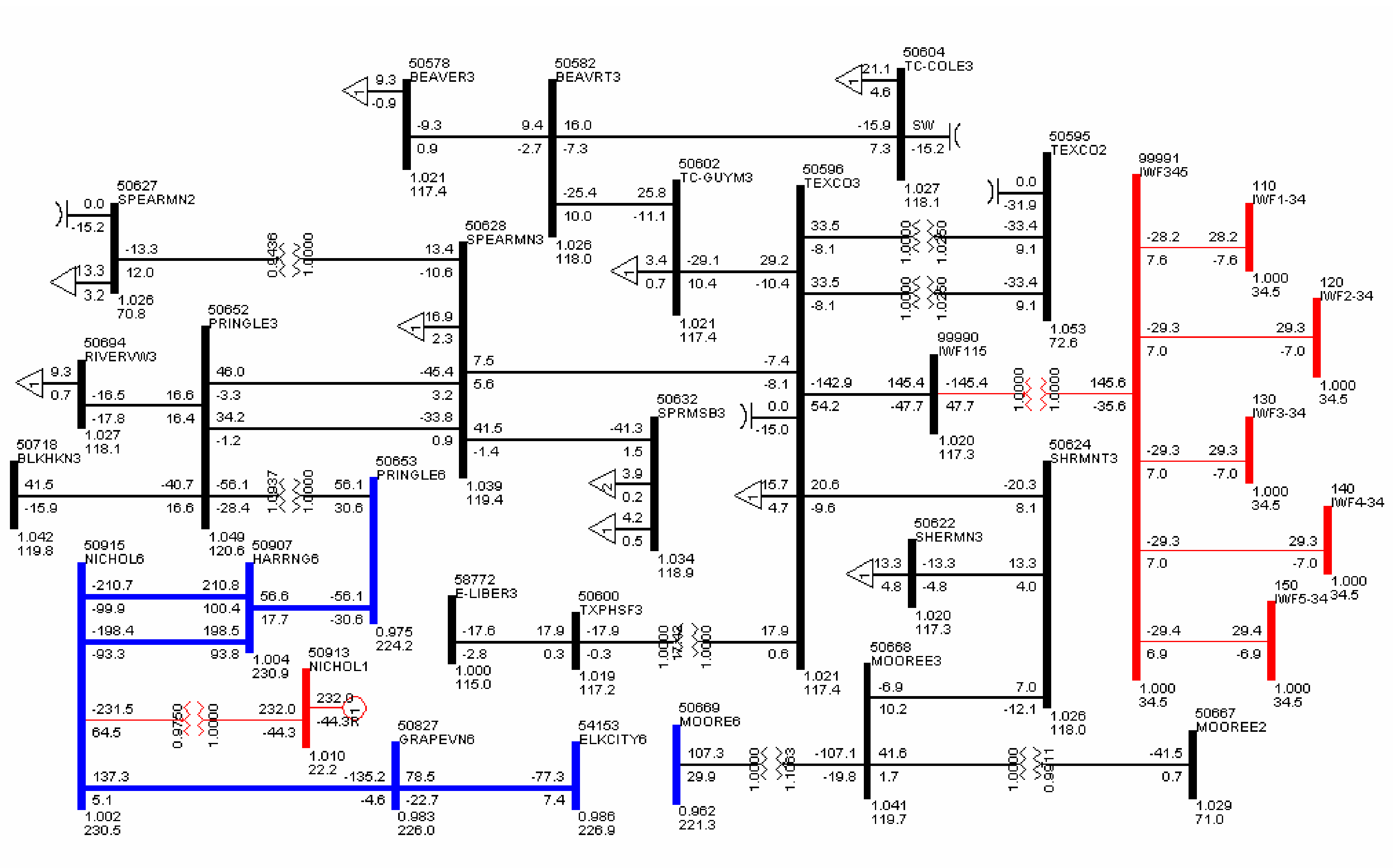


Figure 2-7: One-line Diagram of Xcel Energy's Network Near the In>Omitted Text<roject with In>Omitted Text<roject on-line, PF=0.95 leading

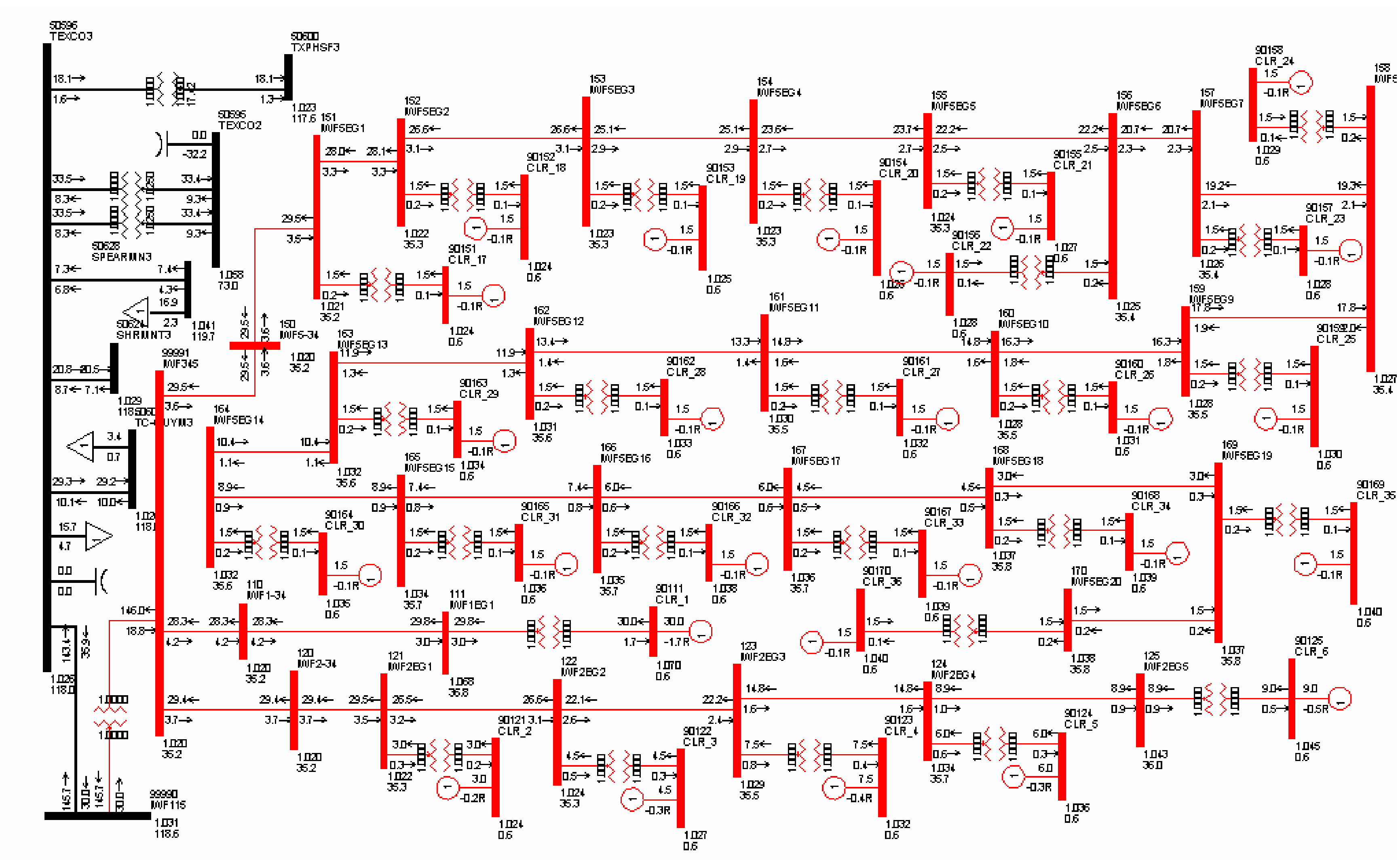


Figure 2-8: Load Flow Model of the Inv>Omitted Text<nd Farm Project, PF = 0.98 leading

