Arabella Wind LLC
Transmission Service Request

(TSR #72831217 for 170 MW)

Facilities Study Report

December 2015

Prepared by:

Public Service Company of New Mexico

Foreword

This report was prepared for Arabella Wind, LLC ("Customer") by the Transmission/Distribution Planning and Contracts Department of the Public Service Company of New Mexico, in accordance to a Facilities Study Agreement executed on (May 20, 2015).

Any correspondence concerning this document, including technical and commercial questions should be referred to:

Director, Transmission/Distribution Planning and Contracts
Public Service Company of New Mexico
2401 Aztec Rd NE MS-Z-220, Albuquerque, NM 87107
Phone: (505) 241-4582
Fax: (505) 241-4363

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1. Introduction

Public Service Company of New Mexico (“PNM”) performed this Transmission Facilities Study (”Study”) in response to a transmission service request (TSR 72831217) from Arabella Wind, LLC (“Transmission Customer “). This Study is based on the System Impact Study (“SIS”)[1] previously completed and provided to the Transmission Customer in May 2015, which identified the need for Network Upgrades to accommodate the Service along with a preliminary cost estimate and construction schedule for the Network Upgrades.

Additional technical studies were also performed using three-phase model (PSCAD) to evaluate whether additional transmission system improvements are necessary to accommodate the TSR since the positive-sequence, reduced-order simulation model used in the SIS do not allow for this type of detailed analysis. The technical PSCAD study concluded that no synchronous condenser will be required (see Appendix C).

This Study provides a detailed summary of costs associated with Network Upgrades identified in the SIS and a more refined construction schedule.

Section 3 includes a description of the Network Upgrades. Section 4 summarizes the cost and construction information with details contained in the Appendices.

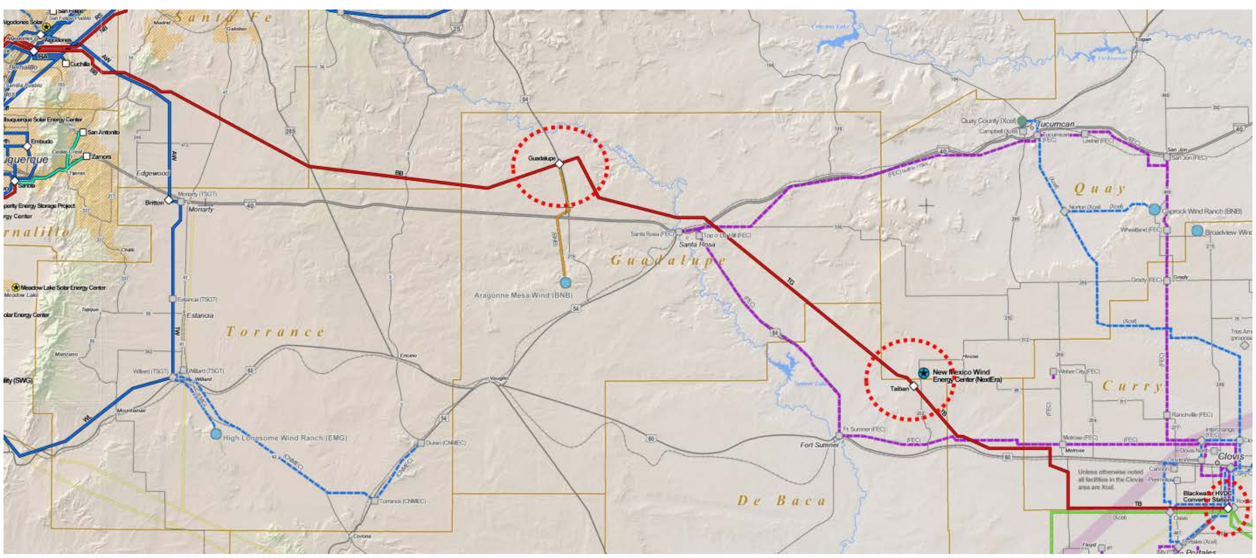

Figure 1: Vicinity of Transmission reinforcements

Figure 1 shows a general location of the transmission reinforcements.

[1] http://www.oatioasis.com/PNM/PNMdocs/TSR_72831217__170_MW_TSIS_Report.pdf

2. Background

The Transmission Customer requested long-term point-to-point transmission service No. 72831217 (“TSR”) associated with a 170 MW reservation of transmission service over PNM’s 345 kV transmission line (“BB Line”) extending from PNM’s 345 kV bulk power switching station north of Bernalillo, New Mexico (“BA Station”) to PNM’s Blackwater 345 kV Station (“Blackwater Station”), located in the Clovis-Portales area of eastern New Mexico. Currently, the BB line has a maximum capacity capability of 662 MW and is fully subscribed. This TSR is from the Guadalupe 345 kV Station as the Point of Receipt in the PNM Balancing Authority Area to the 345 kV switchyard at the Four Corners Generating Station in the Arizona Public Service Balancing Authority Area as the Point of Delivery

PNM performed the SIS associated with the TSR that indicated that a significant amount of voltage support would be necessary to accommodate an additional injection of 170 MW on the BB Line. The SIS report stated that the most effective means of providing the required reactive support would be through construction and installation of a static VAR compensator (“SVC”) at PNM’s Guadalupe Station, along with certain other associated network upgrades including: a) modifications to facilities within Guadalupe Station to accommodate the SVC; b) replacement of wave traps on the BB line with higher rated equipment; and c) installation of a remedial action scheme.

Subsequent to the SIS report being issued, PNM informed the Transmission Customer an additional study would be necessary to determine whether additional transmission system improvements are necessary to accommodate the TSR.

