System Impact Study
For
[redacted] Corporation

80 MW [redacted] Wind Farm
Quay County, New Mexico
SPP #GEN-2001-036

Xcel Energy Services, Inc.
Transmission Planning

September 19, 2002

Executive Summary

[redacted] pursuant to the Southwest Power Pool (SPP) Open Access Transmission Tariff (OATT) is proposing the interconnection of an 80 MW wind farm, approximately fifteen (15) miles south of Tucumcari, New Mexico. The wind farm will utilize forty-five (45) Vestas V80 wind turbines with a limited output of 1.8 MW each. The wind farm will interconnect to the Xcel Energy, Southwestern Public Service Company (SPS) transmission system at a point on circuit V74. This circuit is an eighty (80) mile long radial 115kV transmission circuit that begins at Curry County Interchange in Clovis, New Mexico and ends at Campbell Street Sub, serving the town of Tucumcari, New Mexico. In addition, this line serves a portion of the 69kV transmission system belonging to Farmers Electric Cooperative.

Dynamic stability analysis was performed by Power Technologies Incorporated (PTI) and indicated that an SVC at the 34.5kV bus location would be of benefit to the wind farm. The need for the SVC comes as a result of the wind farm's inability to ride through transient disturbances, causing the plant to trip off-line for faults located close to the wind farm.

Powerflow analysis indicates that the interconnection of this wind farm will cause new adverse system impacts on the 115kV transmission circuit V74 that serves Tucumcari, New Mexico. The loss of the 230/115kV autotransformer at Roosevelt County and the 115kV transmission line from Roosevelt County to Curry County causes voltage collapse at the interconnection point due to extremely low voltage following one of these contingencies. This low voltage condition is true only if the wind farm stays connected to the SPS transmission system following the contingencies mentioned. In the event the wind farm is disconnected from the SPS transmission system and either contingency is present for an extended period of time, the wind farm cannot reconnect to the system until restoration effects have been completed. To mitigate the violation caused by the contingencies mentioned, a 10MVAR shunt capacitor bank is required at the circuit V74 interconnection point, unless an SVC is installed at the wind farm as indicated by the stability analysis.

The requirements for interconnection consist of building a new 115kV switching station at the interconnection point on circuit V74. The station will have three 115kV line terminals to Tucumcari, Curry County Interchange and the [redacted] Farm. To interconnect the wind farm to the proposed 115kV switching station, a new 115kV transmission line approximately one to two miles in length is required.

The total estimated cost for the interconnection of this wind farm is $2.222 million dollars, which is based on estimates provided by our engineering departments. The cost includes the new 115kV switching station on circuit V74 and two miles of 115kV transmission line from the switching station to the wind farm inclusive of right-of-way.

This study examines system impacts on the local SPS transmission system that are associated with the interconnection of this 80 MW wind farm and does not address any issues that exist in determining the available transmission capacity. In order to determine the available transmission capacity, the customer needs to request transmission service through the Southwest Power Pool (SPP) OASIS.

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1. Introduction

[redacted] has proposed an 80MW wind farm approximately fifteen miles south of Tucumcari, NM. The wind farm will consist of forty-five (45) Vestas V80 wind turbines with a limited output of 1.8MW each. The proposed interconnection point is located on the 115kV transmission circuit that serves the town of Tucumcari, NM at Campbell Street Sub, beginning at Curry County Interchange in Clovis, NM. The wind farm location is approximately one to two miles from this 115kV transmission circuit. This eighty mile long radial circuit also serves a portion of the 69kV Farmers Electric transmission system from a tap point five miles south of Tucumcari.

The primary objective of this study was to identify the single-element contingencies that adversely impact the SPS transmission system due to the interconnection of this 80MW wind farm.

2. Load Flow Preparation

To prepare and simplify the model, fifteen wind turbines were combined into one equivalent unit and connected to one of three 690V collector buses. To reflect maximum plant output, it was assumed that the combined output of each group of fifteen wind turbines was 27MW and three generators were used to simulate the forty-five Vestas V80 wind turbines. Three generator step-up transformers having a rating of 30MVA were used and connected to a common 34.5kV bus. In addition, a 34.5/115kV step-up transformer having a 90MVA rating was incorporated for interconnection of the wind farm via a new 115kV transmission line that connects to the 115kV SPS transmission system. A one-line drawing showing the location of interconnection and the transmission system is shown in Figure 2-1.

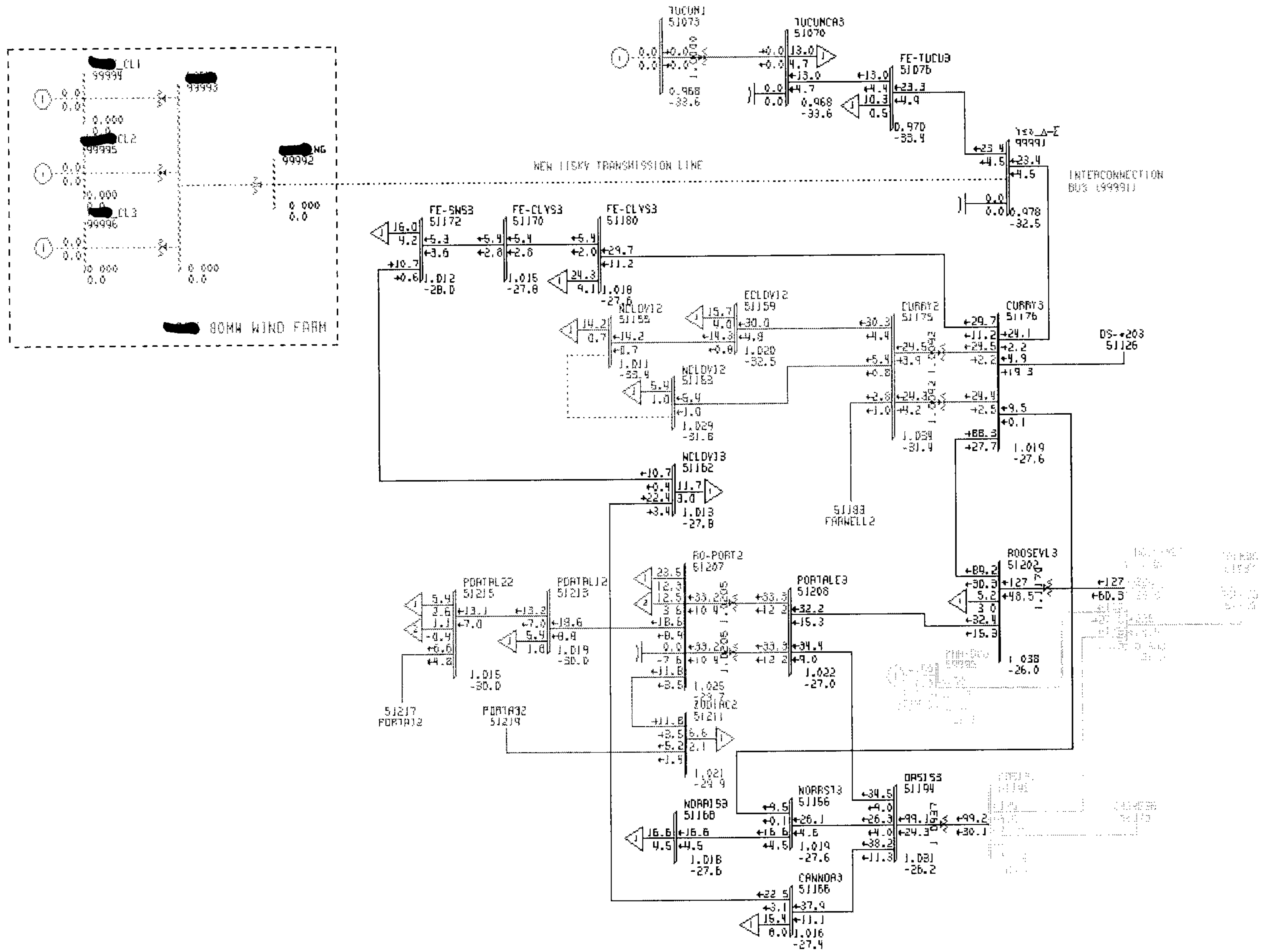


Figure 2-1, Interconnection Point of [redacted] Farm

3. Study Approach

This study uses the 2003 April Minimum and Summer Peak Models as presented to the SPP in January of 2002. The areas of primary concern in this study include Tucumcari and the areas located around Clovis and Portales in New Mexico. Modifications to the model include the addition of the [redacted] Farm and reinforcements that are deemed necessary to mitigate any adverse system impacts.

This power flow study was performed using the Power Technologies, Inc. (PTI) Power System Simulator/Engineering (PSS/E) program and contains a steady-state analysis using AC Contingency Checking (ACCC) with a Fixed Slope Decoupled Newton–Raphson (FDNS) solution. Thermal and voltage limit checks are set in accordance with SPP criteria, which state that for system intact conditions bus voltages must be maintained between 0.95 – 1.05 per-unit of their nominal value. Under single element contingencies, the voltages are allowed to deviate between 0.90 – 1.05 per-unit of their nominal value. Thermal limit checks are comprised of both an A-rating and a B-rating. The A-rating is for system intact conditions, while the B-rating is an emergency rating for single element contingencies.

A comparative study approach was used in determining system impacts caused by the interconnection of the 80MW wind farm. A base case with the [redacted]d Farm not in service was created for the benchmark case. All additional cases have the [redacted]d Farm in service, and single element contingency violations within these cases were compared to the benchmark case.

4. Results

4.1. Non-Convergent Contingencies

Of the different cases studied, two non-convergent contingencies appeared in the 2003 Summer Peak Model with the addition of the [redacted] d Farm. These contingencies include the loss of the 230/115kV autotransformer at Roosevelt County Interchange and the loss of the 115kV line from Roosevelt County Interchange to Curry County Interchange. Examination of these non-convergent contingencies revealed that during the loss of the single elements noted above, voltage collapses at the interconnection point of the [redacted] Farm on circuit V74. In addition, low voltage was also observed on the 115kV bus at Campbell Sub in Tucumcari, New Mexico. Several options were considered to mitigate this problem with one proving as the most cost effective solution. A 10 MVAR shunt capacitor bank placed at the interconnection point on circuit V74 provided the necessary voltage support to prevent voltage collapse in the area.

While other contingencies causing non-convergent results appeared, theses are caused by the transmission systems of network transmission customers served by SPS that are not members of the SPP. These networked systems are modeled within the SPS transmission system and contingencies within these systems cause non-convergent results that, due to the breaker arrangement, are not associated with the SPS transmission system.

4.2. System Intact Conditions

System intact conditions did not indicated adverse impacts on the SPS transmission system. Voltage values below 0.95pu were noticed however only on the 690V generator buses at the wind farm. The voltage values were 0.940pu of nominal.

4.3. Single Element Thermal/Voltage Analysis

The single element thermal and voltage analysis included cases with various proposed reinforcements to mitigate the violations. The interconnection of the wind farm caused non-convergent results for the loss of the 230/115kV autotransformer at Roosevelt County Interchange. In addition, the loss of the 115kV transmission line from Roosevelt County to Curry County also resulted in a non-convergent condition as noted in section 4.1. The options considered for mitigation of these contingencies included capacitor bank installations on the 115kV bus at Tucumcari and on the 115kV bus at the interconnection point on the 115kV switching station. In addition, two distinct cases involving the installation of a 10MVAR SVC were considered. The first was at the wind farm 34.5kV collector bus and the second was located at the new 115kV switching station.

The most cost effective reinforcement, as a solution to the non-convergent contingencies mentioned, is the addition of the 10MVAR bank on the 115kV bus at the new switching station. The addition of this bank will allow the wind farm to reconnect to the SPS transmission system if a prolonged outage is anticipated following the loss of either the 230/115kV Roosevelt County autotransformer or the 115kV line from Roosevelt County to Curry County. This option however, would not be required if [redacted] decides that the installation of an SVC would be necessary at the wind farm as indicated by the dynamic stability study.

5. Interconnection Requirements

The minimal requirements for the interconnection of the wind farm are the construction of a new 115kV switching station approximately fifteen miles south of Tucumcari, New Mexico on circuit V74. In addition, one to two miles of 115kV transmission line connecting the switching station to the wind farm will be required. The requirements for interconnection are illustrated in Figure 9-1.

6. Conclusions

Based on the results of this study, the interconnection of the 80MW wind farm causes adverse impacts on the SPS transmission system in New Mexico. To mitigate these impacts two possible options exist. The first is the addition of 10MVAR shunt capacitor bank at the new 115kV switching station and the second is the addition of the SVC as stated in the Section 4.

7. Estimated Costs

The table below lists the cost associated with the interconnection of the 80MW wind farm and the infrastructure cost due to the addition of the 10MVAR shunt capacitor bank. In addition, the infrastructure modifications include the replacement of a motor operated switch on the 115kV bus at Campbell Street Sub with a 115kV circuit switcher. This infrastructure work is not required for interconnection and is not part of the interconnection cost.

Table 7-1, Wind Farm Interconnection Costs

Estimated Costs	Cost
New 115kV Switching Station[1]	$ 1,882,258
New 115kV Transmission Line[2]	$ 340,000
Total	***$ 2,222,258***

Table 7-2, Wind Farm Infrastructure Costs

Estimated Costs	Cost
10MVAR Shunt Capacitor Bank and associated 115kV Breaker	$ 545,000
Circuit Switcher at Tucumcari (To replace ground trip scheme)	$ 174,906
Total	***$ 719,906***

[1] The cost includes three (3) 115kV breaker line terminals, one (1) 115kV transfer breaker and associated equipment (control house, relays, labor, etc.)