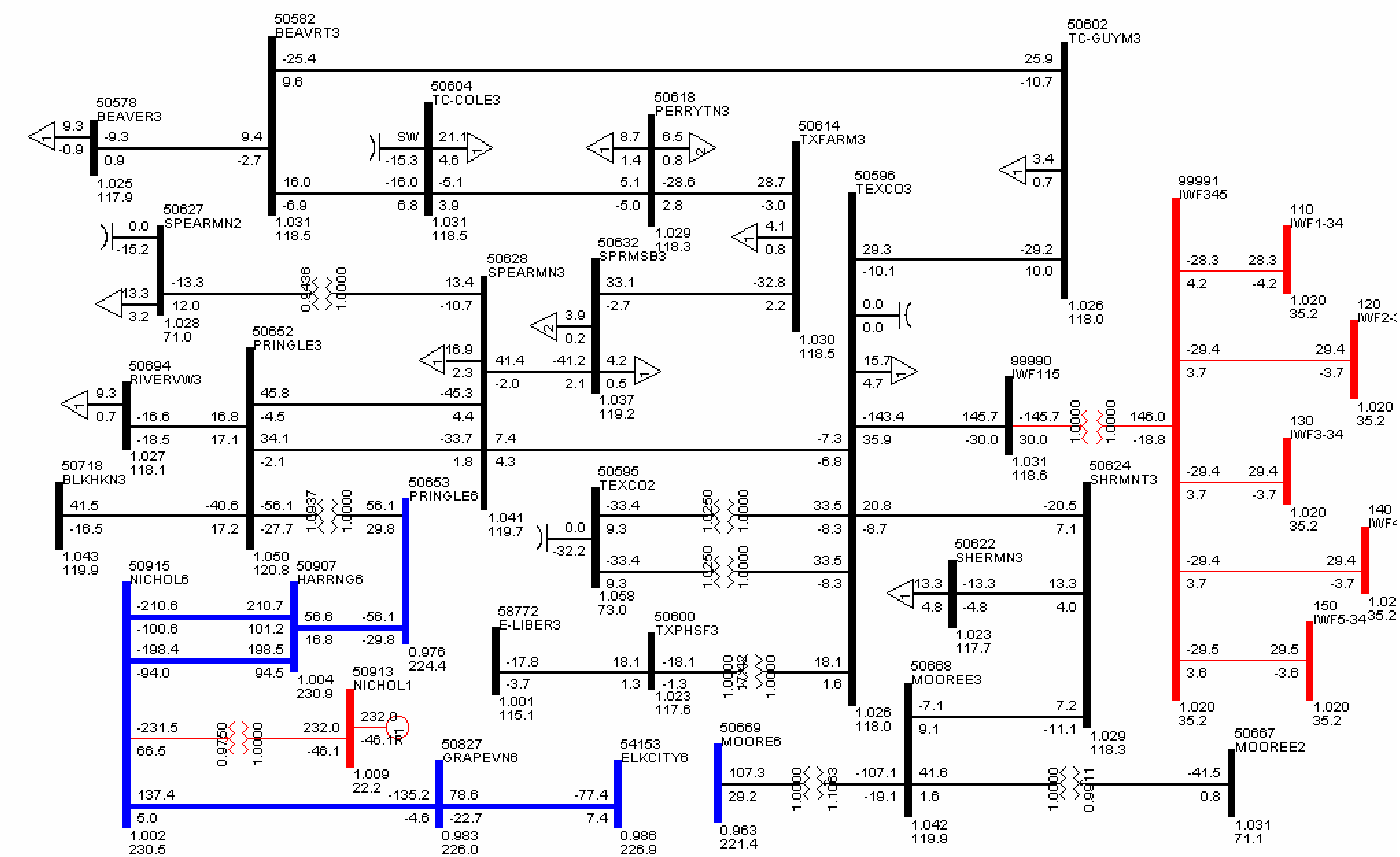
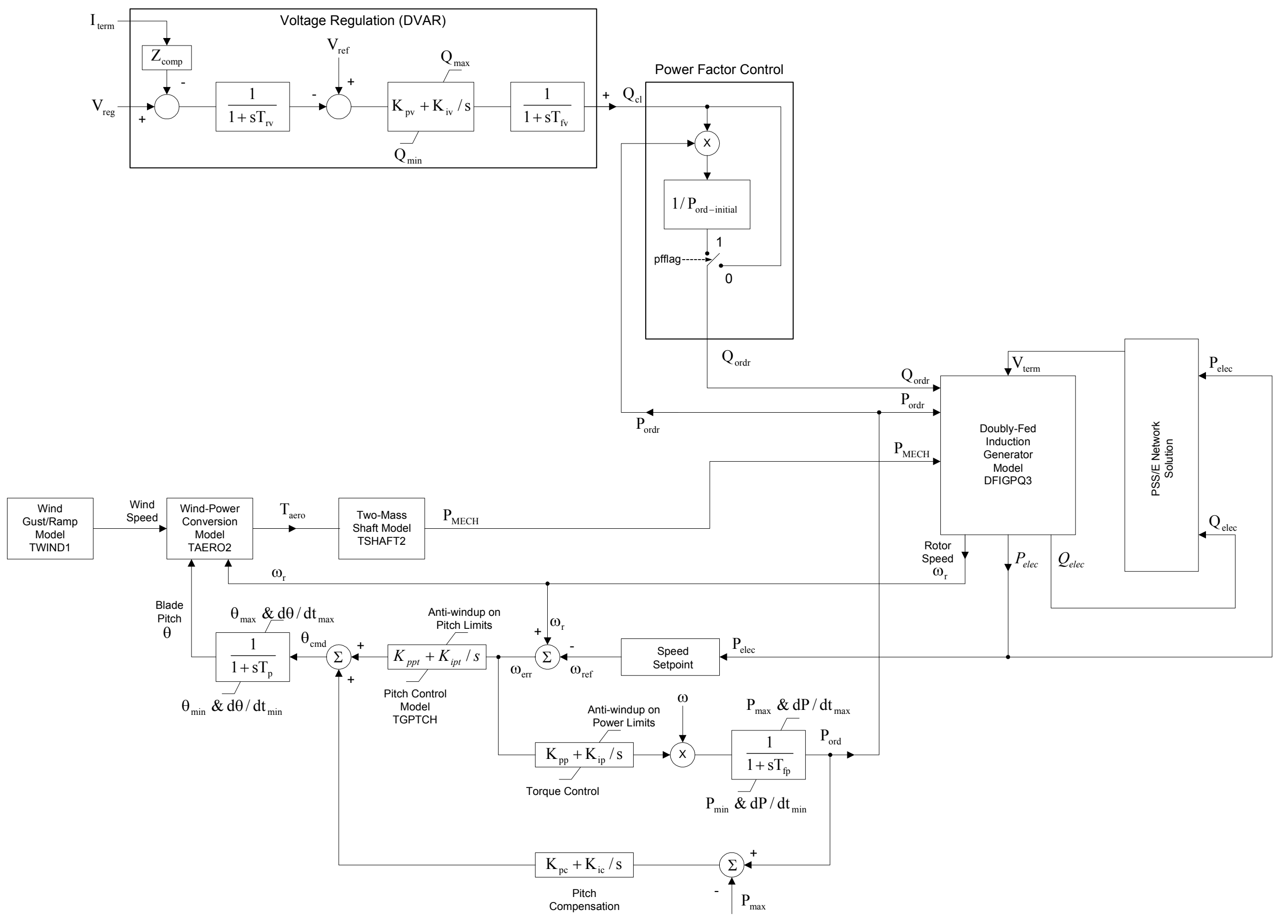


Figure 2-9: One-line Diagram of Xcel Energy's Network Near the I>Omitted Text<Project with>Omitted Text<Project on-line, PF=0.98 leading

2.2 Dynamics Data

The block diagram of the controls of a GE 1.5 MW wind turbine generator is illustrated in Figure 2-10. The block diagram was developed based on “Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators”, published by GE-Power Systems Energy Consulting. Note that only those controls are modeled whose characteristics are relevant to the frequency range typical for power system electromechanical oscillations and PSS/E bandwidth are taken into consideration [Refer to the GE report].



1.5 MW GE Wind Turbine Controls

Figure 2-10: Block Diagram of GE Wind Turbine C1ontrol

Eight user-written models based on the above algorithms and the IPLAN program were developed by PTI and are collectively referred to as the “GE wind turbine package”. The IPLAN program first sets up the wind farm in the load flow (details included in Section 2.1), then writes out to a PSS/E dynamic data file (DYRE file) the dynamic data for the doubly fed induction generator and the rest of the dynamic models.

2.2.1 User-Written Models

2.2.1.1 DFIGPQ

DIFGPQ is a simplified dynamic model of a doubly-fed induction generator controlled by a power converter. All induction generator parameters, such as rotor and stator R and X, inertia of the generator and saturation factors are taken into account in the model. Initial rotor negative slip is obtained from the loadflow solution. Following is the datasheet.

Power Technologies, Inc.
A Shaw Group Company

Nonstandard Model Data Sheet
DFIGPQ3

GE WIND TURBINE DOUBLY-FED (WOUND ROTOR) INDUCTION GENERATOR

This model is located at system bus #_______IBUS
Machine #_______I
This model uses CONs starting with#_______J
and STATEs starting with #_______K
and VARs starting with #_______L
and ICONs starting with #_______M

CONs	#	Value	Description
J			Ra, Stator resistance, pu
J+1			La, Stator Inductance, pu
J+2			Lm, Mutual Inductance, pu
J+3			R1, Rotor Resistance, pu
J+4			L1, Rotor Inductance, pu
J+5			H, total drive train inertia, sec.
J+6			D, Damping Factor, pu
J+7			E1, Saturation Parameter, pu
J+8			S(E1), Saturation Parameter, pu
J+9			E2, Saturation Parameter, pu
J+10			S(E2), Saturation Parameter, pu
J+11			-SLIP, initial rotor negative slip

STATEs	#	Description
K		Rotor Speed Deviation, pu
K+1		Rotor Angle deviation, degrees

VARs	#	Description
L		Ed, Rotor Voltage, pu on MBASE
L+1		Eq, Rotor Voltage, pu on MBASE
L+2		Rotor Speed, pu
L+3		Rotor Slip, pu
L+4		Id, Stator Current, pu on MBASE
L+5		Iq, Stator Current, pu on MBASE
L+6		RTR_P, Rotor Real Power, pu on MBASE
L+7		RTR_Id, Rotor Current, pu on MBASE
L+8		RTR_Iq, Rotor Current, pu on MBASE
L+9		Initial Machine internal Angle(rads)
L+10		Initial Slip, pu
L+11		Initial Mechanical Torque, pu
L+12		PSI_D, Stator Flux Linkage, pu
L+13		PSI_Q, Stator Flux Linkage, pu
L+14		LAM_D_PRIM, Transient Flux Linkage, pu
L+15		LAM_Q_PRIM, Transient Flux Linkage, pu
L+16		Initial desired net power, pu on MBASE
L+17		Initial desired net reactive power, pu on MBASE

ICONs	#	Description
M		Memory

IBUS 'USRMDL' ID 'DFIGPQ' 1 1 1 12 2 18 0 CONs from (J) to (J+11) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the “GE WTG” PSS/E software package.

2.2.1.2 CGECN2

CGECN2 is a GE Wind Turbine generator control model. This control model consists of two parts: voltage regulation (DVAR) and torque control. Inputs for controls are terminal voltage, remote bus number, and the DFIG machine rotor speed deviation. The output of the model is active and reactive power orders for the DFIGPQ model. Following is the datasheet.

Power Technologies, Inc.
A Shaw Group Company

Nonstandard Model Data Sheet
CGECN2

GE WIND TURBINE GENERATOR CONTROL

This model is located at system bus #_______IBUS
Machine #_______I
This model uses CONs starting with#_______J
and STATEs starting with #_______K
and VARs starting with #_______L
and ICONs starting with #_______M

CONs	#	Value	Description
J			Tfv, Filter time constant in Voltage regulator (sec)
J+1			Kpv, Proportional gain in Voltage regulator(pu)
J+2			Kiv, Integrator gain in Voltage regulator (pu)
J+3			Rc, Line drop compensation resistance (pu)
J+4			Xc, Line drop compensation reactance (pu)
J+5			Tfp, Filter time constant in Torque regulator (sec)
J+6			Kpp, Proportional gain in Torque regulator(pu)
J+7			Kip, Integrator gain in Torque regulator (pu)
J+8			PMX, Max limit in Torque regulator)pu)
J+9			PMN, Min limit in Torque regulator)pu)
J+10			QMX, Max limit in Voltage regulator (pu)
J+11			QMN, Min limit in Voltage regulator (pu)
J+12			Iqmax, Max reactive current limit (pu)
J+13			Trv, voltage sensor time constant (sec.)
J+14			RPMX, maximum power order derivative (pu)
J+15			RPMN, minimum power order derivative (pu)

STATEs	#	Description
K		Filter in Voltage regulator
K+1		Integrator in Voltage regulator
K+2		Filter in Torque regulator
K+3		Integrator in Torque regulator
K+4		Voltage sensor

VARs	#	Description
L		Initial rotor speed deviation, pu
L+1		Remote bus ref. voltage
L+2		Initial value of Power Order
L+3		Initial terminal voltage
L+4		Rotor PI-controller output

ICONs	#	Description
M		Remote bus # for voltage control
M+1		Memory
M+2		1 if power factor control enabled

IBUS 'USRMDL' ID 'CGECN2' 4 0 3 16 5 5 ICONs from (M) to (M+2) CONs from (J) to (J+15) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the “GE WTG” PSS/E software package.

2.2.1.3 TWIND1

TWIND1 models wind gusts and ramps. Start time, duration, and magnitude of wind gusts and ramps can be entered to simulate the effects of varying wind conditions. Following is the datasheet.