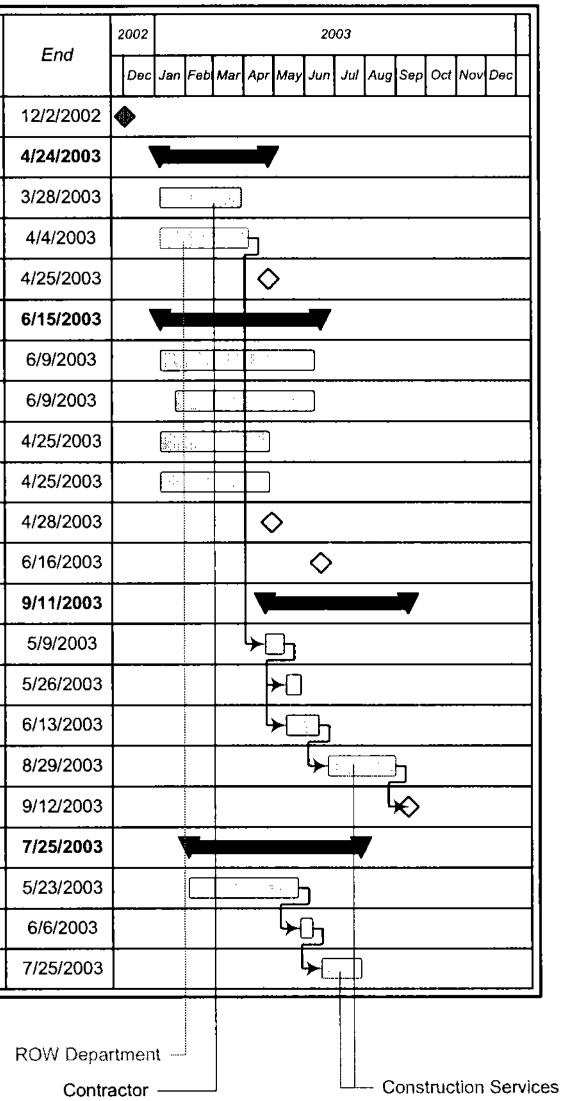
[2] Transmission line from the Wind Farm to the new switching station. The cost is estimated for two (2) miles of 115kV transmission line pending exact location of site. Cost to be adjusted accordingly.

8. Construction Schedule

In order to complete all construction for this project in a timely manner; the estimated construction schedule is shown below and is contingent on the date an Interconnection Agreement is signed. If the agreement is not signed and construction funds have not been provided or approved prior to the date indicated, a new construction schedule would have to be drafted to accommodate any additional projects awaiting construction.

York Greenpower Corporation Wind Farm Project Construction Schedule

ID	Task Name	Start	End
1	Interconnection Agreement Signed	12/2/2002	12/2/2002
2	**Aquire Sub. Site & ROW**	**1/6/2003**	**4/24/2003**
3	Survey Selected Routes	1/6/2003	3/28/2003
4	Aquire Substation Land	1/6/2003	4/4/2003
5	ROW Completion	4/25/2003	4/25/2003
6	**Substation Electrical Design**	**1/6/2003**	**6/15/2003**
7	Order Long Lead Time Materials/Delivery	1/6/2003	6/9/2003
8	Material Order/Delivery/20 weeks & less	1/21/2003	6/9/2003
9	Complete Construction Design	1/6/2003	4/25/2003
10	Complete Electrical Design/Tabs & Schematics	1/6/2003	4/25/2003
11	Issue Engineering Design Package	4/28/2003	4/28/2003
12	Issue Material	6/16/2003	6/16/2003
13	**Substation Construction**	**4/21/2003**	**9/11/2003**
14	Substation Site Work	4/21/2003	5/9/2003
15	Substation Fence Work	5/12/2003	5/26/2003
16	Substation Concrete Foundations	5/12/2003	6/13/2003
17	Substation Construction/Completion	6/23/2003	8/29/2003
18	Commission Substation	9/12/2003	9/12/2003
19	**Transmission Line Design & Materials**	**2/3/2003**	**7/25/2003**
20	Material Order & Delivery	2/3/2003	5/23/2003
21	Foundation Installation	5/26/2003	6/6/2003
22	Transmission Line Construction/Completion	6/16/2003	7/25/2003



9. Drawings

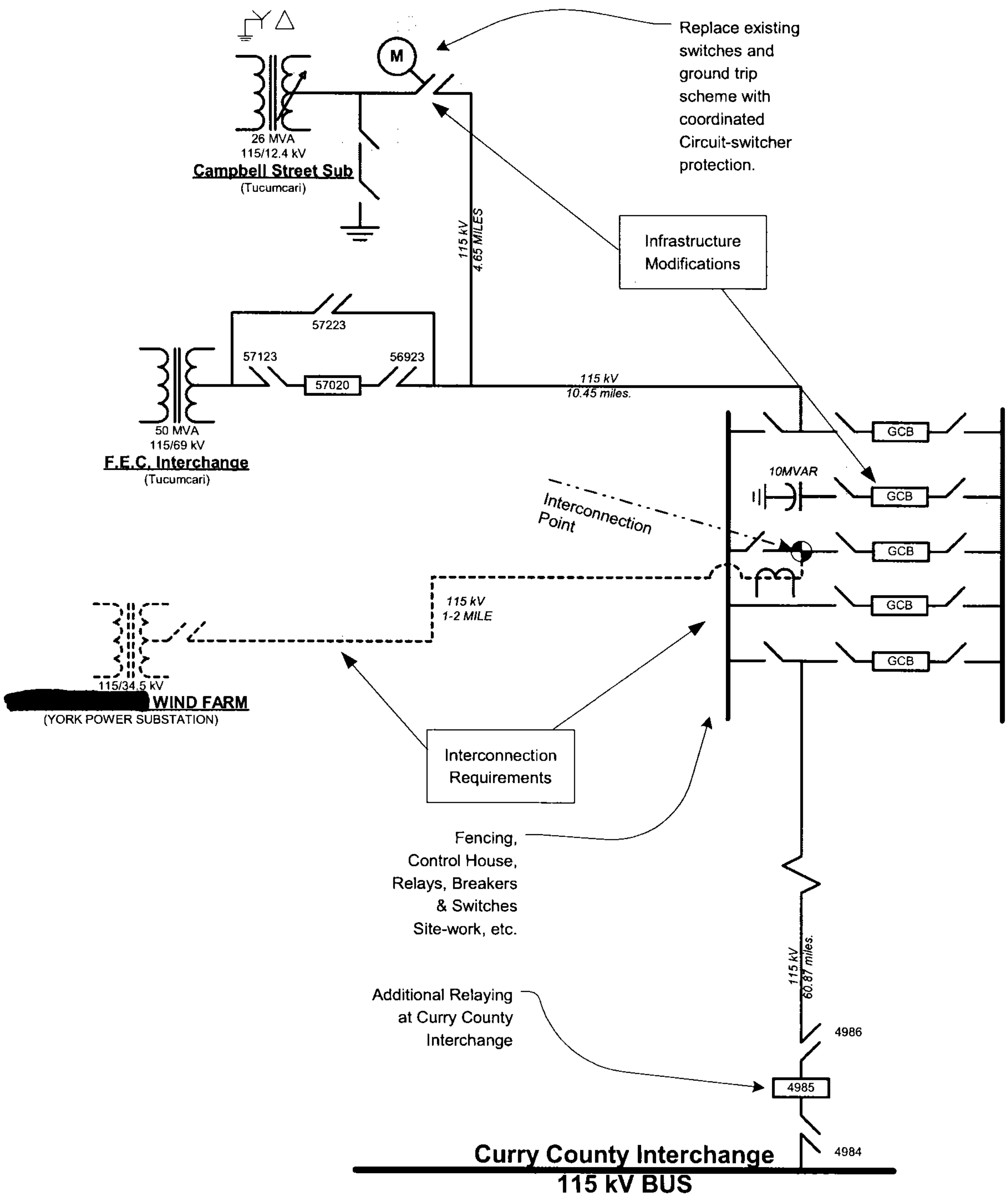


Figure 9-1, One-line Diagram of [redacted] Wind Farm Interconnection.

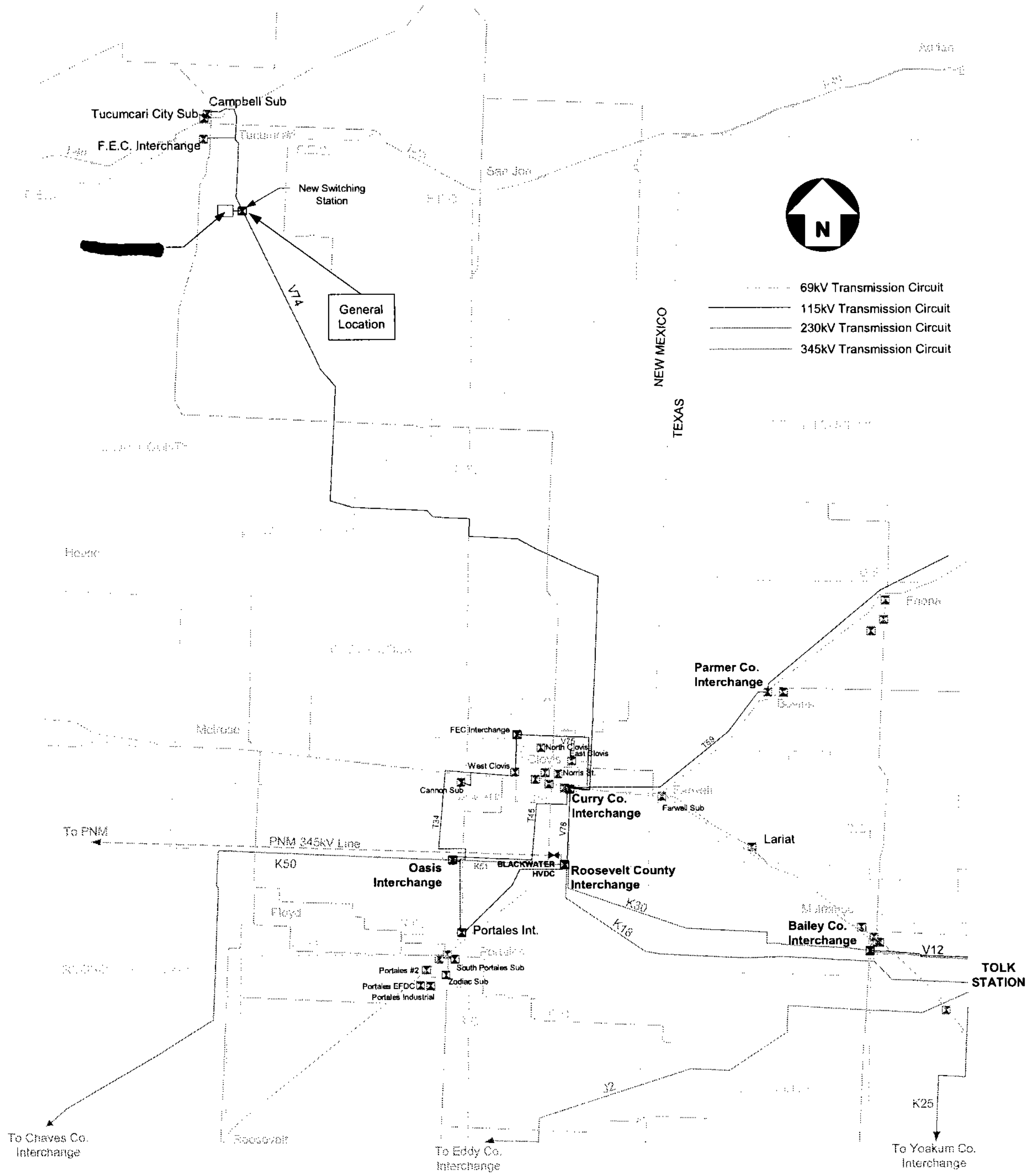


Figure 9-2, Local Transmission System

10. Appendix A: Base Case Contingency Results

10.1. Base Case Contingency Results for 2003 April Minimum

10.2. Base Case Contingency Results for 2003 Summer Peak

11. Appendix B: 2003 April Minimum Contingency Results

Table 11-1, Description of the 2003 April Minimum Cases

Case Name[3]	Description of modifications as compared to Base Case.
03AP-YW-001.SAV	[redacted] Farm in service with no other system improvements.
03AP-YW-001A.SAV	[redacted] Farm in service with 5 MVAR capacitor bank on the 115kV bus at Tucumcari.

[3] The case name is located in the second line of the tile.

12. Appendix C: 2003 Summer Peak Contingency Results

Table 12-1, Description of the 2003 Summer Peak Cases

Case Name[4]	Description of modifications as compared to Base Case.
03SP-YW-002.SAV	[redacted] Farm in service with no other system modifications.
03SP-YW-002A.SAV	[redacted] Farm in service with 5 MVAR capacitor bank on the 115kV bus Tucumcari.
03SP-YW-003A.SAV	[redacted] Farm in service with 5 MVAR capacitor bank on the 115kV bus at the interconnection point on circuit V74.
03SP-YW-003B.SAV	[redacted] Farm in service with a 10 MVAR SVC on the 115kV bus at the wind farm.
03SP-YW-003C.SAV	[redacted] Farm in service with 10 MVAR capacitor bank on the 115kV bus at the interconnection point on circuit V74.
03SP-YW-003D.SAV	[redacted] Farm in service with a 10 MVAR SVC on the 34.5kV collector bus at the wind farm.

[4] The case name is located in the second line of the tile.

13. Dynamic Stability Results

Final Report No. R25-02

Stability Studies of the Proposed [redacted] Farm

Prepared for Xcel Energy

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August 2, 2002

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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 [redacted] Farm near Tucumcari, New Mexico. This report summarizes results of the study.

The proposed plant is located between Curry County Interchange and F.E.C. Interchange in Xcel Energy's transmission system. This wind farm has a nominal output of 81 MW and is interconnected to Xcel Energy's 115 kV network. The wind farm is using Vestas 80 wind turbines rated 1.8 MW each.

The setup for load flow and dynamic simulation was based on the [redacted] study, which was conducted for Xcel Energy in March 2002. A load flow base case with the [redacted] Farm added was created following Xcel Energy's instructions. OPT1 case (without the Potter-Frio line) in the [redacted] study was used. DC lines PNM and EPE are both modeled. The dynamic model for Vestas V80 wind turbines was developed based on manufacturer's data and PTI's experience in wind farm modeling.

A set of stability studies was performed to evaluate the wind farm using PTI's power system simulation program PSS/E, revision 28.

Section

2

Data Preparation

The geographical location of the plant is indicated in Figure 2-1.

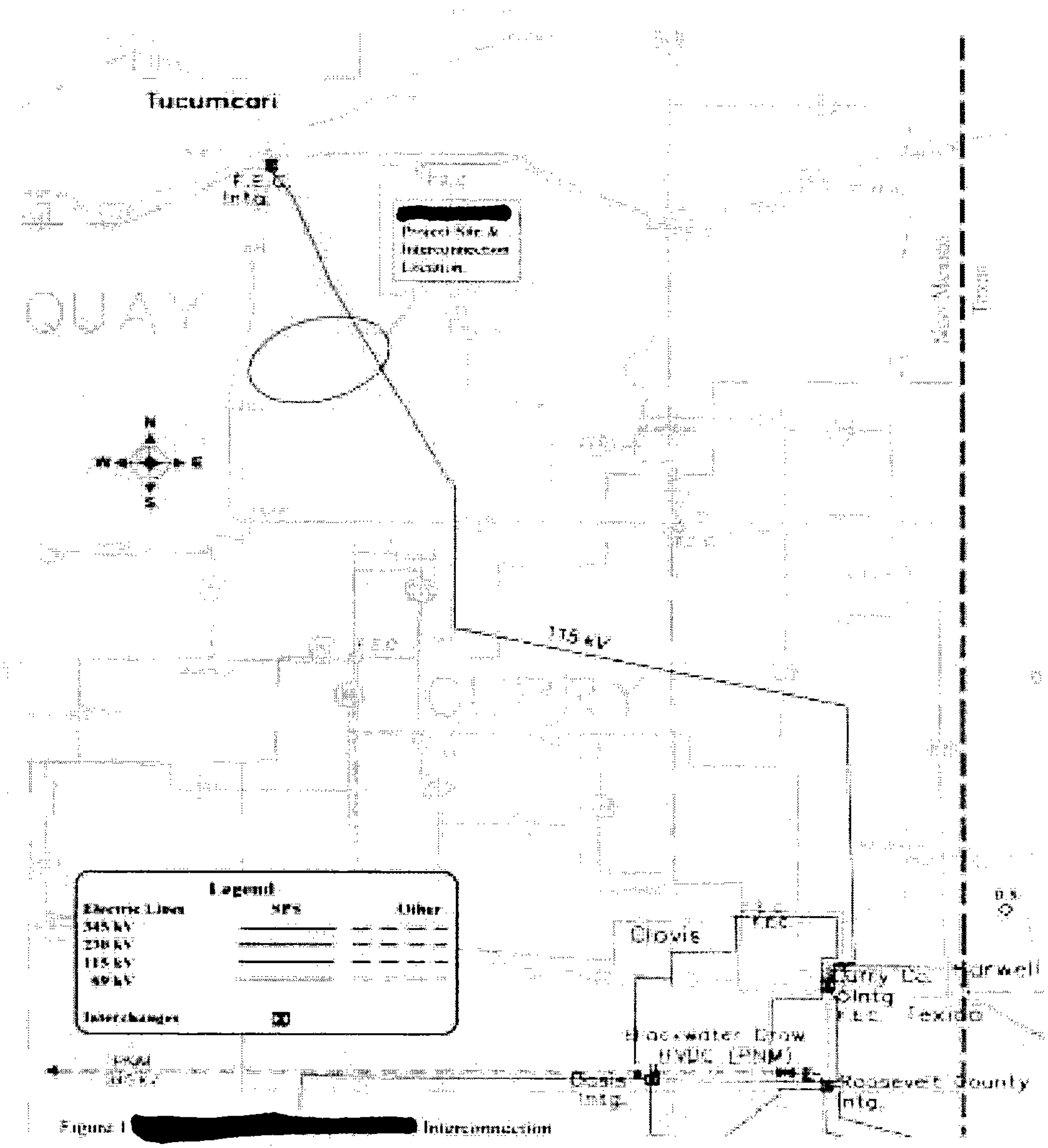


Figure 2-1: geographical location of the [redacted] Farm

2.1 Load Flow Data

OPT1 case (without the Potter-Frio line) in the [redacted] study was used to develop the load flow case for the [redacted]Farm study. The following updates are included, following Xcel Energy's instructions:

- [redacted] Plant added, Pgen = 81 MW
- [redacted] off-line (577 MW)
- Xcel's generation rescheduled:
  51421 Plant X1 at 45 MW
  51422 Plant X2 at 97 MW
  52214 Cunn 4 at 105 MW
  52215 Cunn 3 at 105 MW
  change 52212 Cunn 2 to 160 MW (20 MW increase)
  change 51441 Tolk 1 to 521 MW (10 MW increase)
  change 51442 Tolk 2 to 522 MW (10 MW increase)

The interconnection point of [redacted] Farm is 1.75 miles from the tap on the 115 kV line between Tucumcari (bus 51076) and Curry (bus 51176) substations. The tap (bus 99991) is located 10.45 miles from Tucumcari and 60.87 miles from Curry. The plant (bus 99992) is connected by a 1.75-mile line from the tap. The line was simulated by apportioning the parameters of the 115 kV line between Tucumcri and Curry.

The output of the plant is 81 MW, comprised of forty-five (45) Vestas V80 units. The base voltage of wind turbine generators is 690 V. A generator-step-up (GSU) transformer of 1.85 MVA connects each unit to the high side of 34.5 kV. The maximum power output of a V80 is 1.8 MW, while the actual power output depends on the wind. In order to simplify the load flow representation, and since interconnection details of specific units is presently unavailable, 15 units are aggregated to be one equivalent unit at one 690-Volt collector bus. In this study, we assume all the units are at their maximum output. Therefore, three 690 V collector generators (bus 99994, 99995, and 99996) each have a generator of 27 MW (1.8 MW * 15 units = 27 MW) connected to the 34.5 kV bus (bus 99993) through a 27.75 MVA step-up transformer (1.85 MVA* 15 units = 27.75 MVA). The 34.5 kV bus is connected through a single 48/64/80 MVA transformer to the 115 kV substation (bus 99992).

Each aggregated generator is simulated with active power output of 27 MW (maximum output). Generator rating is 30 MVA. The power factor of the wind turbines was advised by Vestas to be between 1.0 to 0.99 overexcited. Power factor is controlled to be 1.0 at the generator terminal in the load flow case.

The one-line diagram of the network near the [redacted] farm is included in Figure 2-2. Color coding was used on bus base kV level: blue is for 300 kV and above, dark green is between 300 and 200 kV, red is between 200 and 100 kV, and black is below 100 kV. Bus voltages near the [redacted] plant are listed in Table 2-1.

Table 2-1: bus voltages near the [redacted] plant

Bus Name	[redacted]	[redacted]CL1, CL2 and CL3	[redacted]WG	[redacted] tap	Curry	FE-Tucu3	Tucumcari
Bus No.	99993	99994, 99995, 99996	99992	99991	51176	51076	51070
Base KV	34.5	0.69	115	115	115	115	115
Voltage (pu)	0.889	0.885	0.914	0.913	0.980	0.905	0.902

Due to the low voltages in the neighboring network, voltage support is necessary. Capacitor placement was thus investigated.

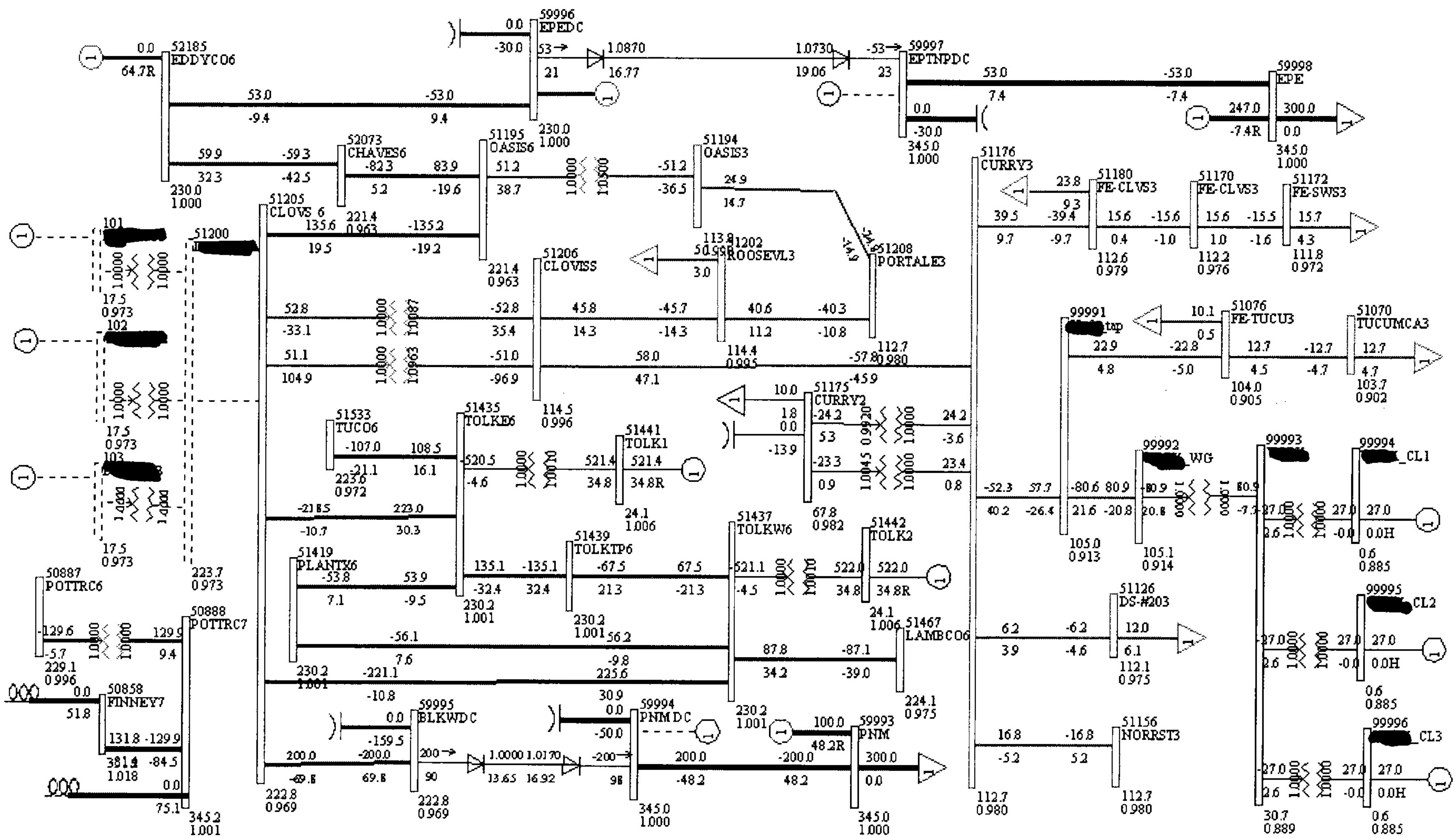


Figure 2-2: one-line diagram of the network neighboring the York plant without capacitors at Tucumcari and York

2.2 Capacitor Placement

Two capacitor locations were considered: Tucumcari 115 kV substation (bus 51070) and [redacted] 34.5 kV substation (bus 99993). A possible capacitor addition of 5 MVAR at Tucumcari substation was proposed by Xcel Energy in order to maintain the voltage on the radial line. Analysis was performed to determine the size of the capacitor that is needed to maintain the voltage at [redacted] 34.5 kV substation to be 1.0 pu under different levels of plant output, with and without the capacitor at Tucumcari. Five levels of plant output at a peak load condition were studied:

- 100%: plant output is 81 MW; bus voltages are summarized in Table 2-2
- 75%: plant output is 60 MW; bus voltages are summarized in Table 2-3
- 50%: plant output is 40.5 MW; bus voltages are summarized in Table 2-4
- 25%: plant output is 20 MW; bus voltages are summarized in Table 2-5
- 0%: no plant output; bus voltages are summarized in Table 2-6

Note that the load pocket at Tucumcari has a total of 22 MW. When the plant output is lower than 22 MW, power is needed from the network to supply the load. Therefore, the flow direction changes on the 115 kV line from Curry (bus 51176) to [redacted] tap (bus 99991) and this impacts how much capacitance is needed at either location.