Power Technologies, Inc. Nonstandard Model Data Sheet
A Shaw Group Company TWIND1

WIND GUST AND RAMP

This model is located at system bus #_______IBUS
Machine #_______I
This model uses CONs starting with#_______J
and VARs starting with #_______L
and ICONs starting with #_______M

CONs	#	Value	Description
J			Vwb, Base wind speed from load flow, m/sec
J+1			T1g, Gust start time, sec.
J+2			Tg, Gust duration, sec.
J+3			MAXG, Gust peak over Vwb, m/sec
J+4			T1r, Ramp start time, sec.
J+5			T2r, Ramp Max time, sec.
J+6			MAXR, Ramp maximum over Vwb, m/sec.

VARs	#	Description
L		Vw, Actual wind speed, m/sec
L+1		Vwg, Gust component, m/sec
L+2		Vwr, Ramp component, m/sec

ICONs	#	Description
M		Generator bus #
M+1		Generator ID

0 'USRMDL' 0 'TWIND1' 8 0 2 7 0 3 ICON(M) ICON(M+1) CONs from (J) to (J+6) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the PSS/E software package.

2.2.1.4 TSHAFT2

TSHAFT2 is a two-mass shaft system model. The 2-mass drive train shaft mechanical system consists of the blade, gearbox/generator and the long shaft. Shaft damping and stiffness are taken into account along with turbine rotor inertia and gearbox ratio. Input as a mechanical torque in physical units comes from the aerodynamic model program. The output of the model is a mechanical torque, which drives the generator rotor and is transferred to the machine program as a mechanical power. Following is the datasheet.

Power Technologies, Inc.
A Shaw Group Company

Nonstandard Model Data Sheet
TSHAFT2

TWO-MASS SHAFT

This model is located at system bus #_______IBUS
Machine #_______I
This model uses CONs starting with#_______J
and STATEs starting with #_______K
and VARs starting with #_______L
and ICONs starting with #_______M

CONs	#	Value	Description
J			D12, Shaft damping (pu)
J+1			K12, Shaft stiffness (pu)
J+2			Ta1, Turbine rotor inertia (sec.)
J+3			POL, a number of generator pole pairs
J+4			Rq, Gear box ratio

STATEs	#	Description
K		Shaft twist angle, rad.
K+1		Turbine rotor speed deviation, pu

VARs	#	Description
L		Initial generator mechanical torque, pu
L+1		Initial generator rotor speed deviation, pu
L+2		Initial turbine rotor mechanical torque, pu

ICONs	#	Description
M		Machine bus #
M+1		Machine ID
M+2		Memory

0 'USRMDL' 0 'TSHAFT' 8 0 3 5 2 3 ICON(M) ICON(M+1) 0 CONs(J) through (J+4) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the "GE WTG" PSS/E software package.

2.2.1.5 TAERO2

TAERO2 is the aerodynamic energy conversion model. This program simulates conversion of the wind energy into electrical energy using design data for the GE 1.5 MW wind turbine. Power extracted from the wind can be expressed as:

$$\mathbf{P_w = C_p P_{w0} = C_p A_1 \rho/2\, v_1^3 = K_w v_1^3}$$

Where v_1 = upstream wind speed
ρ = the air density
C_p = performance coefficient, a function of tip speed ratio (lambda), and pitch angle

The power converter control optimizes aerodynamic efficiency, exploiting the maximum power available at each wind speed. Following is the datasheet.

Power Technologies, Inc. Nonstandard Model Data Sheet
A Shaw Group Company TAERO2

GE WIND TURBINE AERODYNAMICS

This model is located at system bus #_______IBUS
Machine #_______I
This model uses CONs starting with#_______J
and VARs starting with #_______L
and ICONs starting with #_______M

CONs	#	Value	Description
J			Vwinit, Initial eff. wind speed from load flow, m/sec
J+1			RoArHalf, Design parameter #1
J+2			Kb, Design parameter #2
J+3			Lambda_Max, Max. Lambda from Cp curves
J+4			PITCH_MAX
J+5			PITCH_MIN

VARs	#	Description
L		K_ADJ from initialization

ICONs	#	Description
M		Machine Bus #
M+1		Machine ID
M+2		Memory

0 'USRMDL' 0 'TAERO2' 8 0 3 6 0 1 ICON(M) ICON(M+1) 0 CONs from (J) to (J+5) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the “GE WTG” PSS/E software package.

2.2.1.6 TGPTCH

TGPTCH is the pitch control model. This model simulates the GE pitch control. Inputs for controls are initial and current machine rotor speed and generator electric power. The output of the program is a pitch angle in degrees. Following is the datasheet.

Power Technologies, Inc.
A Shaw Group Company

Nonstandard Model Data Sheet
TGPTCH

GE PITCH CONTROL

This model is located at system bus #_______IBUS
Machine #_______I
This model uses CONs starting with#_______J
and STATEs starting with #_______K
and VARs starting with #_______L
and ICONs starting with #_______M

CONs	#	Value	Description
J			Tp, Time constant of the output lag (sec)
J+1			Kpp, Proportional gain of PI regulator (pu)
J+2			Kip, Integrator gain of PI regulator (pu)
J+3			Kpc, Proportional gain of the compensator (pu)
J+4			Kic, Integrator gain of the compensator (pu)
J+5			BetaMin, Lower pitch angle limit (degrees)
J+6			BetaMax, Upper pitch angle limit (degrees)
J+7			RBetaMin, Lower pitch angle rate limit (degrees/sec.)
J+8			RBetaMax, Upper pitch angle rate limit (degrees/sec.)
J+9			PMX, power reference

STATEs	#	Description
K		Output Lag
K+1		Pitch Control
K+2		Pitch compensator

VARs	#	Description
L		Initial machine rotor speed, pu
L+1		Initial pitch angle, degrees
L+2		Initial power reference

ICONs	#	Description
M		Machine bus #
M+1		Machine ID
M+2		Memory

0 'USRMDL' 0 'TGPTCH' 8 0 3 10 3 3 ICON(M) ICON(M+1) 0 CONsfrom (J) to (J+9) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the “GE WTG” PSS/E software package.

2.2.1.7 VTGTRP

VTGTRP models over/under-voltage protection. This model monitors the voltage of the selected bus and trips the generator when under/over voltage conditions occur unless voltage is restored within the relay time delay. Following is the datasheet.

Power Technologies, Inc.
A Shaw Group Company

Nonstandard Model Data Sheet
VTGTRP

UNDERVOLTAGE/OVERVOLTAGE GENERATOR RELAY MODEL

This model is located at system bus #_______IBUS
Machine #_______IM
This model uses CONs starting with#_______J
and VARs starting with #_______K
and ICONs starting with #_______I

CONs	#	Value	Description
J			VL, lower voltage threshold (pu)
J+1			VU, upper voltage threshold (pu)
J+2			TP, relay pickup time (sec)
J+3			TB, breaker time (sec)

VARs	#	Description
L		Timer memory

ICONs	#	Description
I		Bus number where voltage is monitored
I+1		Bus number of generator bus where relay is located
I+2		Delay flag
I+3		Time-out flag
I+4		Timer status

Note: ICONs (I+2) through (I+4) are control flags that are not to be changed by the user

0 'USRMDL' 0 'VTGTRP' 0 2 5 4 0 1 ICON(M) ICON(M+1) 0 0 0 CONs from (J) to (J+3) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the PSS/E software package.

2.2.1.8 FRQTRP

FRGTRP models over/under frequency protection. This model monitors frequency of the selected bus and trips the generator when under/over frequency conditions occur unless frequency is restored within the relay time delay. Following is the datasheet.

Power Technologies, Inc.
A Shaw Group Company

Nonstandard Model Data Sheet
FRQTRP

UNDERFREQUENCY/OVERFREQUENCY GENERATOR RELAY MODEL

This model is located at system bus #_______IBUS
Machine #_______IM
This model uses CONs starting with#_______J
and VARs starting with #_______K
and ICONs starting with #_______I

CONs	#	Value	Description
J			FL, lower frequency threshold (pu)
J+1			FU, upper frequency threshold (pu)
J+2			TP, relay pickup time (sec)
J+3			TB, breaker time (sec)

VARs	#	Description
L		Timer memory

ICONs	#	Description
I		Bus number where frequency is monitored
I+1		Bus number of generator bus where relay is located
I+2		Generator ID
I+3		Delay flag
I+4		Time-out flag
I+5		Timer status

Note: ICONs (I+3) through (I+5) are control flags that are not to be changed by the user

0 'USRMDL' 0 'FRQTRP' 0 2 6 4 0 1 ICON(I) ICON(I+1) ICON(I+2) 0 0 0 CONs from (J) to (J+3) /

Note: input data to a dyre file are prepared by the IPLAN program which is a part of the PSS/E software package.

2.2.2 Setting up the user-written models for the study

The CGECN2 model is setup to dynamically maintain voltage at bus 99991 (the 34.5 kV collector bus). The turbine generator control of all thirty-six (36) equivalent generators in the wind farm will contribute reactive power consumption or generation to achieve the goal of voltage control.

The TWIND1 model is defined so that wind speed is constant during the stability simulation term period, that is, no wind gusts or ramps were simulated.

All parameters needed for the user-written models are entered according to standard 1.5 MW GE wind turbine units. The values of control parameters were also suggested by GE Wind. After the construction and installation of the wind turbines, field engineers might tune the controls according to the local network strength. In this study, we also encountered the need to tune some control. The goal of our tuning was not to find the optimized combination of controls, but to find a set of reasonable control parameters for Xcel Energy's system in this study.

The voltage regulator (DVAR) controls the reactive power generation/consumption in order to regulate the voltage at the designated bus, the 34.5 kV collector bus 99991. With the GE Wind suggested control parameters, the reactive power might change in the manner that would result in high voltage (above 1.15 pu) and cause 43 units out of total of 100 units being tripped in the simulation of FLT1_3PH (description of the disturbance included in Chapter 3). The 43 units tripped included all three levels of model detail:

- Equivalent 1, 20 units tripped: bus 90111
- Equivalent 2, 18 units tripped: bus 90125 (6 units), 90135 (6 units), 90145 (6 units)
- Equivalent 0, 5units tripped: 90166 to 90170 (1 unit each).

For the most detailed level of modeling (all 20 units modeled individually), only the last 5 units tripped. So if all 5 feeders had been modeled with this level of detail, it can be estimated that a total of 25 units would trip.

Two constants were adjusted in the user-written model CGECN2: the filter time constant and the proportional gain in the voltage regulator. Table 2-2 shows the differences in value between the suggested "general" values and the values used in these simulations.

Table 2-2: Comparison of Control Parameters

Parameter	Suggested value	Working value
Tfv, filter time constant in DVAR (sec)	5.0	2.0
Kpv, proportional gain in DVAR (pu)	10.0	1.0

Figure 2-11 shows a comparison of bus voltage at 99991 between "suggested" and "tuned" parameters. With the values suggested by GE Wind, response of DVR caused a fast increase in reactive power from consumption to generation in attempt to maintain the voltage at bus 99991 dynamically. After the fault was cleared for the second time due to the re-closing, the reactive power generation increased so much that the terminal bus voltage at bus 90151 (first unit on the feeder modeled in detail) reached 1.135 pu while voltage at bus 90170 reached 1.155 pu. The over-voltage protection at bus 90170 (fartherest unit on the feeder modeled in detail) was thus triggered and then tripped the generator, along with 4 other units near the end of the feeder. As a result, the voltage at bus 99991 reached 1.118 pu, and then decreased to 1.025 pu, the same as in the initial condition.