Table 2-2: comparison of bus voltages with different sizes of switched capacitor at 100% plant output

100% output	Switched cap (MVAR)		Voltage (pu)						
Location of the cap	Tucumcari	[redacted]	[redacted] 34.5 kV	[redacted] generator	[redacted] 115 kV	[redacted] tap	Curry	FE-Tucu3	Tucumcari
No SW	0	0	0.889	0.885	0.914	0.913	0.980	0.905	0.902
[redacted]	0	10.1	1.000	0.997	1.002	1.000	0.994	0.992	0.990
[redacted] and Tucumcari	5.0	6.3	1.000	0.997	1.008	1.006	0.995	1.002	1.001

Table 2-3: comparison of bus voltages with different sizes of switched capacitor at 75% plant output

75% output	Switched cap (MVAR)		Voltage (pu)						
Location of the cap	Tucumcari	[redacted]	[redacted] 34.5 kV	[redacted] generator	[redacted] 115 kV	[redacted] tap	Curry	FE-Tucu3	Tucumcari
No SW	0	0	0.967	0.965	0.977	0.976	0.993	0.969	0.966
[redacted]	0	4.3	1.000	0.998	1.003	1.001	0.997	0.994	0.992
[redacted] and Tucumcari	5.0	0.5	1.000	0.998	1.009	1.008	0.998	0.997	0.992

Table 2-4: comparison of bus voltages with different sizes of switched capacitor at 50% plant output

50% output	Switched cap (MVAR)		Voltage (pu)						
Location of the cap	Tucumcari	[redacted]	[redacted] 34.5 kV	[redacted] generator	[redacted] 115 kV	[redacted] tap	Curry	FE-Tucu3	Tucumcari
No SW	0	0	0.986	0.985	0.990	0.989	0.997	0.982	0.979
[redacted]	0	2.1	1.000	0.999	1.001	1.000	0.998	0.995	0.990
[redacted] and Tucumcari	5.0	0	1.011	1.011	1.015	1.015	1.001	1.010	1.009

Table 2-5: comparison of bus voltages with different sizes of switched capacitor at 25% plant output

25% output	Switched cap (MVAR)		Voltage (pu)						
Location of the cap	Tucumcari	[redacted]	[redacted] 34.5 kV	[redacted] generator	[redacted] 115 kV	[redacted] tap	Curry	FE-Tucu3	Tucumcari
No SW	0	0	0.978	0.978	0.979	0.979	0.996	0.971	0.969
[redacted]	0	3.3	1.000	1.000	0.996	0.995	0.998	0.987	0.985
[redacted] and Tucumcari	5.0	0	1.002	1.002	1.003	1.003	0.999	0.998	0.997

Table 2-6: comparison of bus voltages with different sizes of switched capacitor at 0% plant output

0% output	Switched cap (MVAR)		Voltage (pu)						
Location of the cap	Tucumcari	[redacted]	York 34.5 kV	[redacted] generator	[redacted] 115 kV	[redacted] tap	Curry	FE-Tucu3	Tucumcari
No SW	0	0	0.949	0.949	0.949	0.949	0.990	0.941	0.938
[redacted]	0	8.0	1.000	1.000	0.988	0.987	0.996	0.979	0.977
[redacted] and Tucumcari	5.0	4.3	1.000	1.000	0.993	0.993	0.997	0.988	0.987

Based on the results above, the following capacitor banks were added into the load flow case to provide voltage support with plant output at 100%:

- one 5 MVAR capacitor bank at the Tucumcari 115 kV bus
- two 3 MVAR capacitor banks at the York 34.5 kV bus, in-service when the plant is on-line at full power output. Two banks allow the capacitance to be adjusted to meet the requirements at different plant outputs.

Note that the intent of this analysis was not to optimize the shunt requirements but to get a reasonable starting point for the stability studies.

This scenario should be able to maintain satisfactory voltages in the nearby area during peak load with plant output of 100%. It is recommended that further studies address different load levels to determine the best coordination between capacitor allocation scenarios and load conditions.

Figure 2-3 is the one-line diagram with the capacitors added to the load flow case.

Table 2-7 summarizes the bus voltages with the plant output of 50% and both capacitors in-service. Bus voltages are high indicating the need for switching capability and control.

Table 2-7: comparison of bus voltages with switched capacitors in-service at 50% plant output

50% output	Switched cap (MVAR)		Voltage (pu)						
Location of the cap	Tucumcari	[redacted]	[redacted] 34.5 kV	[redacted]generator	[redacted] 115 kV	[redacted] tap	Curry	FE-Tucu3	Tucumcari
[redacted]and Tucumcari	5.0	6.0	1.055	1.054	1.049	1.047	1.006	1.043	1.043

100% output, SW=5 MVAR

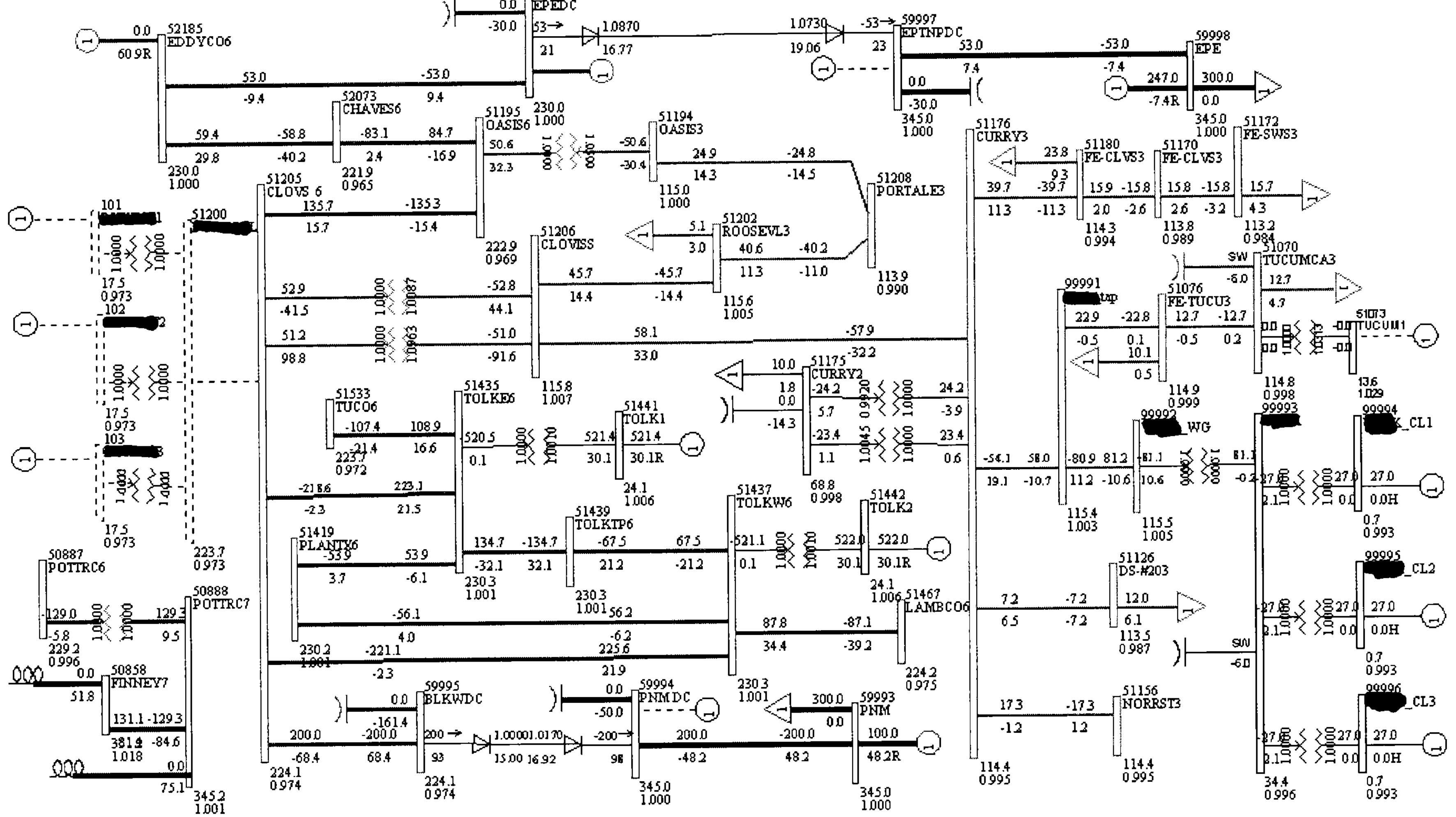


Figure 2-3: one-line diagram of the network neighboring the York plant with capacitors at Tucumcari and York

2.3 Dynamics Data

A dynamic model of the wind turbine generators was developed to represent the Vestas V80 turbines. One should note that this is an approximate model and incorporates only those components that are known to influence system performance in the timeframe of interest. It is not meant for in-depth studies of wind turbine generator dynamics or to analyze the dynamics of the power factor correction scheme.

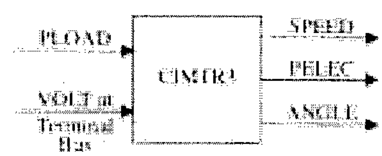
2.3.1 Generator model

Wound-rotor induction generators are used by the Vestas V80 wind turbines. The PSS/E model CIMTR3 is used to represent the generator. The following is the PSS/E model data:

CIMTR3

Induction Generator Model

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 ICON #_____ M.
The machine MVA is _____ for each of _____ units = _____ MBASE.



CONs	#	Value	Description
J			T' (sec) (>0)
J+1			T'' (sec) (≥0)*
J+2			Inertia, H
J+3			X
J+4			X'
J+5			X''*
J+6			X_l
J+7			E_1 (≥0)
J+8			$S(E_1)$
J+9			E_2
J+10			$S(E_2)$
J+11		0.	Switch
J+12			SYN-POW, mechanical power at synchronous speed (>0). Used only to start machine, otherwise ignored.

*If T'' = 0 or X'' = 0, machine is assumed to be single cage and ZSORCE should be set equal to X'

STATEs	#	Description
K		E'_q
K+1		E'_d
K+2		E''_q
K+3		E''_d
K+4		Δ speed (pu)
K+5		Angle deviation

VARs	#	Description
L		Admittance of initial condition Mvar difference
L+1		Motor Q
L+2		T_{elec}

ICON	#	Description
M		Memory

X, X', X'', X_l, and H are in pu, machine MVA base

IBUS, 'CIMTR3', I, T', T'', H, X, X', X'', X_l, E_1, $S(E_1)$, E_2, $S(E_2)$, 0., SYN-POW/

2.3.2 Induction generator parameters

2.3.2.1 Moment of Inertia

The following equation can be used to compute the moment of inertia of the whole drivetrain:

$$H = \frac{1.37 \cdot GD^2 \cdot RPM^2 \cdot 10^{-6}}{kVA}$$

where

H	= Inertia Constant in kW-sec/kVA
GD^2	= Moment of inertia in kg-m^2 including turbine blades
RPM	= Rotational speed of mass in revolutions/minute
kVA	= Base kVA
Rated speed	= Synchronous speed = 1 pu = 1800 rpm

For the inertia at the blade:
Moment of inertia = 4,260,000 kg-m^2
Gear Ratio = 110:1
Moment of inertia of the rotor = 4,260,000/$(110)^2$ kg-m^2

$$H = \frac{1.37 \times (4260000/110^2) \times 1800^2 \times 10^{-6}}{1998.2} = 0.7821$$

For the inertia of the generator:
Moment of inertia of the generator = 65 kg-m^2

$$H = \frac{1.37 \times 65 \times 1800^2 \times 10^{-6}}{1998.2} = 0.1444$$

Total moment of inertia of the wind turbine = 0.7821 + 0.1444 = 0.9265

2.3.2.2 Saturation factors

Two factors are required to represent the saturation, S(1.0) and S(1.2), in the generator model. The following data was retrieved from the Vestas data sheet:

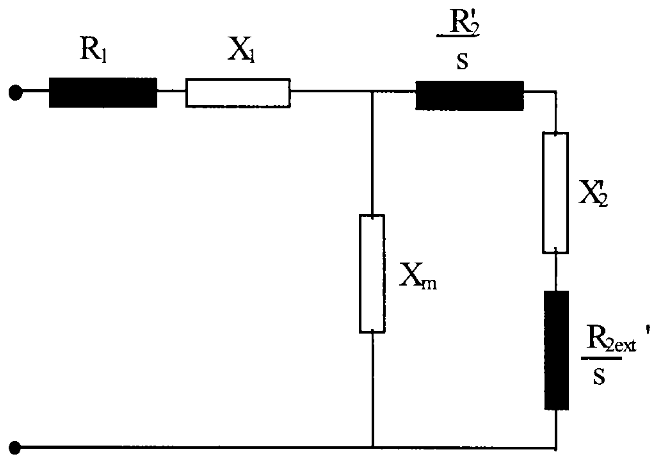
Voltage (V)	0	69	138	207	276	345	414	483	552	621	690	759	828
Voltage (pu)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
Current (A)	0	19	38	57	76	95	114	133	162	195	240	305	425

$$S(1.0) = \frac{240 - 190 * 1.0}{190 * 1.0} = 0.2632$$

$$S(1.2) = \frac{425 - 190 * 1.2}{190 * 1.2} = 0.8640$$

2.3.2.3 Generator parameters

The following parameters were given in manufacturer's data sheet.



Parameter	Ohm	Per unit
Stator resistance, R_l	0.001164	0.0049
Stator leakage inductance, X_l	0.03	0.1262
Magnetizing inductance, X_m	1.628245	6.85
Rotor resistance, R'_2	0.001052	0.0044
Rotor leakage inductance, X_2	0.04305	0.1811
Rotor resistance external at 1% slip, R'_{2ext}	0.00157	0.0066
Rotor resistance external at 10% slip, R'_{2ext}	0.02512	0.1060

External rotor resistance at rated 4% slip was not given in the data sheet. The PSS/E utility IMD was used to calculate the approximate resistance at 4%. Using the data given above at 1% and 10% to verify the calculation, external resistance at the rated 4% slip was estimated to be 0.008 Ohm. At 4% slip, $R_2 + R_{2ext}$ is estimated to be about 0.0385 pu.

The following equations are used to convert the parameters given in manufacturer's data sheet into equivalent reactances and time-constants that can be used by model CIMTR3. These equations were obtained from Section 19.2.4.4 of the PSS/E Program Application Guide, v. II. All reactances are expressed in per-unit and time constants are expressed in seconds.

$$X_\ell = X_l = 0.1262 \text{ pu}$$
$$X = X_l + X_m = 6.9762 \text{ pu}$$

$$X^{'} = X_1 + \frac{1}{\left(\frac{1}{X_m} + \frac{1}{X_2^{'}}\right)} = Zsorce = 0.1262 + \frac{1}{\frac{1}{6.85} + \frac{1}{0.1811}} = 0.303 \text{ pu}$$

$$X^{''} = 0$$

$$T_0^{'} = \frac{X_m + X_2^{'}}{377 * \left(R_2^{'} + R_{2ext}^{'}\right)} = \frac{6.85 + 0.1811}{377 * 0.0385} = 0.4844 \quad \text{where } 377 \approx 2*\pi*60 \text{ rad/sec}$$

$$T^{''} = 0$$

2.3.3 Undervoltage/Overvoltage protection scheme: VTGTRP and VBDCN

The following voltage parameters for V80 were retrieved from the Vestas data sheet:

	Parameter value (%)	Parameter value (S)	Action
High voltage	+ 10%	60	Disconnect turbine (pause)
High voltage	+ 11%	0.08	Disconnect power factor correction
Extreme high voltage	+ 13.5%	0.2	Disconnect turbine (emergency)
Extreme extreme high voltage	+ 20%	0.08	Disconnect turbine
Low voltage	- 6%	60	Disconnect turbine (pause)
Extreme low voltage	-15%	0.4	Disconnect turbine (emergency)
Extreme extreme low voltage	-25%	0.08	Disconnect turbine (emergency)

Two user-written models were introduced to perform the undervoltage/overvoltage protection scheme. VTGTRP is an undervoltage/overvoltage generator-tripping relay, and VBDCN is an undervoltage/overvoltage bus-tripping relay.

- VTGTRP Model :Undervoltage/Overvoltage generator tripping relay

  Model VTGTRP is a special user-written relay model that represents the under- and over-voltage protection developed for wind turbine units. This model is assumed to be located at the generator bus to which the WTG equivalent is connected and continuously monitors the voltage on that bus or a remote bus specified by the user. It trips the WTG equivalent for under- and overvoltage conditions on the specific bus.

  The relay timer is started during undervoltage conditions (i.e., when voltage is less than or equal to the undervoltage pickup threshold) or overvoltage conditions (i.e., when voltage is greater than or equal to the overvoltage pickup threshold). The relay resets instantaneously if the voltage is within the two pickup thresholds. A trip signal is sent to the circuit breaker if the timer reaches its setting; voltage must have remained in an undervoltage condition (or overvoltage condition) for the entire pickup time for generator tripping to occur. Generator tripping is delayed by the circuit breaker time. See Figure 2-4 and Figure 2-5.

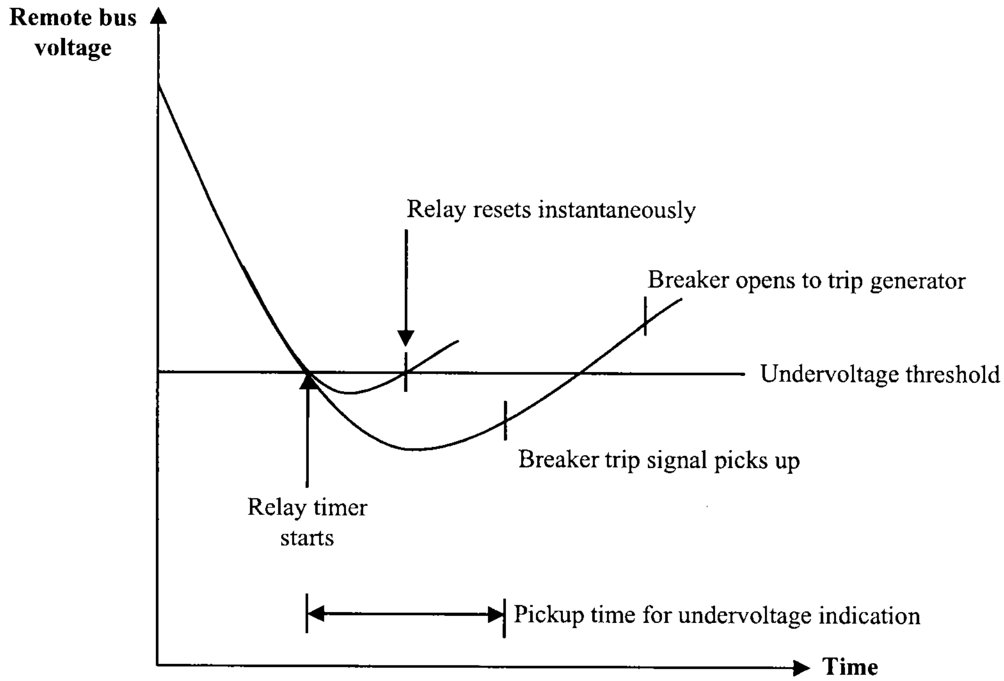


Figure 2-4: Undervoltage Detection and Generator Tripping by Model VTGTRP

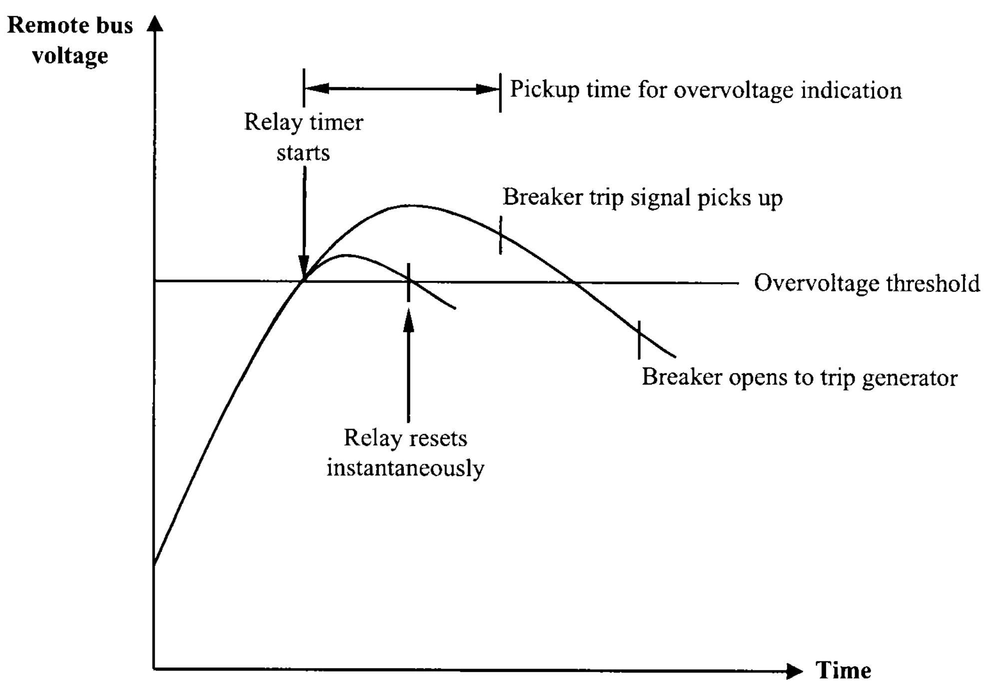


Figure 2-5: Overvoltage Detection and Generator Tripping by Model VTGTRP

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

Table 2-8: relay setup

Variable	Description	Relay 1 Settings	Relay 2 Settings
VLOW	VL, lower voltage threshold (pu)	0.75	0.85
VUP	VU, upper voltage threshold (pu)	5.0	5.0
PICKUP_TIME	TP, relay pickup time (sec)	0.08	0.4
BREAKER_TIME	TB, breaker time (sec)	0.083	0.083

The breaker_time was not available and was assumed to be 5 cycles (0.083 seconds). The duration of the simulations was typically 10 to 20 seconds, and thus overvoltage / undervoltage protection which takes longer than the simulation duration was not modeled. Overvoltage conditions were monitored, but not modeled explicitly.

- VBDCN Model :Undervoltage/Overvoltage bus tripping relay

  A capacitor bank is assumed to be installed at the 34.5 kV bus of [redacted] plant to maintain the voltage. If the generators are tripped due to disturbances, the capacitor should be taken off-line as well. Also, if the wind farm puts out less than 100% output, the capacitor bank may need to be switched off to prevent high voltage at the 34.5 kV bus. The status (in-service/out-of-service) and the size of the capacitor should coordinate with plant output and generator status. A more sophisticated method to coordinate between the capacitor bank and the plant may need to be developed. At this point, the user-written model VBDCN is introduced to perform part of this task. This model is similar to VTGTRP, but instead of tripping the generator, the user-written model will trip the bus when experiencing overvoltage or undervoltage for a certain period of time. This model uses the same parameters as the model VTGTRP in Table 2-8, that is, the same high/low voltage threshold and same relay pickup time. By doing so, the capacitor and the bus would be tripped at the same time as generators are tripped, assuming the 34.5 kV voltage is approximately the same as the generator voltages.

VTGTRP

Undervoltage/Overvoltage Generator Tripping Relay Model

This model incorporates code based on information provided by Enron Wind Corp (EWC) and was developed under the sponsorship of EWC.

CALL VTGTRP(I, J, 0, K) from CONET
This model uses ICONs starting with # _________ I,
and CONs starting with # _________ J,
and VAR # _________ K.

ICONs	#	Value	Description
I			IV, bus number where voltage is monitored
I+1			GB, bus number of generator bus where relay is located
I+2		0	Delay flag
I+3		0	Time-out flag
I+4		0	Timer status

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

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)

VAR	#	Description
K		Timer memory

The generator where the relay is placed is assumed to have a generator ID of '1 '

0, 'USRMDL', 0, 'VTGTRP', 0, 2, 5, 4, 0, 1, IV, GB, 0, 0, 0, VL, VU, TP, TB/

VBDCN

Undervoltage/Overvoltage Bus Tripping Relay Model

CALL VBDCN(I, J, O, K) from CONET

This model uses ICONs starting with # ________ I,

and CONs starting with # ________ J,

and VAR # ________ K.

ICONs	#	Value	Description
I			IV, bus number where voltage is monitored
I+1		0	Delay flag
I+2		0	Time-out flag
I+3		0	Timer status

Note: ICONs I+1 through I+3 are control flags that are not to be changed by the user

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)

VAR	#	Description
K		Timer memory

0, 'USRMDL', 0, 'VBDCN', 0, 2, 4, 4, 0, 1, IV, 0, 0, 0, VL, VU, TP, TB/

2.3.4 Modification of the generator model at bus 33403

The generators at bus 33403 had the following parameters in the original load flow and snapshot:

```
PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E       TUE, APR 30 2002   13:53
 02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
 2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

 PLANT MODELS

 REPORT FOR ALL MODELS                             BUS 33403 [PLANT   D69.000] MODELS


 ** GENCLS **  BUS X-- NAME --X BASEKV MC     C O N S      S T A T E S
             33403      PLANT  D 69.000 5   26097-26098    11739-11740

    MBASE      Z S O R C E           X T R A N        GENTAP      H       DAMP
     17.6  0.00000+J 0.18600  0.26230+J 4.65060  5.00000     3.00    3.000


 ** GENCLS **  BUS X-- NAME --X BASEKV MC     C O N S      S T A T E S
             33403      PLANT  D 69.000 6   26099-26100    11741-11742

    MBASE      Z S O R C E           X T R A N        GENTAP      H       DAMP
     15.7  0.00000+J 0.25000  0.40210+J 7.13090  5.00000     3.00    3.000


 ** GENCLS **  BUS X-- NAME --X BASEKV MC     C O N S      S T A T E S
             33403      PLANT  D 69.000 7   26101-26102    11743-11744

    MBASE      Z S O R C E           X T R A N        GENTAP      H       DAMP
     23.5  0.00000+J 0.16800  0.19120+J 3.39020  5.00000     3.00    3.000


 ** GENCLS **  BUS X-- NAME --X BASEKV MC     C O N S      S T A T E S
             33403      PLANT  D 69.000 8   26103-26104    11745-11746

    MBASE      Z S O R C E           X T R A N        GENTAP      H       DAMP
     41.2  0.00000+J 0.18600  0.21710+J 3.59590  5.00000     3.00    3.000
```

Due to the extremely high step-up transformer impedance and tap, Xtran and Gentap, the initialization of the machine would give the following results. Note the terminal voltages of 17 to 35 per unit for these machines.

```
---------------------------MACHINE INITIAL CONDITIONS---------------------------
X------ BUS -----X ID  ETERM    EFD     POWER      VARS   P.F.   ANGLE    ID      IQ
33403 PLANT  D69.0 5 22.676323.5759    14.92      8.00 0.8814   30.23 4.8368 0.2971
33403 PLANT  D69.0 6 35.418936.6529    13.68      7.00 0.8902   31.45 4.9364 0.2920
33403 PLANT  D69.0 7 17.473118.3308    21.14     11.00 0.8871   30.84 5.1057 0.3220
33403 PLANT  D69.0 8 18.855219.8211    37.43     20.00 0.8820   30.05 5.1937 0.3426
```

The Xtran should be represented on machine base, and was changed to a more reasonable number, 0.01 + j0.12. Gentap is the step-up transformer tap position, and should have a value close to 1.0 per unit. It was set to 1.0 in order to achieve reasonable terminal conditions. The followings are the new terminal conditions:

```
---------------------------MACHINE INITIAL CONDITIONS---------------------------
X------ BUS -----X ID  ETERM   EFD     POWER      VARS   P.F.  ANGLE    ID      IQ
33403 PLANT  D69.0 5  1.0581 1.1673   14.92      8.00 0.8814 -15.35 0.6346 0.7325
33403 PLANT  D69.0 6  1.0578 1.2090   13.68      7.00 0.8902 -12.65 0.6683 0.7291
33403 PLANT  D69.0 7  1.0609 1.1638   21.14     11.00 0.8871 -15.32 0.6608 0.7812
33403 PLANT  D69.0 8  1.0633 1.1820   37.43     20.00 0.8820 -14.56 0.6915 0.7782
```

2.3.5 York Plant Dynamic Data

- The following is the model data for the 34.5 kV bus at York Plant.

```
PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:48
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

CONET MODELS

REPORT FOR ALL MODELS                              BUS 99993 [redacted]     34.500] MODELS

              *** CALL VBDCN(    932,115331,      0,  5702) ***

               BUS    NAME   BSKV          GENR BUS    NAME   BSKV
              99993 [redacted]    34.5                 0 [redacted]     34.5

                  I C O N S       C O N S        V A R
                   932-935     115331-115334     5702

                    VLO         VUP        PICKUP      TB
                    0.750       5.000       0.080      0.083

              *** CALL VBDCN(    936,115335,      0,  5703) ***

               BUS    NAME   BSKV          GENR BUS    NAME   BSKV
              99993 [redacted]    34.5                 0 [redacted]     34.5

                  I C O N S       C O N S        V A R
                   936-939     115335-115338     5703

                    VLO         VUP        PICKUP      TB
                    0.850       5.000       0.400      0.083
```