With the "tuned" parameters, the reactive power increased more slowly to meet the demand from the DVR. During the simulation, the maximum bus voltage at bus 90151 reached 1.099 pu, and bus 90170 reached 1.121

before both voltages reduced to less than 1.05 pu at the end of 10-second simulation. As a result, the bus voltage at bus 99991 reached 1.091 pu and then also decreased to 1.025 pu.

The four figures, from Figure 2-12 to Figure 2-15, demonstrate the comparison of reactive power of the Equivalent 0 model (most detailed) under disturbance FLT1_3PH during the first two seconds of simulation. Figure 2-12 shows a comparison of voltage at generator 90151, closest to the collector substation on feeder 5, with the suggested and "tuned" parameters, while Figure 2-13 shows the comparison of reactive power consumption/generation. Figure 2-14 and Figure 2-15 show a comparison for the unit at bus 90170, fartherest unit from the collector substation on the same feeder. The other 18 units along Feeder 5 have similar response between that of 90151 and 90170.

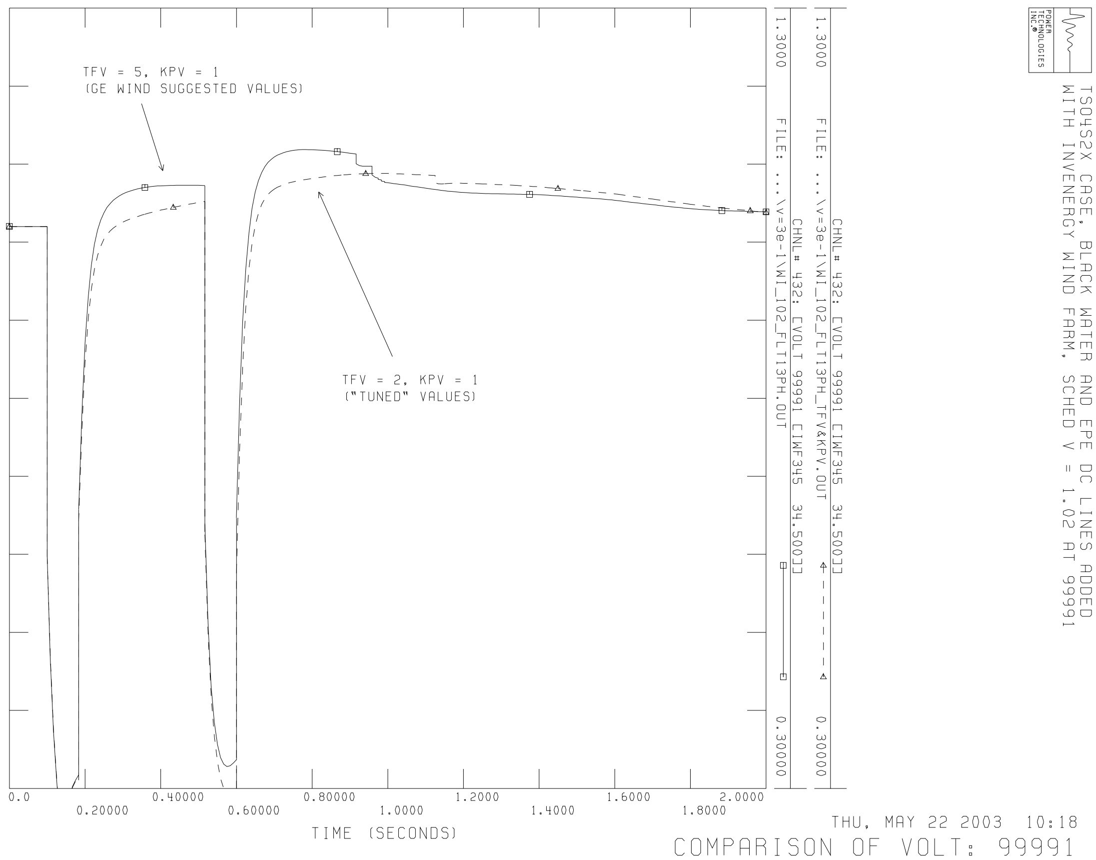


Figure 2-11: Comparison of Voltage at Bus 99991

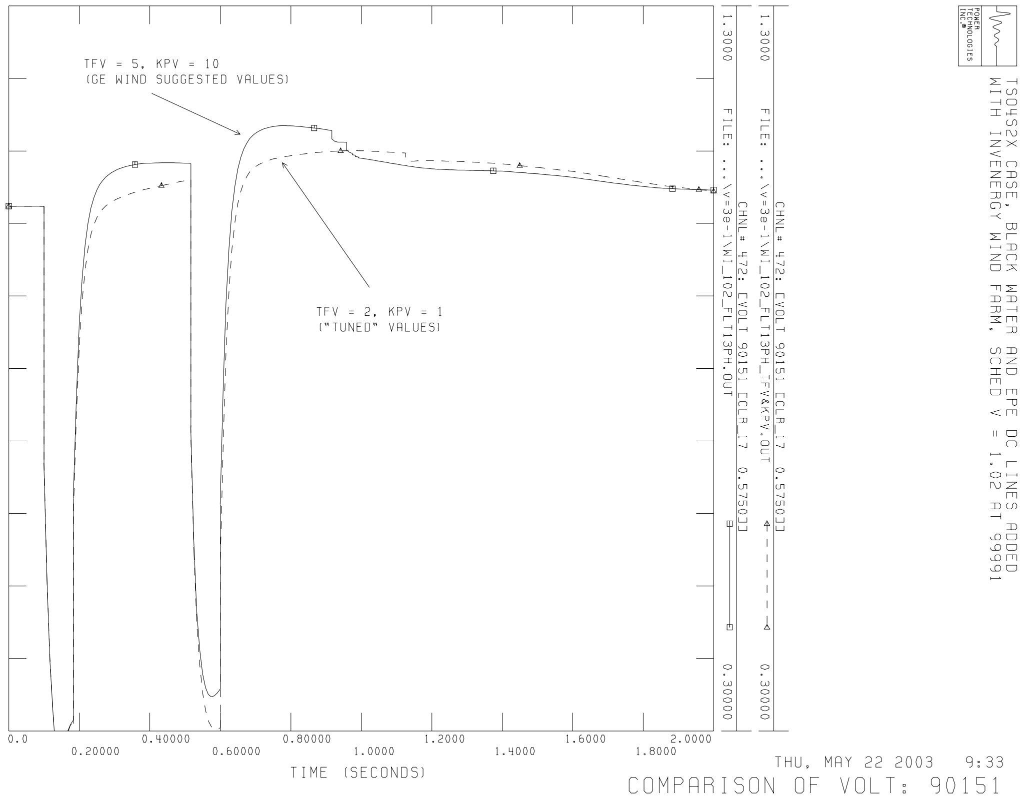


Figure 2-12: Comparison of Voltage at Bus 90151

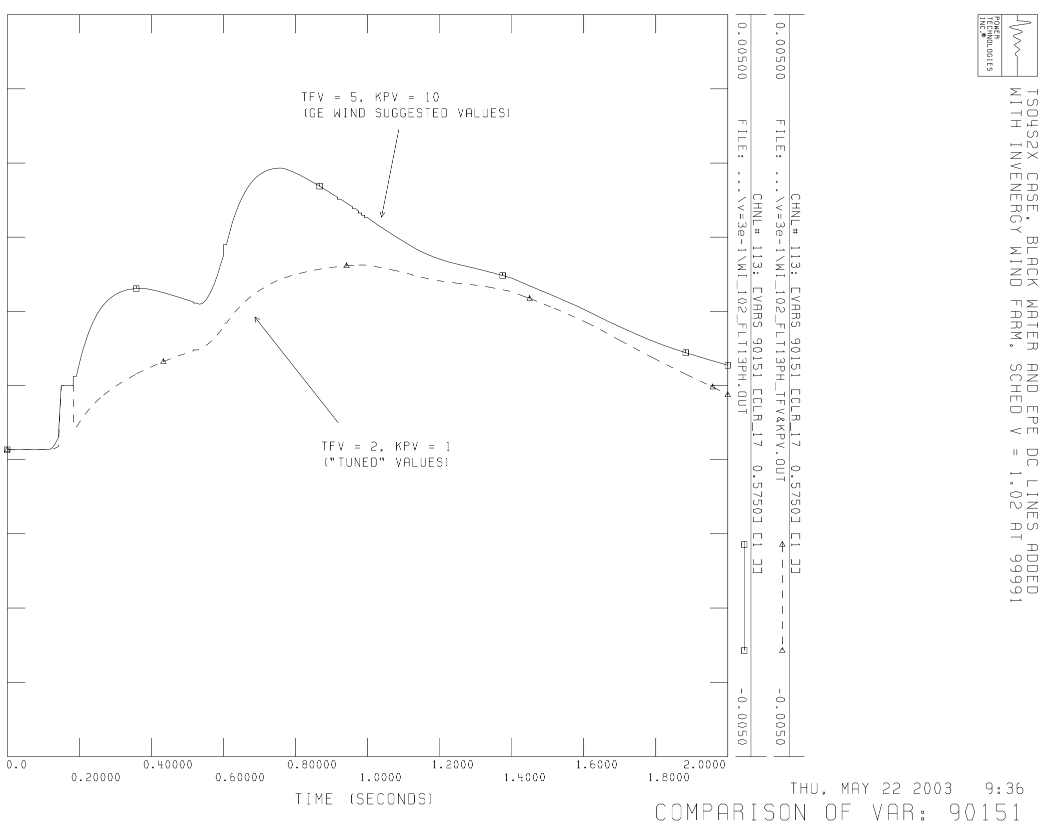


Figure 2-13: Comparison of Reactive Power /Generation Consumption at Bus 90151

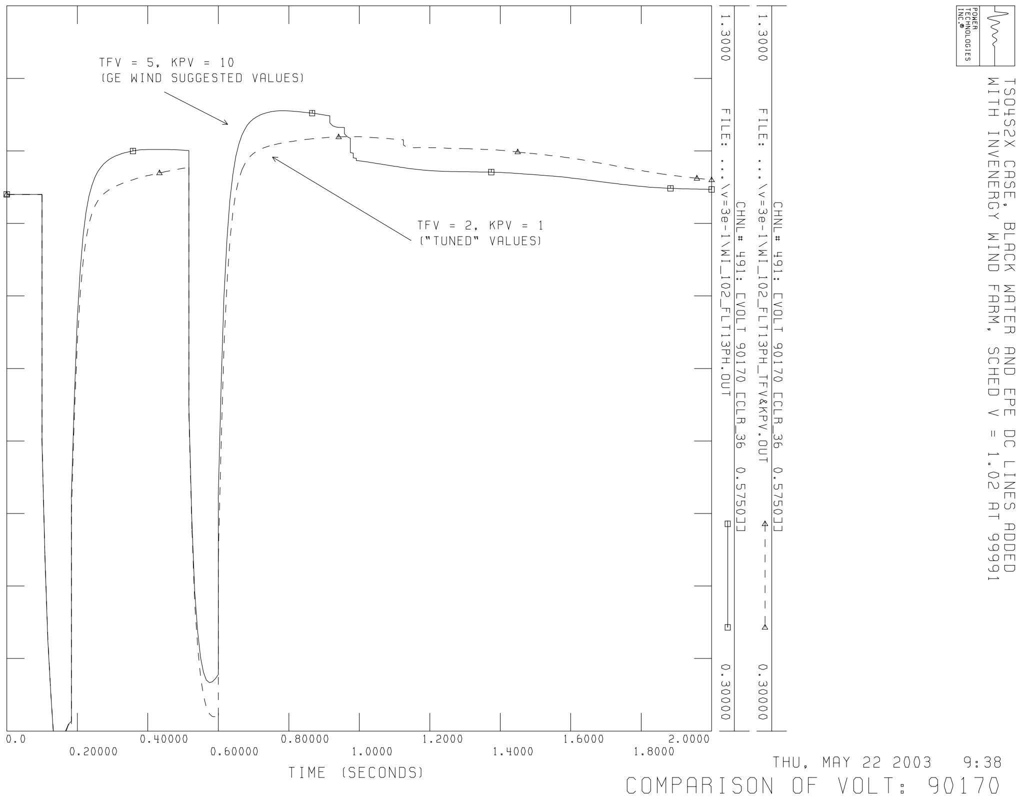


Figure 2-14: Comparison of Voltage at Bus 90170

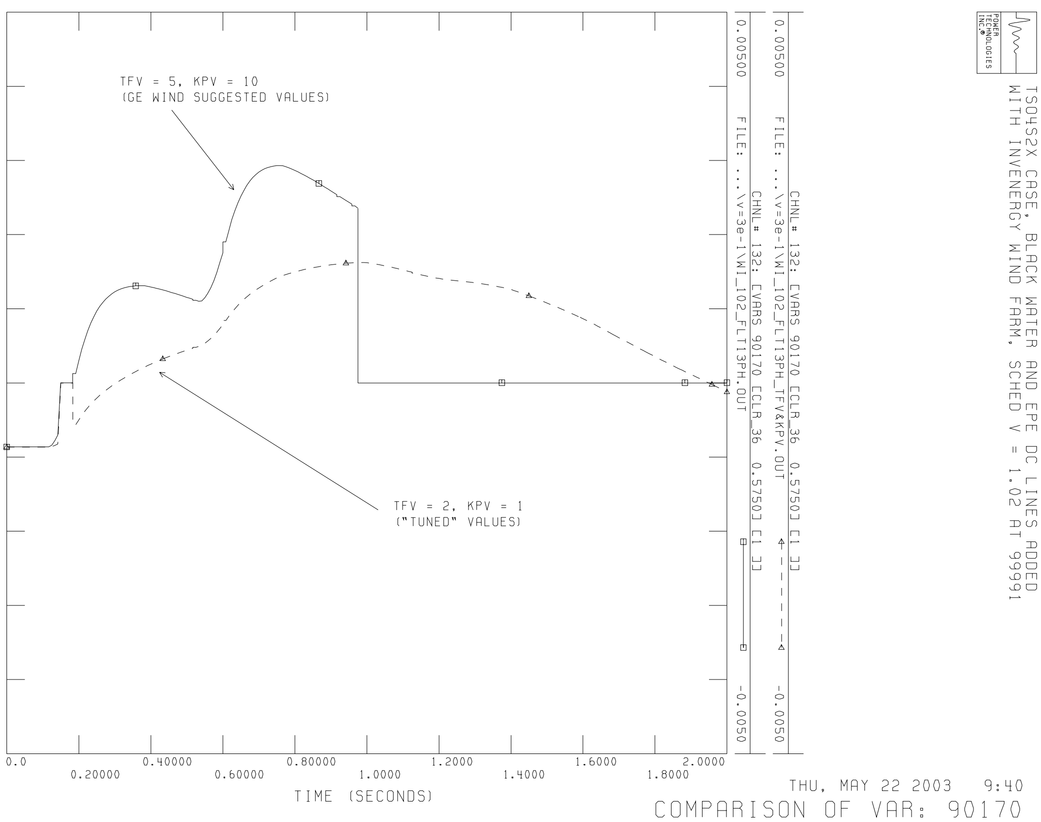


Figure 2-15: comparison of reactive power consumption at bus 90170

The sensing rate for the relays was not available at the time when the study was conducted. A time delay of 1 cycle was used to represent the time required by the sensors of the relay to capture and process the data. Following the performance of the simulations, information was received from GE Wind that this time delay is to be 20ms, slightly larger than the 1 cycle used in the study. However, in the simulation performed, no relay exercises this tripping logic.

The following is the voltage protection scheme for GE wind turbines giving thresholds and timing information:

MONITORED BUS : THE WIND TURBINE GENERATOR BUS
VOLTAGE BELOW 70% : 0.2 SECONDS
VOLTAGE 70% TO 75% : 1 SECOND
VOLTAGE 75% TO 85% : 10 SECONDS
VOLTAGE 85% TO 110% : CONTINUOUS
VOLTAGE 110% TO 115%: 1 SECOND
VOLTAGE 115% TO 130%: 0.1 SECONDS
VOLTAGE ABOVE 130% : TRIP IMMEDIATELY

The following parameters are developed to simulate the voltage protection scheme. Six relays are modeled for each WTG equivalent machine:

	Description	Relay 1 Settings	Relay 2 Settings	Relay 3 Settings	Relay 4 Settings	Relay 5 Settings	Relay 6 Settings
VLOW	VL, lower voltage threshold (pu)	0.70	0.75	0.85	0.0	0.0	0.0
VUP	VU, upper voltage threshold (pu)	5.0	5.0	5.0	1.10	1.15	1.30
PICKUP_TIME	TP, relay pickup time (sec)	0.2	1.0	10.0	20.0	1.0	0.0166*
BREAKER_TIME	TB, breaker time (sec)	0.15	0.15	0.15	0.15	0.15	0.15

* 1 cycle is assumed to account for minimum sensing rate for microprocessor.

The following is the frequency protection scheme for GE wind turbines giving thresholds and timing information:

MONITORED BUS : COLLECTOR BUS
FREQUENCY BELOW 56.5 HZ : TRIP IMMEDIATELY
FREQUENCY 56.5 TO 56.9 HZ : 7.2 CYCLES
FREQUENCY 56.9 TO 57.4 HZ : 45 CYCLES
FREQUENCY 57.4 TO 57.9 HZ : 7.5 SECONDS
FREQUENCY 57.9 TO 58.5 HZ : 30 SECONDS
FREQUENCY 58.5 TO 61.5 HZ : CONTINUOUS
FREQUENCY 61.5 TO 61.7 HZ : 30 SECONDS
FREQUENCY ABOVE 61.7 HZ : TRIP IMMEDIATELY

The following parameters are developed to simulate the frequency protection scheme. Seven relays are modeled for each WTG equivalent machine:

Variable	Description	Relay 1 Settings	Relay 2 Settings	Relay 3 Settings	Relay 4 Settings	Relay 5 Settings	Relay 6 Settings	Relay 7 Settings