- The following is the model data for the wind turbine generators. Please note that buses 99994, 99995, and 99996 all have the same model representation and parameters.

```
     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:10
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

PLANT MODELS

REPORT FOR ALL MODELS                           BUS 99994 [[redacted]_CL10.6900] MODELS

** CIMTR3 **  BUS X-- NAME --X BASEKV MC     C O N S       S T A T E S      V A R S      ICON
           99994       [redacted]CL1 0.6900 1  115292-115304  43099-43104     5693-5695      929

              MBASE      Z S O R C E          X T R A N        GENTAP
               30.0   0.00000+J 0.30300   0.00000+J 0.00000   1.00000

                T'     T''       H       X       X'       X''      XL
              0.484   0.000    0.93   6.9762   0.3030   0.0000   0.1262

                E1      S(E1)      E2      S(E2)          D      SYN-POW
             1.0000   0.2632   1.2000   0.8640        0.00    0.0000

     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:10
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

CONET MODELS

REPORT FOR ALL MODELS                           BUS 99994 [[redacted]_CL10.6900] MODELS
```

```
*** CALL VTGTRP(   940,115339,      0,  5704) ***

  BUS   NAME  BSKV          GENR BUS   NAME  BSKV
99994 YORK_CL1.690           99994 YORK_CL1.690

     I C O N S      C O N S       V A R
      940-944    115339-115342    5704

       VLO        VUP      PICKUP      TB
      0.750      5.000      0.080     0.083


*** CALL VTGTRP(   945,115343,      0,  5705) ***

  BUS   NAME  BSKV          GENR BUS   NAME  BSKV
99994 YORK_CL1.690           99994 YORK_CL1.690

     I C O N S      C O N S       V A R
      945-949    115343-115346    5705

       VLO        VUP      PICKUP      TB
      0.850      5.000      0.400     0.083
```

```
     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:47
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

PLANT MODELS

REPORT FOR ALL MODELS                        BUS 99995 [YORK_CL20.6900] MODELS

** CIMTR3 **  BUS X-- NAME --X BASEKV MC    C O N S      S T A T E S     V A R S      ICON
            99995     YORK_CL2 0.6900 1  115305-115317  43105-43110    5696-5698      930

             MBASE     Z S O R C E          X T R A N      GENTAP
              30.0  0.00000+J 0.30300  0.00000+J 0.00000  1.00000

                T'     T''       H       X       X'       X''      XL
              0.484  0.000    0.93  6.9762  0.3030  0.0000  0.1262

               E1      S(E1)     E2      S(E2)         D     SYN-POW
             1.0000  0.2632  1.2000  0.8640       0.00    0.0000

     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:47
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

CONET MODELS

REPORT FOR ALL MODELS                        BUS 99995 [YORK_CL20.6900] MODELS
```

```
*** CALL VTGTRP(   950,115347,      0,  5706) ***

  BUS   NAME  BSKV          GENR BUS   NAME  BSKV
99995 YORK_CL2.690           99995 YORK_CL2.690

     I C O N S      C O N S       V A R
      950-954    115347-115350    5706

       VLO        VUP      PICKUP      TB
      0.750      5.000      0.080     0.083


*** CALL VTGTRP(   955,115351,      0,  5707) ***

  BUS   NAME  BSKV          GENR BUS   NAME  BSKV
99995 YORK_CL2.690           99995 YORK_CL2.690

     I C O N S      C O N S       V A R
      955-959    115351-115354    5707
```

```
                    VLO        VUP       PICKUP      TB
                    0.850      5.000      0.400      0.083



     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:47
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

PLANT MODELS

REPORT FOR ALL MODELS                             BUS 99996 [[redacted]_CL30.6900] MODELS

** CIMTR3 **  BUS X-- NAME --X BASEKV MC    C O N S      S T A T E S     V A R S       ICON
            99996     [redacted]_CL3 0.6900 1  115318-115330  43111-43116    5699-5701      931

             MBASE      Z S O R C E          X T R A N       GENTAP
              30.0  0.00000+J 0.30300  0.00000+J 0.00000  1.00000

               T'     T''      H       X       X'      X''      XL
              0.484  0.000   0.93  6.9762  0.3030  0.0000  0.1261

               E1     S(E1)     E2     S(E2)          D     SYN-POW
             1.0000  0.2632  1.2000  0.8640        0.00    0.0000

     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E      TUE, APR 30 2002  14:47
02SP-11205-OPT1 CLOVIS GENERATION STATION EVALUATION
2002 SUMMER PEAK (TS02SP4), TRANSIENT STABILITY MODEL

CONET MODELS

REPORT FOR ALL MODELS                             BUS 99996 [[redacted]_CL30.6900] MODELS

             *** CALL VTGTRP(    960,115355,       0,   5708) ***

              BUS    NAME  BSKV         GENR BUS    NAME  BSKV
             99996 [redacted]_CL3.690            99996 [redacted]_CL3.690

                   I C O N S       C O N S       V A R
                    960-964     115355-115358    5708

                     VLO        VUP       PICKUP      TB
                     0.750      5.000      0.080      0.083

             *** CALL VTGTRP(    965,115359,       0,   5709) ***

              BUS    NAME  BSKV         GENR BUS    NAME  BSKV
             99996 [redacted]_CL3.690            99996 [redacted]_CL3.690

                   I C O N S       C O N S       V A R
                    965-969     115359-115362    5709

                     VLO        VUP       PICKUP      TB
                     0.850      5.000      0.400      0.083
```

Section

3

Stability Analysis

3.1 Disturbances

For each powerflow case, the following faults were run (3 phase and single phase).

1. Faults on the Tolk (51435) – [redacted] (51205) 230kV Line (mid-line). A new bus (*Mid-Line bus*) was established in the electrical middle of the line.

   FLT13PH - 3 Phase Fault
   a. Apply the fault at the *Mid-Line bus*.
   b. Clear Fault after 5 cycles as indicated in (c).
   c. Remove lines from 51435 to *Mid-Line bus* and *Mid-Line bus* to 51205.
   d. Wait 20 cycles and then re-close both lines in (c) back into the fault.
   e. Leave fault on for 5 cycles, then trip both lines in (c) to remove fault.

   FLT11PH - 1 phase Fault
   a. Same as FLT13PH above.

2. Fault on the Tucumcari 115kV Bus (51070), removing the load bus.

   FLT23PH - 3 Phase Fault
   a. Apply the fault on the Tucumcari 115kV Bus (51070).
   b. Clear Fault after 5 cycles as indicated in (c).
   c. Remove the load at 51070 and 51076. Remove the lines from the [redacted] (99991) to FE-Tucumcari (51076) and from FE-Tucumcari (51076) to the Tucumcari Bus (51070).
   d. Wait 20 cycles then re-close the lines in (c) and load at 51076 back removing the load bus 51070.

   This simulates a high side transformer fault at Tucumcari.

   FLT21PH - 1 phase Fault
   a. Same as FLT23PH above.

3. Fault on the Curry County (51176) – [redacted] (51206) 115kV Line.

   FLT33PH - 3 Phase Fault
   a. Apply fault at the [redacted] bus (51206).
   b. Clear Fault after 5 cycles as indicated in (c).
   c. Remove the 115kV line from 51176 – 51206. Clear the Fault.
   d. Wait 20 cycles, then re-close line in (c) into the fault.
   e. Leave fault on for 5 cycles, then trip the line in (c) and remove the fault.

   FLT31PH - 1 phase Fault
   a. Same as FLT33PH above.

4. Fault on the Curry County (51176) – York Tap (99991) 115kV Line.
   FLT43PH - 3 Phase Fault
   a. Apply fault at bus 51176.
   b. Clear Fault after 5 cycles as indicated in (c).
   c. Remove the 115kV line from 51176 – 99991. Clear the Fault.
   d. Wait 20 cycles, then re-close line in (c) into the fault.
   e. Leave fault on for 5 cycles, then trip the line in (c) and remove the fault.

   FLT41PH - 1 phase Fault
   a. Same as FLT43PH above.

5. Fault on Tolk (51435) – Tuco (51533) 230kV Line.
   FLT53PH - 3 Phase Fault
   a. Apply fault at the Tuco bus (51533).
   b. Clear Fault after 5 cycles as indicated in (c).
   c. Remove the 230kV line from 51435 – 51533. Clear the Fault.
   d. Wait 20 cycles, then re-close line in (c) into the fault.
   e. Leave fault on for 5 cycles, then trip the line in (c) and remove the fault.

   FLT51PH - 1 phase Fault
   a. Same as FLT53PH above.

The actual single-line-to-ground fault MVA's at substations simulated were not available. Fault MVA's were calculated and applied so the bus voltage of the substation with the SLG fault applied dropped to between 0.6 and 0.7 pu. The PSAS files 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 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. All oscillations were well damped. The wind farm was tripped by the voltage-monitoring relay in all cases simulated. Table 3-1 summarizes the time for the wind farm to be tripped after the fault was applied:

Table 3-1: comparison of the timing of tripping the plant in all disturbances

Time (second)	FLT 1, 3PH	FLT 1, 1PH	FLT 2, 3PH	FLT 2, 1PH	FLT 3, 3PH	FLT 3, 1PH	FLT 4, 3PH	FLT 4, 1PH	FLT 5, 3PH	FLT 5, 1PH
[redacted] 34.5 kV	0.164	0.494	0.164	0.450	0.164	0.584	0.164	0.180	0.586	1.778
[redacted] generator	0.164	0.450	0.164	0.404	0.164	0.190	0.164	0.186	0.584	1.712

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

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

- The significance of the over/under voltage protection relay
- The adequacy of coordination between the switched capacitors at [redacted] and the plant
- The characteristic of an induction generator's transient response

The concerns listed above are addressed in different fault simulations. The significance of over/under voltage protection relay was addressed by disabling the relays while the same fault sequence was applied. The details are given in Section 3.2.1. The adequacy of coordination between the capacitor banks and the plant was addressed by observing bus voltages with the plant tripped while the capacitor at [redacted] still remained in service. The details are given in Section 3.2.2. The characteristic of an induction generator's transient responses was addressed by applying a single-phase-to-ground fault at a remote bus, which caused voltage drop without activating the voltage monitoring relay immediately. The low voltage led to the wind turbines losing synchronism with the Xcel Energy's system. The details are given in Section 3.2.3.

3.2.1 Over/under voltage protection

The over/under voltage protection scheme was simulated by two user-written models: VBDCN for the [redacted] 34.5 kV bus, and VTGTRP for the [redacted] generators. Both models have two undervoltage set points, and the setup of the relays is listed in Table 2-8. Only the undervoltage protection scheme is implemented in the study. Bus voltage exceeding 1.2 pu is not likely to result from the disturbances in this study and thus the overvoltage protection scheme is not discussed here.

Relay 1 monitors bus voltage below 0.75 pu. If the voltage remains lower than 0.75pu for over 0.08 seconds, relay 1 would trip the bus/generator. Relay 2 monitors bus voltages between 0.85 and 0.75 pu. If bus voltage remains in this range for over 0.4 seconds, relay 2 would trip the bus/generator. With the over/under voltage protection scheme in service, [redacted] wind farm was tripped due to low voltages for all faults in Section 3.1. To test the system with the undervoltage protection scheme out-of-service or failed, four faults were simulated with the over/under voltage protection relays disabled:

- FLT13PH: Three-phase fault on the Tolk (51435) – [redacted] (51205) 230kV Line (mid-line)
- FLT11PH: Single-line-to-ground fault on the Tolk (51435) – [redacted] (51205) 230kV Line (mid-line)
- FLT23PH: Three-phase fault on Tucumcari 115kV Bus (51070), removing the load bus
- FLT21PH: Single-line-to-ground fault on Tucumcari 115kV Bus (51070), removing the load bus

With the undervoltage protection scheme disabled, all four faults resulted in instability of the wind farm. Figure 3-1 and Figure 3-2 are the comparisons of bus voltage and speed deviation of the collector generator at bus 99994 when FLT11PH was applied. The voltage at bus 99994 could not recover to its pre-fault level even after the SLG fault was cleared. Without the voltage protection scheme, bus voltage continued to decrease to 0.35 pu while the speed of the wind generator continued to increase, losing stability with respect to the rest of the system.

Thus the voltage protection scheme performs the essential task of removing the wind farm before instability occurs for close-in disturbances.