FLOW	FL, lower frequency threshold (Hz)	56.5	56.9	57.4	57.9	58.5	54.0	54.0
FUP	FU, upper frequency threshold (Hz)	66.0	66.0	66.0	66.0	66.0	61.5	61.7
PICKUP_TIME	TP, relay pickup time (sec)	0.0166*	0.12	0.75	7.5	30.0	30.0	0.0166*
BREAKER_TIME	TB, breaker time (sec)	0.15	0.15	0.15	0.15	0.15	0.15	0.15

* 1 cycle is assumed to account for minimum sensing rate for microprocessor.

The following gives the DOCU output of generator bus 90111. Note that the same models and setup are applied to all the wind turbine generators.

```
     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, MAY 15 2003   9:51
TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
WITH >Omitted Text< WIND FARM

PLANT MODELS

REPORT FOR ALL MODELS                        BUS 90111 [CLR_1   0.5750] MODELS


** DFIGPQ **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S        VAR        ICON
            90111     CLR_1    0.5750 1  139821-139832  52525-52526    6874-6891     1465

    LA        LM        R1        L1        H        DAMP
  0.1714    2.9040    0.0050    0.1563    0.6400    0.0000

    E1        S(E1)     E2        S(E2)        -SLIP
  1.0000    0.0000    1.2000    0.0000    0.2000



** CGECN2 for DFIGPQ **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S        VAR        ICON
                      90111     CLR_1    0.5750 1  140253-140268  52597-52601    7522-7526     1501-1503

    TFV      KPV      KIV       RC        XC        TFP        KPP
  2.0000    1.0000   10.0000    0.0000    0.0000    0.0500    3.0000

    KIP       PMX     PMN        QMX        QMN     IQMAX     TRV
  0.6000    0.9000    0.0900    0.2930   -0.4400    1.1100    0.0500

    RPMX      RPMN
  0.4000   -0.4000

     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, MAY 15 2003   9:51
TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
WITH >Omitted Text< WIND FARM

CONEC MODELS

REPORT FOR ALL MODELS                        BUS 90111 [CLR_1   0.5750] MODELS


                *** CALL TWIND1(  1609,140829,     0,  7702) ***


 ** TWIND1 ** BUS X-- NAME --X BASEKV MC    C O N S       V A R S       ICONS
            90111 CLR_1        0.5750 1  140829-140835   7702-7704     1609-1610

    VWB     T1G       TG    MAXG      T1R      T2R    MAXR
 12.0009999.000   5.000  30.0009999.0009999.000  30.000

              Wind generator Bus #  90111
              Wind Generator ID       1


** TSHAFT for a machine **  BUS X-- NAME --X BASEKV MC    C O N S         STATE         VAR        ICON
                      90111     CLR_1    0.5750 1  141081-141085   52777-52778    7810-7812     1681-1683

          D12       K12         Ta1           p          Rq
      0.0300       0.6286       4.0000       3.0000       72.0000
```

```
              Wind Generator Bus #  90111
              Wind Generator ID       1


 ** TAERO2 for DFIGPQ **  BUS X-- NAME --X BASEKV MC    C O N S     VAR         ICON
                       90111     CLR_1    0.5750 1  141261-141266    7918    1789-1791

     VWinit      RoArHalf      Kb       Lambda_Max       PITCH_MAX       PITCH_MIN
      12.0000       0.0016      56.6000      20.0000      27.0000      -4.0000


              Wind Generator Bus #  90111
              Wind Generator ID       1


 ** TGPTCH for DFIGPQ **  BUS X-- NAME --X BASEKV MC    C O N S         STATE         VAR          ICON
                       90111     CLR_1    0.5750 1  141477-141486   52849-52851    7954-7956     1897-1899

        Tp            Kpp        Kip           Kpc           Kic
       0.2000     150.0000      25.0000       3.0000      30.0000
         TetaMin   TetaMax   RTetaMin   RTetaMax    PMX
         -4.0000   27.0000  -10.0000   10.0000    0.9000


              Wind Generator Bus #  90111
              Wind Generator ID       1
```

The following gives the DOCU output for relay models:

```
CONET MODELS
      PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, MAY 15 2003   9:51
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 CONET MODELS

 REPORT FOR ALL MODELS                         BUS 90111 [CLR_1   0.5750] MODELS


              *** CALL VTGTRP(  2005,141837,     0,  8062) ***

               BUS   NAME  BSKV        GENR BUS   NAME  BSKV
             90111 CLR_1   .575           90111 CLR_1   .575

                  I C O N S      C O N S       V A R
                  2005-2009   141837-141840    8062

                    VLO       VUP      PICKUP     TB
                    0.700     5.000     0.100     0.150


              *** CALL VTGTRP(  2010,141841,     0,  8063) ***

               BUS   NAME  BSKV        GENR BUS   NAME  BSKV
             90111 CLR_1   .575           90111 CLR_1   .575

                  I C O N S      C O N S       V A R
                  2010-2014   141841-141844    8063

                    VLO       VUP      PICKUP     TB
                    0.750     5.000     1.000     0.150


              *** CALL VTGTRP(  2015,141845,     0,  8064) ***

               BUS   NAME  BSKV        GENR BUS   NAME  BSKV
             90111 CLR_1   .575           90111 CLR_1   .575

                  I C O N S      C O N S       V A R
                  2015-2019   141845-141848    8064

                    VLO       VUP      PICKUP     TB
                    0.850     5.000    10.000     0.150


              *** CALL VTGTRP(  2020,141849,     0,  8065) ***

               BUS   NAME  BSKV        GENR BUS   NAME  BSKV
```

```
   90111 CLR_1   .575           90111 CLR_1   .575

        I C O N S      C O N S       V A R
        2020-2024   141849-141852    8065

          VLO       VUP      PICKUP     TB
          0.000     1.100     1.000     0.150


    *** CALL VTGTRP(  2025,141853,     0,  8066) ***

     BUS   NAME  BSKV        GENR BUS   NAME  BSKV
   90111 CLR_1   .575           90111 CLR_1   .575

        I C O N S      C O N S       V A R
        2025-2029   141853-141856    8066

          VLO       VUP      PICKUP     TB
          0.000     1.150     0.100     0.150


    *** CALL VTGTRP(  2030,141857,     0,  8067) ***

     BUS   NAME  BSKV        GENR BUS   NAME  BSKV
   90111 CLR_1   .575           90111 CLR_1   .575

        I C O N S      C O N S       V A R
        2030-2034   141857-141860    8067

          VLO       VUP      PICKUP     TB
          0.000     1.300     0.017     0.150
```

2.2.3 Blackwater and Eddy County HVDC Lines

The setup for the Blackwater and Eddy County DC lines is obtained from the Duke Study. The following gives the DOCU output:

```
PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, APR 24 2003  15:42
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 PLANT MODELS

 REPORT FOR ALL MODELS                         BUS 59973 [PNM     345.00] MODELS


 ** GENCLS **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S
           59973     PNM      345.00 1  139775-139776  52519-52520

     MBASE     Z S O R C E         X T R A N       GENTAP      H     DAMP
     121.9  0.00000+J 0.25000  0.00000+J 0.00000  1.00000    0.00   0.000

      PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, APR 24 2003  15:42
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 PLANT MODELS

 REPORT FOR ALL MODELS                         BUS 59978 [EPE     345.00] MODELS


 ** GENCLS **  BUS X-- NAME --X BASEKV MC    C O N S     S T A T E S
           59978     EPE      345.00 1  139773-139774  52517-52518

     MBASE     Z S O R C E         X T R A N       GENTAP      H     DAMP
     176.1  0.00000+J 0.25000  0.00000+J 0.00000  1.00000    0.00   0.000

      PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, APR 24 2003  15:42
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 CONEC MODELS

 REPORT FOR ALL MODELS                         BUS 59974 [PNM DC  345.00] MODELS
```

```
               *** CALL CDC4( 2,139799, 52523,  6859,  1462) ***

 ** CDC4 **   DC#  RECBUS X-- NAME --X BASEKV  INVBUS X-- NAME --X BASEKV
                2   59975     BLKWDC   230.00   59974     PNM DC   345.00

                C O N S    S T A T E S    V A R S     I C O N S
             139799-139820  52523-52524    6859-6873     1462-1464

                  MDC    RDC  RCOMP SETVAL  VSCHED VCMODE  DELTI
                    1   0.00   0.00  200.0    55.0   45.0 0.1000

  ALFDY  GAMDY   TVDC   TIDC VBLOCK  VUNBL  TBLOCK VBYPAS  VUNBY  TBYPAS  RSVOLT
   5.00  15.00  0.500  0.500 0.6000 0.6500   0.100   30.0 0.6500   0.100   30.00

   RSCUR  VRAMP  CRAMP     C0      V1      C1      V2      C2      V3      C3
  550.00 10.000 10.000   300.0    25.0  1500.0    40.0  3000.0    55.0  4000.0

                      TCMODE          DCCUR   KVDCR   KVDCI
                       0.145         3636.1    55.0    55.0

    ALF/GAM   MIN    MAX    PAC     QAC  NB   EBASE    RC     XC    TR     TAP
 R:  13.64  12.00  18.00   200.0    89.7  2   230.0  0.000  0.550 0.1006 1.0000
 I:  16.92  14.50  18.00  -200.0    98.2  2   345.0  0.000  0.550 0.0671 1.0170

PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, APR 24 2003  15:42
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 CONEC MODELS

 REPORT FOR ALL MODELS                         BUS 59976 [EPEDC   230.00] MODELS


               *** CALL CDC4( 1,139777, 52521,  6844,  1459) ***

 ** CDC4 **   DC#  RECBUS X-- NAME --X BASEKV  INVBUS X-- NAME --X BASEKV
                1   59976     EPEDC    230.00   59977     EPTNPDC  345.00

                C O N S    S T A T E S    V A R S     I C O N S
             139777-139798  52521-52522    6844-6858     1459-1461

                  MDC    RDC  RCOMP SETVAL  VSCHED VCMODE  DELTI
                    1   0.00   0.00   53.0    82.0   69.7 0.1000

  ALFDY  GAMDY   TVDC   TIDC VBLOCK  VUNBL  TBLOCK VBYPAS  VUNBY  TBYPAS  RSVOLT
   5.00  15.00  0.050  0.050 0.6000 0.6500   0.100   30.0 0.6500   0.100   45.00

   RSCUR  VRAMP  CRAMP     C0      V1      C1      V2      C2      V3      C3
  365.00 10.000 10.000   200.0    40.0  1000.0    60.0  2000.0    82.0  2700.0

                      TCMODE          DCCUR   KVDCR   KVDCI
                       0.145          646.3    82.0    82.0

    ALF/GAM   MIN    MAX    PAC     QAC  NB   EBASE    RC     XC    TR     TAP
 R:  16.77  12.00  21.00    53.0    20.6  2   345.0  0.000  1.860 0.1027 1.0870
 I:  19.06  14.50  21.00   -53.0    22.6  2   345.0  0.000  1.860 0.1027 1.0730


      PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, APR 24 2003  15:42
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 CONET MODELS

 REPORT FOR ALL MODELS                         BUS 59974 [PNM DC  345.00] MODELS


               *** CALL TDC4( 2,139799, 52523,  6859,  1462) ***

 ** TDC4 **   DC#  RECBUS X-- NAME --X BASEKV  INVBUS X-- NAME --X BASEKV
                2   59975     BLKWDC   230.00   59974     PNM DC   345.00

                C O N S    S T A T E S    V A R S     I C O N S
             139799-139820  52523-52524    6859-6873     1462-1464


      PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      THU, APR 24 2003  15:42
 TSO4S2X CASE, BLACK WATER AND EPE DC LINES ADDED
 WITH >Omitted Text< WIND FARM

 CONET MODELS

 REPORT FOR ALL MODELS                         BUS 59976 [EPEDC   230.00] MODELS
```

```
               *** CALL TDC4( 1,139777, 52521,  6844,  1459) ***

** TDC4 **   DC#  RECBUS X-- NAME --X BASEKV  INVBUS X-- NAME --X BASEKV
              1   59976     EPEDC    230.00   59977     EPTNPDC  345.00

              C O N S     S T A T E S     V A R S      I C O N S
            139777-139798  52521-52522    6844-6858     1459-1461
```

Section
3

Stability Analysis

3.1 Disturbances

The following faults were simulated (3 phase and single phase) for each power flow case.

1. Faults on Spearman (50628)– Texas County (50596) 115 kV line (mid-length). Establish a mid-bus in the electrical middle of the line.
   FLT13PH - 3-phase Fault
   a. Apply fault to mid-bus.
   b . Clear Fault after 5 cycles by removing lines from 50628 to mid-bus and mid-bus to 50596.
   c. Wait 20 cycles, and then reclose both lines in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip both lines in (b) to remove fault.
   FLT11PH - 1-phase Fault
   Timing same as FLT13PH above.

2. Faults on Moore County (50668)– Texas County (50596) 115 kV line (at Sherman Tap 50624). Sherman Tap is a mid-point bus in the electrical middle of the line breakers.
   FLT23PH - 3-phase Fault
   a. Apply fault to Sherman Tap bus (50624).
   b . Clear Fault after 5 cycles by removing lines from 50668 to 50624 and 50624 to 50596.
   c. Wait 20 cycles, and then reclose both lines in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip both lines in (b) to remove fault.
   FLT21PH - 1-phase Fault
   Timing same as FLT23PH above

3. Fault on Texas County Phase Shifter (50600) – Liberal (58772) 115 kV line. Establish a mid-bus in the electrical middle of the line.
   FLT33PH - 3-phase Fault
   a. Apply fault to mid-bus.
   b . Clear Fault after 5 cycles by removing lines from 50600 to mid-bus and mid-bus to 58772.
   c. Wait 20 cycles, and then reclose both lines in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip both lines in (b) to remove fault..
   FLT31PH - 1-phase Fault
   Timing same as FLT33PH above

4. Fault on Spearman Interchange (50628) – Spearman Sub (50632) 115 kV line (near Spearman Interchange)
   FLT43PH - 3-phase Fault
   a. Apply fault at Spearman Interchange bus 50628.
   b . Clear Fault after 5 cycles by removing line from 50628 - 50632.

c. Wait 20 cycles, and then reclose line in (b) into the fault.
d. Leave fault on for 5 cycles, then trip line in (b) and remove fault.

FLT41PH - 1-phase Fault
Timing same as FLT43PH above

5. Fault on the Grapevine (50827) – Elk City (54153) 230 kV line (near Grapevine)

FLT53PH - 3-phase Fault

a. Apply fault at bus 50827.
b . Clear Fault after 5 cycles by removing line from 50827 – 54153.
c. Wait 20 cycles, and then reclose line in (b) into the fault.
d. Leave fault on for 5 cycles, then trip line in (b) and remove fault.