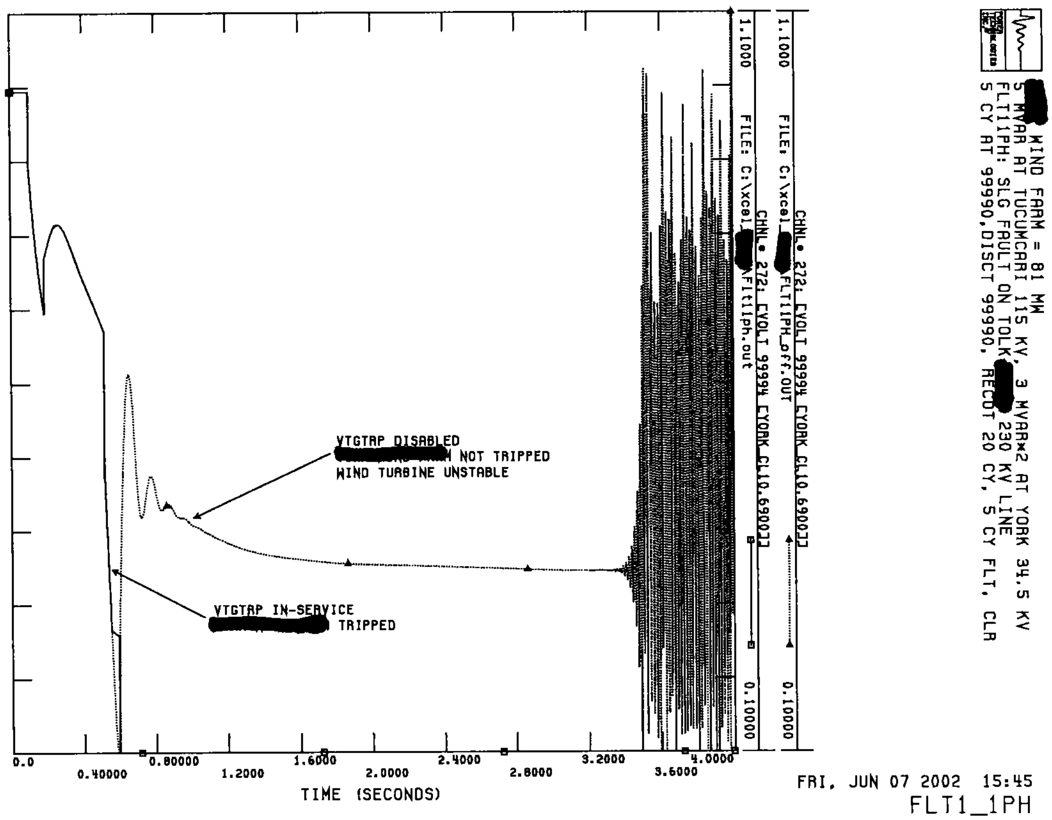


Figure 3-1: comparison of bus voltage at bus 99994

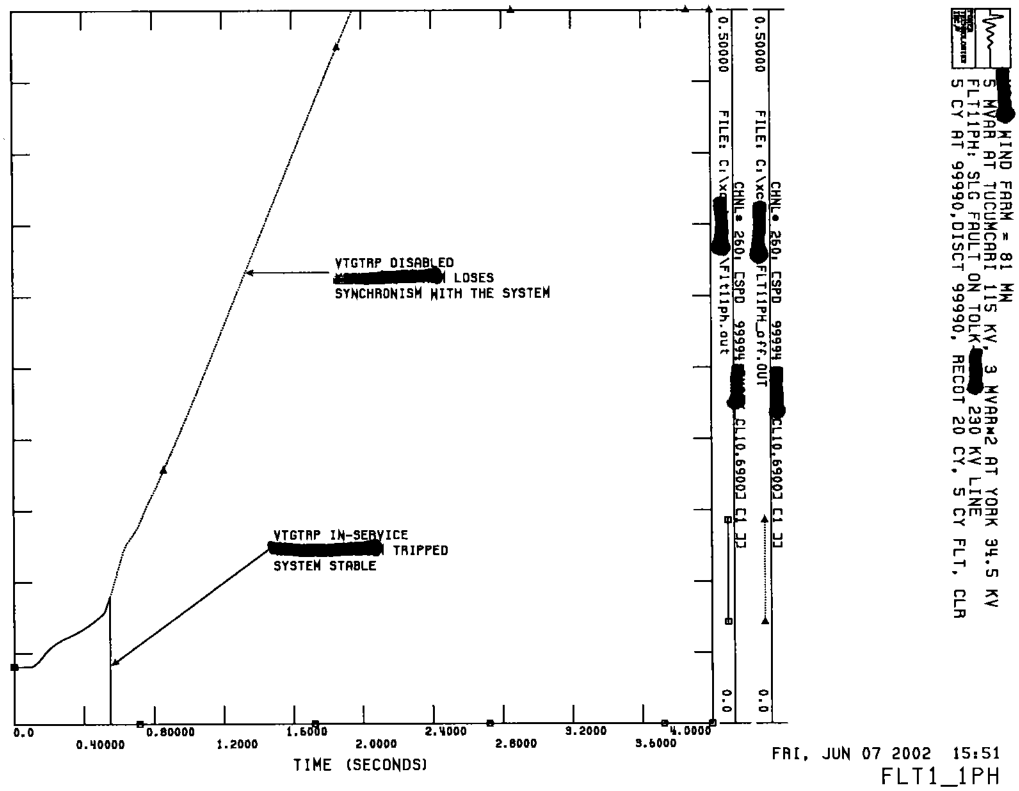


Figure 3-2: comparison of speed deviation of the collector generator at bus 99994

3.2.2 Coordination between the capacitors and [redacted] wind farm

Two capacitors were added into the case: 5 MVAR at 115 kV Tucumcari bus and 6 MVAR at [redacted] 34.5 kV bus. The sizes of the capacitors are reasonable when the [redacted] wind farm is on-line with 100% output of 81 MW during peak load. Under different load/generation conditions, such as light load or if the plant is off-line, the capacitor banks might result in high voltage on the nearby system. The 5 MVAR capacitor bank was in-service except in FLT2, where the substation was lost due to the fault. The adequacy of coordination between the switched capacitor at [redacted] 34.5 kV bus and the plant is addressed in two fault simulation cases:

- FLT21PH: observe the system with the disturbance and loss of Tucumcari's capacitor bank
- FLT31PH: observe the system with the disturbance but without loss of Tucumcari's capacitor bank.

3.2.2.1 FLT21PH

A single-line-to-ground fault was applied at the Tucumcari 115 kV substation (bus 50170) at t = 0.1 second. Both loads at the end of this radial line are lost (bus 50170 and bus 50176). The load at bus 50176 was restored after the fault was cleared, but the capacitor and load at bus 50170 were both lost due to the fault. As a result, the wind farm units were tripped at t = 0.502 second, and the switched shunt at bus 99993 was tripped at t = 0.550 second. Figure 3-3 is the voltage response of FE-TU3 115 kV substation for the first two seconds of simulation. With the 6 MVAR capacitor at the [redacted] 34.5 kV bus for an additional 0.05 seconds after the plant was tripped, FE-TU3 115 kV bus (bus 50176) experienced a peak voltage of 1.02 pu, well within capabilities. If the plant output reduces, a higher bus voltage at FE-TU3 115 kV bus can be anticipated as a result of loss of both the load and capacitor bank at Tucumcari 115 kV bus. Figure 3-4 is the voltage response of the neighboring 115 kV network during the first second following the disturbance.

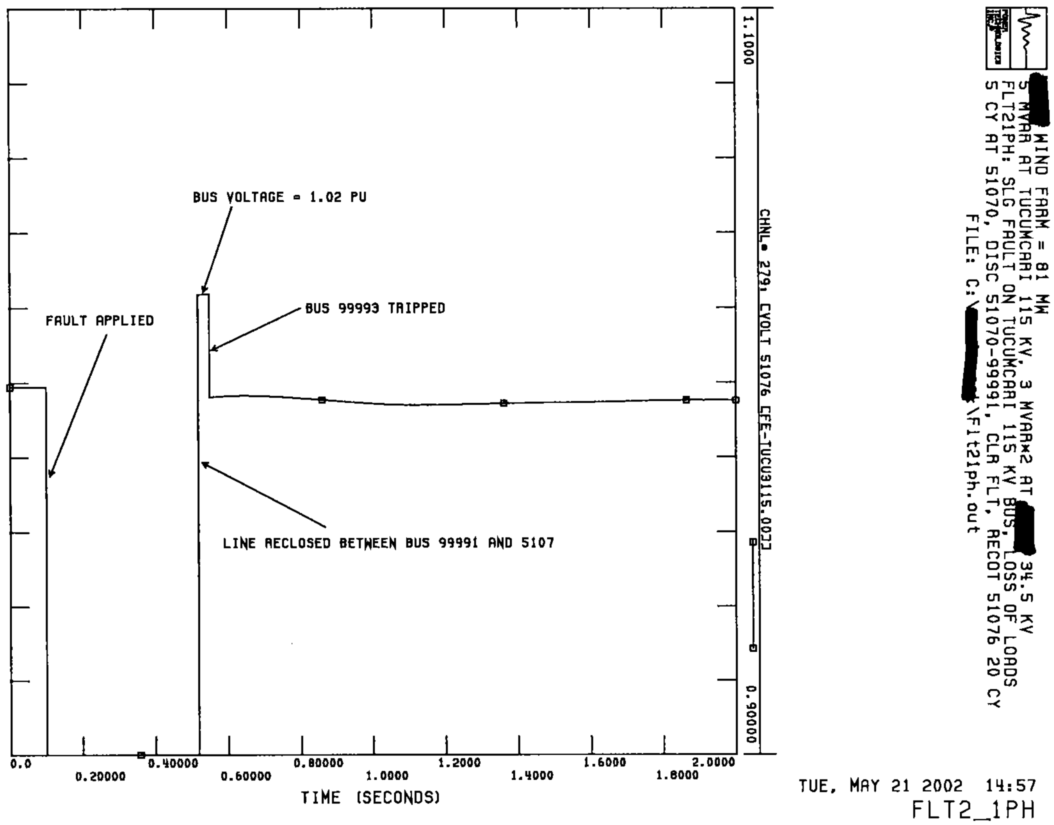


Figure 3-3: voltage of FE-TU3 115 kV bus (51076)

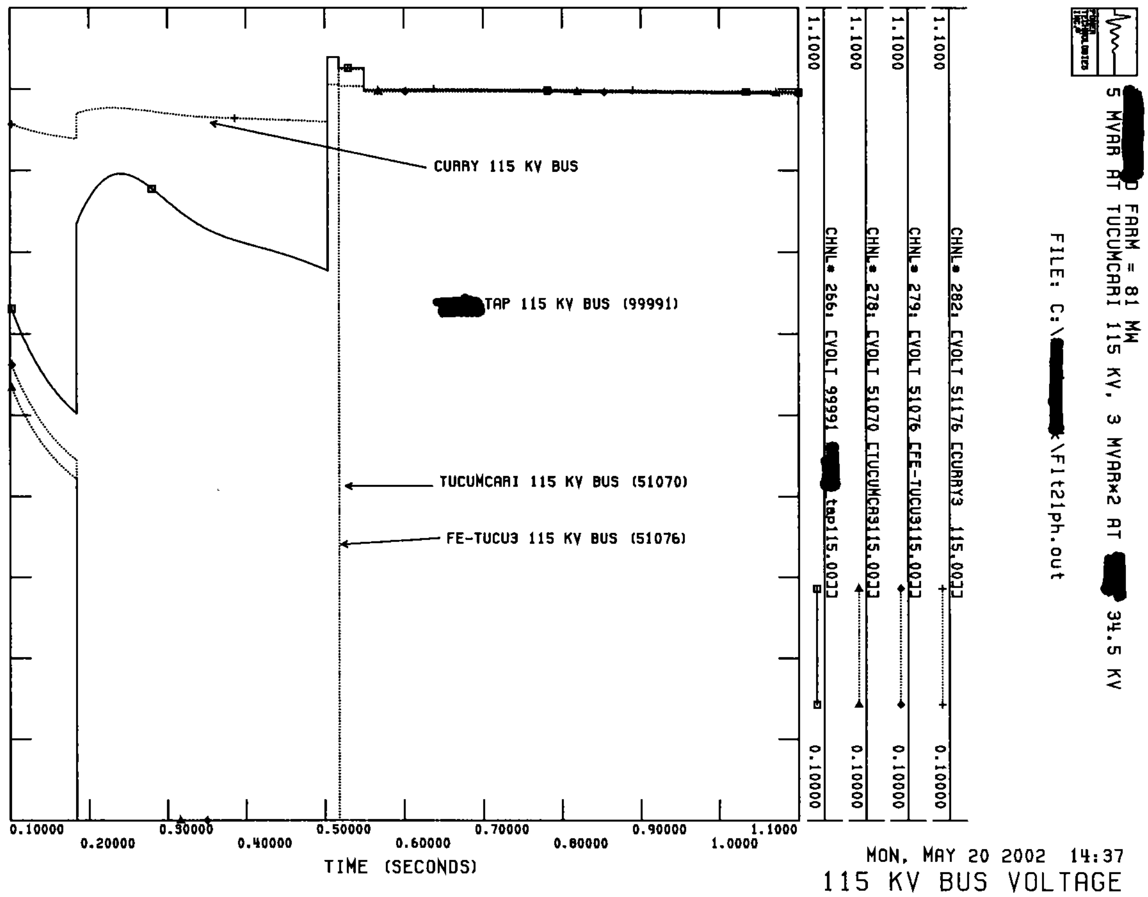


Figure 3-4: bus voltages of neighboring 115 kV buses

3.2.2.2 FLT31PH

A single-line-to-ground fault was applied at the[redacted] Plant 115 kV bus at t = 0.1 second. The fault was cleared after 5 cycles and the 115 kV line between Curry and[redacted]Plant was disconnected. Twenty cycles later, the line was re-closed back into the fault, and was disconnected again after 5 cycles. The generators were tripped at t = 0.29 second while the[redacted] 34.5 kV bus (along with the 6 MVAR switched capacitor) were not tripped until t = 0.684 second. The capacitors thus remained in service for 0.374 seconds after the plant was tripped. The voltage at bus 99991 was 0.942 pu, and bus 99993 was 0.953 before the capacitors tripped, and both dropped to 0.92 pu after the capacitors tripped. This fault simulation demonstrated the situation where the generators of the wind farm were tripped while the switched capacitor at[redacted] 34.5 kV bus remained in-service. In this case, the failure of tripping the switched capacitor at the plant simultaneously with the units would not impose high voltages on the system. In this simulation, failure to trip [redacted] capacitor actually helped to maintain the bus voltage levels at a more reasonable range.