FLT51PH - 1-phase Fault
Timing same as FLT53PH above

6. Fault on the Harrington (50907) – Pringle Interchange (50653) 115 kV line (near Pringle Interchange)

FLT63PH - 3-phase Fault

a. Apply fault at bus 50653.
b . Clear Fault after 5 cycles by removing lines from 50907 to 50653.
c. Wait 20 cycles, and then reclose lines in (b) into the fault.
d. Leave fault on for 5 cycles, then trip lines in (b) and remove fault.

The actual single-line-to-ground fault MVA's at the above substations were not available. Fault MVA's were calculated and applied so the bus voltage of the substation with the SLG fault applied dropped to approximately 0.65 pu. The PSAS files for simulating the faults with the plant on-line are included in Appendix A.

3.2 Results and Discussion

Simulations were performed with a 0.1-second steady-state run followed by the appropriate disturbance as described in Section 3.1. Simulations were run for a minimum 10-second duration to confirm proper machine damping. The system remained stable for all the faults simulated both with and without the >Omitted Text< Wind Farm project. All oscillations were well damped.

Based on the dynamic simulation results obtained, the study demonstrated that the addition of >Omitted Text< Wind Farm does not have negative impacts on the transient stability performance of the Xcel Energy system. The stability plots of simulations with >Omitted Text< Wind Farm Project in-service are included in Appendix B.1, and the plots of simulations without >Omitted Text< Wind Farm Project in-service are included in Appendix B.2.

When running the simulations with tuned control parameters, in the case with lower power factor of the wind farm (WI_IWF.SAV), no units were tripped due to the fault. With higher power factor (WI_IWF_102.SAV), also with tuned control parameters, the equivalent generator at 90111 was tripped by the over-voltage protection scheme in nine disturbances out of the total of 12. However, the tripping is due to the overly conservative, fully lumped model, and should not be treated representing the actual operation. More details are discussed in the following sections.

Both DC lines PNM and EPE regained control after the fault was cleared in all faults simulated. No HVDC blocking resulted from the fault.

A few concerns were raised due to the electrical and mechanical nature of wind turbines:

- The significance of equivalent wind farm modeling
- Desired plant operation in steady-state versus under disturbances
- The adequacy of control parameters

As described in Section 2.1.2, the five 34.5 kV feeders of the >Omitted Text< wind farm have been modeled in three levels of detail. Differences in the model result in different voltage fluctuations seen by the unit during disturbances. Details are given in Section 3.2.1.

Comparing cases with different power factor control, the higher power factor is more desirable in steady-state operation while resulting higher generator terminal voltages might cause generators to be tripped under disturbances. Details are given in Section 3.2.2.

As described in Section 2.2.2, some control parameters will be tuned in field according to the actual network conditions. The control parameters suggested by GE Wind may be applied to a different network strength. In this study, two parameters in the DVAR are adjusted. Again, our goal is not to find the optimum combination of control parameters, but to find reasonable working values for this study. Further tuning might improve the response even more. Details are given in Section 3.2.3.

3.2.1 Wind Farm Equivalent

As described in Section 2.1.2, three different levels of model detail were modeled for the five 34.5 kV feeders:

- cluster all 20 units at the end of a 34.5 kV line of 20,000 feet, resulting in 1 equivalent generator. ("Equivalent 1")

- cluster units at end of each section of different cable sizes, resulting in 5 equivalent generators. ("Equivalent 2")

- model all 20 units separately, resulting in 20 units; no equivalent was made. ("Equivalent 0")

Equivalent 1 is to locate the generator at the end of a 3.8-mile line. The generator bus 90111 has a higher bus voltage in steady state in order to maintain the same power factor for the equivalent unit. This model thus exaggerates the voltage rise along the feeder. As a result, generator 90111 was tripped in some disturbances due to over-voltage.

To test a case with reduced extremity of Equivalent level 1, the same equivalent generator and generator-step-up-transformer were moved up from the end of the line to 2/3 of the same 3.8 mile line in IW_IWF_102.SAV. When FLT13PH was applied, the generator was no longer tripped on over-voltage.

Modeled with more details, such as 5 equivalent generators per feeder or with each unit modeled individually, generators were not tripped due to over-voltage under all twelve disturbances with interconnection power factors of 0.95 or 0.98 . In addition, the voltages and machine response of Equivalent 2 are very similar to those of the most detailed model, Equivalent 0. This leads to the conclusion that some equivalencing of the wind farm model can be used.

Table 3-1 summarizes the bus voltages of different modeling details in steady-state. Bus 90111 is the equivalent generator of Equivalent 1; bus 90121 is at the beginning of the feeder of Equivalent 2 while 90125 is at the end. Bus 90151 is at the beginning of the feeder of Equivalent 5 while 90170 is at the end; bus 90155, 90160 and 90165 distributed along the same feeder.

Table 3-1: Comparison of Bus Voltages in Steady-State

Case	PF	Equivalent 1	Equivalent 2		Equivalent 0				
		90111	90121	90125	90151	90155	90160	90165	90170
WI_IWF	0.95 leading	1.0410	0.9984	1.0173	0.9980	1.0001	1.0039	1.0090	1.0126
WI_IWF_102	0.98 leading	1.0700	1.0243	1.0450	1.0238	1.0266	1.0309	1.0364	1.0400

In all twelve disturbances, all wind turbine generators rode through the disturbances and remained on-line in the case WI_IWF.SAV. However, the generator at bus 90111 was tripped in all but three disturbances in the case WI_IWF_102.SAV. The tripping should be treated as a result of the model, not due to wind turbine behavior under disturbances. Table 3-2 summaries the time when generator 90111 is tripped under disturbances. "X" stands for no tripping during the simulation.

Table 3-2: Tripping Time of Generator 90111

PF	F1_3PH	F1_1PH	F2_3PH	F2_1PH	F3_3PH	F3_1PH	F4_3PH	F4_1PH	F5_3PH	F5_1PH	F6_3PH	F6_1PH
0.95	X	X	X	X	X	X	X	X	X	X	X	X
0.98	1.125	1.833	1.8083	1.8667	1.025	X	1.833	1.9417	X	X	1.850	2.0917

Table 3-3 summarizes the highest voltage wind turbine generators experienced under the fault FLT13PH (three-phase-to-ground fault at the mid-point of 115 kV branch between Spearman and Texas County).

Table 3-3: Highest Voltage During the Disturbance FLT13PH

Case	PF	Equivalent 1	Equivalent 2		Equivalent 0				
		90111	90121	90125	90151	90155	90160	90165	90170
WI_IWF	0.95	1.1459	1.0955	1.1186	1.0948	1.0982	1.1033	1.1092	1.1131
WI_IWF_102	0.98	1.1531	1.1013	1.1253	1.1005	1.1043	1.1096	1.1158	1.1197

The key point to note from this is that the layout of the wind farm impacts the wind turbine generator's behavior under disturbances. We suggest that once the details are available of how turbines are distributed along the line, a more detailed study to be conducted to determine the actual bus voltages under a variety of system conditions to check the voltage/reactive power strategies.

3.2.2 Desired plant operation in steady-state versus under disturbances

Judging solely by steady-state operation, the load flow case with a power factor closer to unity at the interconnection point is more desirable. However, if the wind farm is operated under uniform power factor control, the generator bus at the end of the feeder far away from the 34.5 kV collector substation will experience higher voltage than those closer to the collector substation. In the load flow case with a higher power factor, the slightly higher bus voltage might trigger the voltage protection scheme during disturbances. Note that information supplied on feeder layout and length is approximate design data, but actual feeders could be longer and layout different.

In Table 3-1, we can observe that when the overall power factor is 0.98, the bus voltage at the first generator of the detailed model (90151) is generator 90125 is 1.0238 pu while the voltage at farthest generator 90170 is 1.04 pu. If the operator wants to raise the overall power factor to be higher, such as 1.0 pu, the generator bus voltage at 90151 will reach 1.0625 pu while that of 90170 will reach 1.0795. These bus voltages are above normal equipment steady-state capabilities of 105% voltage.

In short, desired plant operation point has to take into account both steady-state voltages and dynamic response. Higher initial voltages increase the chance of tripping due to swings in voltage in response to disturbances. Therefore there is a trade-off between higher power factor operation and steady-state and dynamic voltage constraints in the wind farm.

3.2.3 Tuning control parameters

As described in Section 2.2.2, the control parameters of the voltage regulator were tuned for a more desirable behavior. Our goal was not to find the optimum control, but to find reasonable parameters to work with in these simulations. Figure 3-1 demonstrates how the control parameters of the voltage regulator can be tuned further. With Kiv adjusted to 1 from 10, the oscillation of the reactive power at approximately 3 Hz can be eliminated. However, any further tuning requires validation from the wind turbine manufacturer to make sure such tuning in the field is feasible.

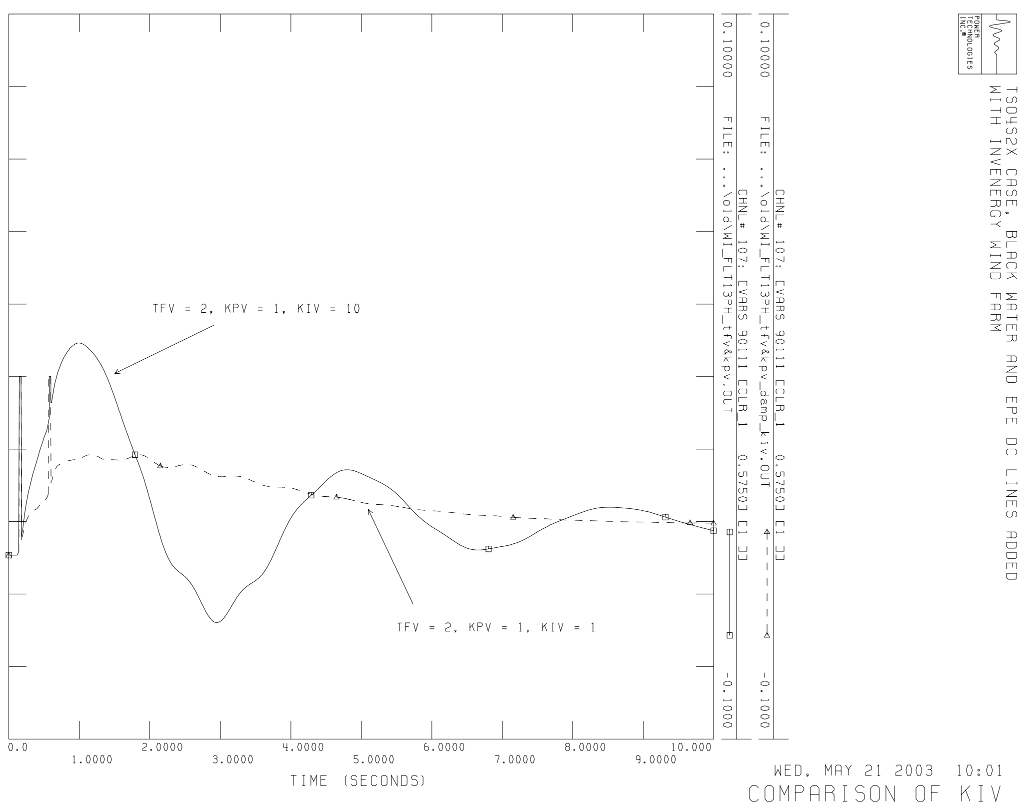


Figure 3-1: Comparison of Kiv

Section
4

Conclusions

Based on the dynamic simulation results obtained, the study demonstrates that the addition of >Omitted Text< Wind Farm does not have negative impacts on the transient stability performance of the Xcel Energy system but several operational concerns were indicated. The system remains stable for all the faults simulated both with and without the >Omitted Text< Wind Farm project. That is, no units lose synchronism with the system. All oscillations were well damped.

From the point of view of system operation, operating the plant at a power factor closer to unity at the interconnection point is more desirable. However, if the wind farm is operated under uniform power factor control as specified by GE, the generator buses at the far end of the feeder (away from the 34.5 kV collector substation) will experience higher voltage than those closer to the collector substation. For example, at unity power factor the fartherest generator has a terminal voltage of almost 108%. For higher power factors, the higher bus voltage might trigger the voltage protection scheme during disturbances.

The control parameters for the voltage regulator were tuned for a more desirable behavior. With the original control parameters, tripping due to over-voltage protection occurred. However, the ability to tune the controls requires input from the manufacturer.

Thus, more study is required to identify solutions satisfying both the higher power factor demand at the interconnection point and stable operation of wind turbine units without tripping following disturbances.

Appendix

A

PSAS files

- FLT13PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT13PH.txt
ODEV
2 1 1
PDEV_WI_FLT13PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_f1_cnv.sav
INITIALIZE OUTPUT WI_FLT13PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 9999
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52186 TO BUS 52185 CIRCUIT 1
TRIP LINE FROM BUS 52186 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 51439 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51435 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51437 CIRCUIT 1
RUN FOR 30 CYCLES PRINT 240 PLOT 1
CHANGE BUS 9999 CODE TO 1
CHANGE BUS 52186 CODE TO 1
CHANGE BUS 51440 CODE TO 1
CHANGE BUS 51439 CODE TO 1
APPLY FAULT AT BUS 9999
CLOSE LINE FROM BUS 52186 TO BUS 52185 CIRCUIT 1
CLOSE LINE FROM BUS 52186 TO BUS 9999 CIRCUIT 1
CLOSE LINE FROM BUS 51440 TO BUS 9999 CIRCUIT 1
CLOSE LINE FROM BUS 51440 TO BUS 51439 CIRCUIT 1
CLOSE LINE FROM BUS 51439 TO BUS 51435 CIRCUIT 1
CLOSE LINE FROM BUS 51439 TO BUS 51437 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52186 TO BUS 52185 CIRCUIT 1
TRIP LINE FROM BUS 52186 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 51439 CIRCUIT 1
```

```
TRIP LINE FROM BUS 51439 TO BUS 51435 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51437 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT11PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT11PH.txt
ODEV
2 1 1
PDEV_WI_FLT11PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_f1_cnv.sav
INITIALIZE OUTPUT WI_FLT11PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 9999 ADMITTANCE 21.7 -1121.4 MVA
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52186 TO BUS 52185 CIRCUIT 1
TRIP LINE FROM BUS 52186 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 51439 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51435 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51437 CIRCUIT 1
RUN FOR 30 CYCLES PRINT 240 PLOT 1
CHANGE BUS 9999 CODE TO 1
CHANGE BUS 52186 CODE TO 1
CHANGE BUS 51440 CODE TO 1
CHANGE BUS 51439 CODE TO 1
APPLY FAULT AT BUS 9999 ADMITTANCE 21.7 -1121.4 MVA
CLOSE LINE FROM BUS 52186 TO BUS 52185 CIRCUIT 1
CLOSE LINE FROM BUS 52186 TO BUS 9999 CIRCUIT 1
CLOSE LINE FROM BUS 51440 TO BUS 9999 CIRCUIT 1
CLOSE LINE FROM BUS 51440 TO BUS 51439 CIRCUIT 1
CLOSE LINE FROM BUS 51439 TO BUS 51435 CIRCUIT 1
CLOSE LINE FROM BUS 51439 TO BUS 51437 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52186 TO BUS 52185 CIRCUIT 1
TRIP LINE FROM BUS 52186 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 9999 CIRCUIT 1
TRIP LINE FROM BUS 51440 TO BUS 51439 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51435 CIRCUIT 1
TRIP LINE FROM BUS 51439 TO BUS 51437 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN
END
```

- FLT2_3PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT23PH.txt
ODEV
2 1 1
PDEV_WI_FLT23PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_f2_cnv.sav
INITIALIZE OUTPUT WI_FLT23PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 9999
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 9999 CIRCUIT 2
TRIP LINE FROM BUS 51205 TO BUS 9999 CIRCUIT 2
RUN FOR 20 CYCLES PRINT 240 PLOT 1
CHANGE BUS 9999 CODE TO 1
APPLY FAULT AT BUS 9999
CLOSE LINE FROM BUS 51435 TO BUS 9999 CIRCUIT 2
CLOSE LINE FROM BUS 51205 TO BUS 9999 CIRCUIT 2
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 9999 CIRCUIT 2
TRIP LINE FROM BUS 51205 TO BUS 9999 CIRCUIT 2
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT21PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT21PH.txt
ODEV
2 1 1
PDEV_WI_FLT21PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_f2_cnv.sav
INITIALIZE OUTPUT WI_FLT21PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 9999 ADMITTANCE 275.7 -2056.3 MVA
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 9999 CIRCUIT 2
TRIP LINE FROM BUS 51205 TO BUS 9999 CIRCUIT 2
RUN FOR 20 CYCLES PRINT 240 PLOT 1
CHANGE BUS 9999 CODE TO 1
APPLY FAULT AT BUS 9999 ADMITTANCE 275.7 -2056.3 MVA
CLOSE LINE FROM BUS 51435 TO BUS 9999 CIRCUIT 2
CLOSE LINE FROM BUS 51205 TO BUS 9999 CIRCUIT 2
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 9999 CIRCUIT 2
TRIP LINE FROM BUS 51205 TO BUS 9999 CIRCUIT 2
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT33PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT33PH.txt
ODEV
2 1 1
PDEV_WI_FLT33PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_cnv.sav
INITIALIZE OUTPUT WI_FLT33PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 51195
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51195 TO BUS 99990 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 51195
CLOSE LINE FROM BUS 51195 TO BUS 99990 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51195 TO BUS 99990 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN
END
```

- FLT31PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT31PH.txt
ODEV
2 1 1
PDEV_WI_FLT31PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_cnv.sav
INITIALIZE OUTPUT WI_FLT31PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 51195 ADMITTANCE 268.2 -1758.3 MVA
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51195 TO BUS 99990 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 51195 ADMITTANCE 268.2 -1758.3 MVA
CLOSE LINE FROM BUS 51195 TO BUS 99990 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51195 TO BUS 99990 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT43PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT43PH.txt
ODEV
2 1 1
PDEV_WI_FLT43PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_cnv.sav
INITIALIZE OUTPUT WI_FLT43PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 52073
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52073 TO BUS 99990 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 52073
CLOSE LINE FROM BUS 52073 TO BUS 99990 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52073 TO BUS 99990 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT41PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT41PH.txt
ODEV
2 1 1
PDEV_WI_FLT41PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_cnv.sav
INITIALIZE OUTPUT WI_FLT41PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 52073 ADMITTANCE 35.3 -827.7 MVA
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52073 TO BUS 99990 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 52073 ADMITTANCE 35.3 -827.7 MVA
CLOSE LINE FROM BUS 52073 TO BUS 99990 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 52073 TO BUS 99990 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT53PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT53PH.txt
ODEV
2 1 1
PDEV_WI_FLT53PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_cnv.sav
INITIALIZE OUTPUT WI_FLT53PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 51533
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 51533 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 51533
CLOSE LINE FROM BUS 51435 TO BUS 51533 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 51533 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT51PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT51PH.txt
ODEV
2 1 1
PDEV_WI_FLT51PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND WI_IWF_cnv.sav
INITIALIZE OUTPUT WI_FLT51PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 51533 ADMITTANCE 133.9 -2149.9 MVA
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 51533 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 51533 ADMITTANCE 133.9 -2149.9 MVA
CLOSE LINE FROM BUS 51435 TO BUS 51533 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51435 TO BUS 51533 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT63PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT63PH.txt
ODEV
2 1 1
PDEV_WI_FLT63PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND TEST_WI_cnv.sav
INITIALIZE OUTPUT WI_FLT63PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 51176
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51194 TO BUS 51156 CIRCUIT 1
TRIP LINE FROM BUS 51156 TO BUS 51176 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 51176
CLOSE LINE FROM BUS 51194 TO BUS 51156 CIRCUIT 1
CLOSE LINE FROM BUS 51156 TO BUS 51176 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51194 TO BUS 51156 CIRCUIT 1
TRIP LINE FROM BUS 51156 TO BUS 51176 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

- FLT61PH:

```
PSS
pdev
2 1 1
PDEV_WI_FLT61PH.txt
ODEV
2 1 1
PDEV_WI_FLT61PH.txt
FIN
RECOVER FROM CATAMOUNT.SNP AND TEST_WI_cnv.sav
INITIALIZE OUTPUT WI_FLT61PH.OUT
RUN TO .1 SECONDS PRINT 240 PLOT 1
APPLY FAULT AT BUS 51176 ADMITTANCE 115.8 -970.4 MVA
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51194 TO BUS 51156 CIRCUIT 1
TRIP LINE FROM BUS 51156 TO BUS 51176 CIRCUIT 1
RUN FOR 20 CYCLES PRINT 240 PLOT 1
APPLY FAULT AT BUS 51176 ADMITTANCE 115.8 -970.4 MVA
CLOSE LINE FROM BUS 51194 TO BUS 51156 CIRCUIT 1
CLOSE LINE FROM BUS 51156 TO BUS 51176 CIRCUIT 1
RUN FOR 5 CYCLES PRINT 240 PLOT 1
CLEAR FAULT
TRIP LINE FROM BUS 51194 TO BUS 51156 CIRCUIT 1
TRIP LINE FROM BUS 51156 TO BUS 51176 CIRCUIT 1
RUN TO 5 SECONDS PRINT 240 PLOT 1
RUN TO 10 SECONDS PRINT 240 PLOT 7
PSS
pdev
1
ODEV
7
FIN

END
```

Appendix

B

Plots of Simulation Outputs

B.1 Specified Disturbances with >Omitted Text< Wind Farm Project in-service

B.1.1 WI_IWF.SAV case

- FLT13PH
- FLT11PH
- FLT23PH
- FLT21PH
- FLT33PH
- FLT31PH
- FLT43PH
- FLT41PH
- FLT53PH
- FLT51PH
- FLT63PH
- FLT61PH