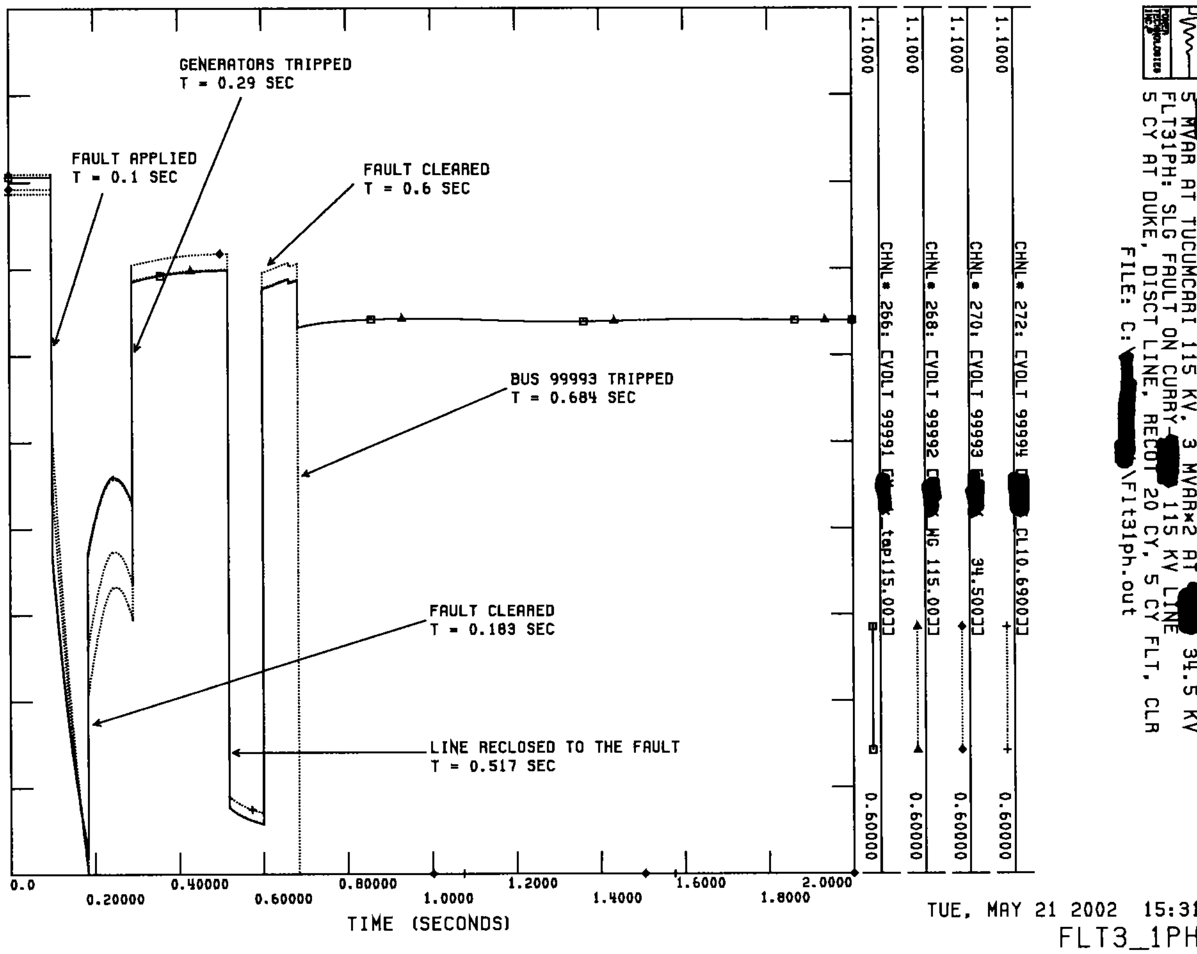


Figure 3-5: bus voltages at [redacted] 115 kV/34.5 kV/690 V buses

3.2.3 Stability of the induction generators

In previous simulations, the ability of the [redacted] plant to remain in synchronism with the system was not tested, as the plant was tripped by the undervoltage protection. The stability of the induction generators was addressed by applying a fault at a remote bus. A remote fault would have a less severe impact on the wind farm bus voltage, and thus the voltage protection scheme wouldn't be triggered immediately after the fault. This plant stays on-line are thus needs to remain stable. This issue is addressed in the fault simulation case FLT51PH.

FLT51PH: A single-line-to-ground fault was applied at Tuco 230 kV bus at t = 0.1 second. The fault was cleared after 5 cycles and the 230 kV line between Tuco (bus 51533) and Tolk (bus 51435) was disconnected. Twenty cycles later, the line was re-closed back into the fault, and was disconnected again after 5 cycles.

Figure 3-6 shows the voltage and speed deviation of the [redacted] plant. Voltage is depressed due to the remote fault and the machine speed begins to increases. The machine is not able to reach a stable operating point after the fault is cleared. The terminal voltage of the generator decreases rapidly and thus activates the voltage protection scheme of the generator. The wind turbines were disconnected at t = 1.812 second, and the [redacted] 34.5 kV bus along with the switched shunt were disconnected at t = 1.878 second. This can be considered essentially a disconnection as the plant goes out-of-step with the system.

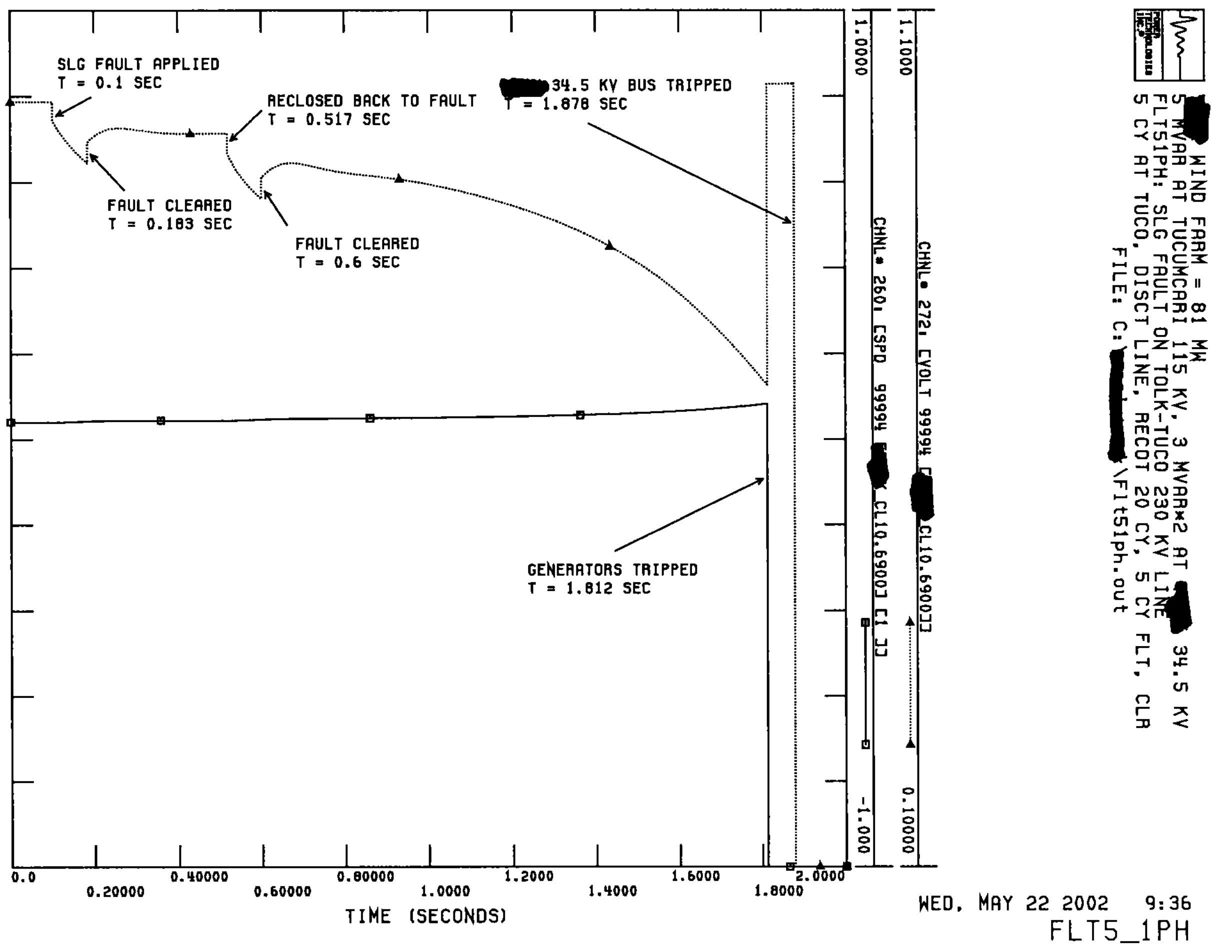


Figure 3-6: wind turbine generator response at bus 99994

3.3 Application of an SVC at [redacted]

Voltage fluctuations and the wind farm being tripped are common among the 10 simulations performed. To investigate the ability to stabilize voltages, a 10 MVAR Static Var Compensator (SVC) was placed at [redacted] 34.5 kV bus (99993) to replace the switched shunt. Tests were performed to determine how effective the SVC would be at supporting the bus voltage during disturbances. The SVC was tuned to reflect the network strength at bus 99993. However, the analysis was not meant to suggest the optimum sizing and tuning parameters of the SVC at [redacted] 34.5 kV bus. The parameters used for the SVC at [redacted] 34.5 kV bus are given below:

```
REPORT FOR ALL MODELS                    BUS 99993 [redacted]      34.500] MODELS


              *** CALL CSSCS1(   986,115363, 43117,   5732) ***


 ** CSSCS1 **  BUS X-- NAME --X BASEKV   I C O N S     C O N S      S T A T E S     V A R S
              99993 YORK        34.500   986-987    115363-115371  43117-43119    5732-5735
```

REMOTE BUS	K	T1	T2	T3	T4	T5	VMAX	VMIN	VOV
0	2000.0	0.000	0.000	0.372	0.000	0.030	0.0	0.0	99.000

Four simulations were performed:

- FLT23PH: 3-phase fault onTucumcari 115kV Bus (51070), removing the load bus
- FLT21PH: Single-line-to-ground fault on Tucumcari 115kV Bus (51070), removing the load bus
- FLT53PH: 3-phase fault on Tolk (51435) - Tuco (51533) 230 kV line
- FLT51PH: Single-line-to-ground fault on Tolk (51435) - Tuco (51533) 230 kV line

Due to the support from the 10 MVAR SVC, the plant was not tripped in the less severe fault, FLT51PH. Figure 3-7 is the SVC output for the first 5 seconds of the simulation for FLT51PH. The highest demand of reactive support from the SVC occurred during the fault. 10 MVAR was needed to help the bus to ride through the disturbance and maintain voltage at 1.0 pu.

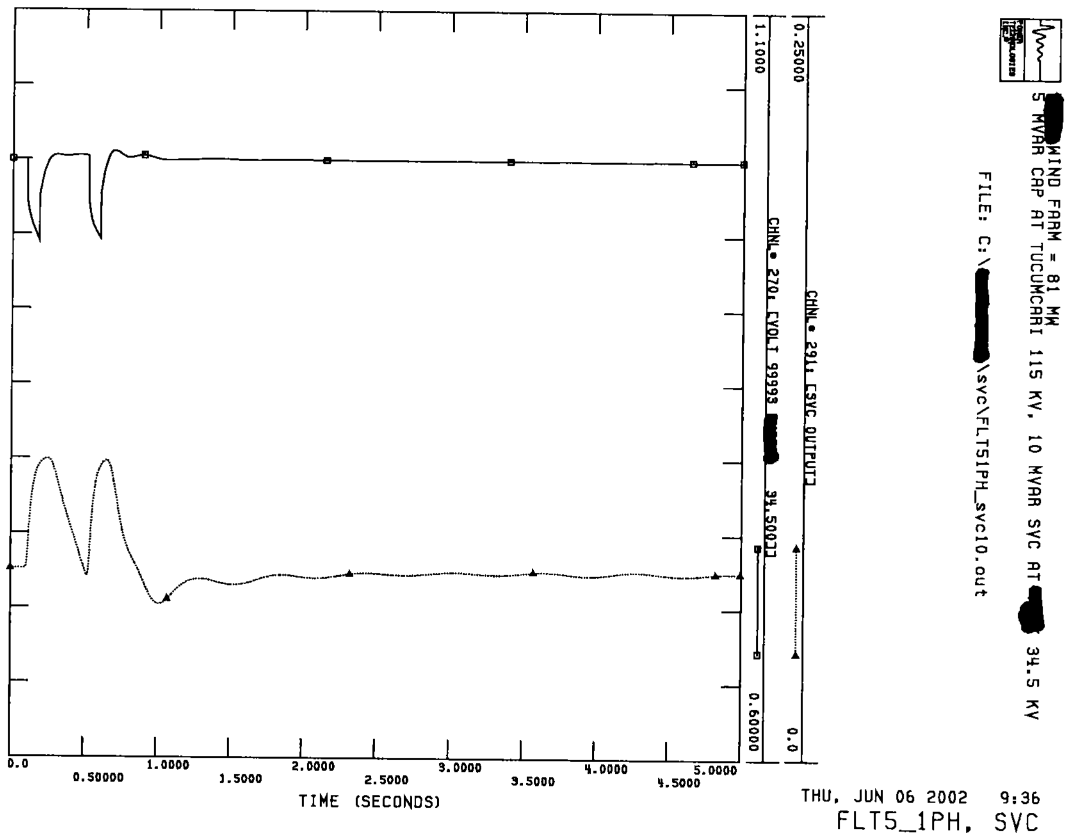


Figure 3-7: SVC response and voltage at bus 99993

The wind farm was tripped due to undervoltage protection for the more severe faults, such as three-phase-to-ground faults (i.e. FLT23PH and FLT53PH) or a single-line-to-ground fault at a nearby bus (i.e. FLT21PH). In order to determine whether a larger SVC could help the system ride through more severe disturbances, the 10 MVAR SVC was replaced with a 30 MVAR SVC. Table 3-2 summarizes the simulation results.

Table 3-2: SVC test results

	SVC of 10 MVAR	SVC of 30 MVAR
FLT23PH	[redacted] wind farm tripped	[redacted] wind farm tripped
FLT21PH	[redacted] wind farm tripped	[redacted] wind farm didn't trip; highest output from the SVC was about 30 MVAR
FLT51PH	[redacted] wind farm didn't trip; highest output from the SVC was about 10 MVAR	[redacted] wind farm didn't trip; highest output from the SVC was about 20 MVAR
FLT53PH	[redacted] wind farm tripped	[redacted] wind farm didn't trip; highest output from the SVC was about 30 MVAR

An SVC of larger size (i.e. 30 MVAR) can help the wind farm ride through more severe disturbances, and maintain the voltage in the neighboring network.