Prior to PNM completing this additional study, the Transmission Customer requested that PNM tender an Expedited Service Agreement (ESA) consistent with Section 19.9 of PNM’s OATT. On July 2, 2015, PNM tendered the Transmission Customer an ESA and notified Transmission Customer that the report for the additional study is estimated to be issued in November 2015.

Pursuant to the Transmission Customer request, PNM and the Transmission Customer entered into the ESA. On August 11, 2015, PNM filed the ESA in Docket No. ER15-2410-000. This Study completes the requirements outlined in the ESA by providing a detailed summary of costs associated with Network Upgrades identified in the SIS and a more refined construction schedule. In addition, the supplementary technical studies were completed (see Appendix C).

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3. Required System Reinforcements

The following transmission system reinforcements are required to facilitate transmission service as originally determined in the SIS and were verified the PSCAD analysis for this facilities study:

- SVC +250/-100 MVAr[2]
- Expand Guadalupe 345 kV Station for SVC interconnection (3 Breakers)
- Remedial Action Scheme (RAS) for N-2 contingencies and SVC forced outage.
- Replace Wave Traps at Blackwater and Taiban Mesa Switching Stations.

Figure 2 shows a general configuration of Guadalupe Station and the SVC with the Network Upgrades. A detailed proposed Guadalupe Station layout is provided in Appendix B.

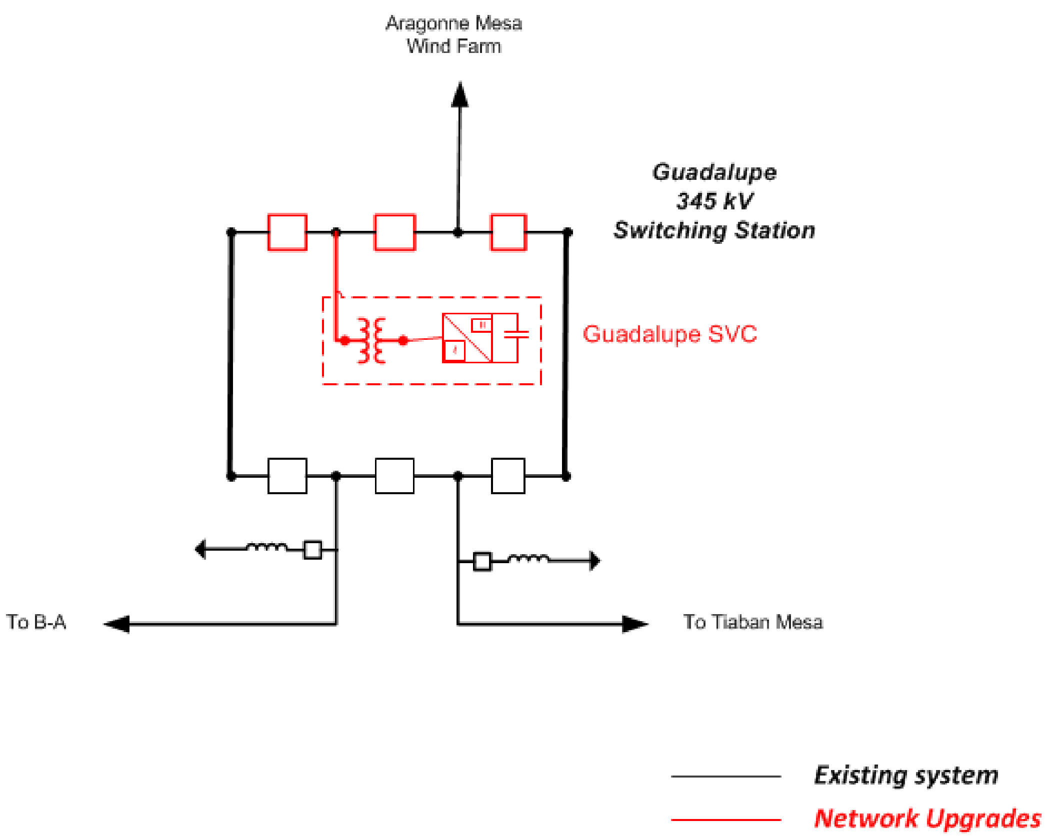

Figure 2: Guadalupe 345 kV Switching Station

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[2] The SVC reactive range was changed from the original SIS report (+221/-90 MVAr) to take advantage of a similar sized SVC design PNM is installing at the Rio Puerco 345 kV station. This will significantly reduce the engineering design and to standardize PNM's FACTS devices for employee knowledge and operational expertise, as well as on premises maintenance of critical spare parts.

3 Summary of Cost Estimates and Work Schedule

The total cost and construction schedule estimates are summarized in the table below. Construction schedule estimates are from the date that the Transmission Customer provides written authorization to proceed, provided all interconnection agreements and funding arrangements are in place.

System Upgrade	Cost (M$)	Construction Time (Months)
SVC +250/-100 Mvar	23.7	19
Expand Guadalupe Switching Station 345 kV for SVC interconnection (3 Breakers)	4.8	18
Remedial Action Scheme for low probability N-2 contingencies.	0.2	6
Replace Wave Traps at Blackwater and Taiban Switching Stations	0.3	6
Loads, Tax, AFUDC, Contingency	10.1	N/A
Total	**39.1**	**30***

* Total Construction time is measured by the entire time it takes to complete all network upgrades associated with a defined transmission service request. Individual system upgrades may be done in parallel and as a result may not cumulatively equal the total construction time.

PNM may incur outage related costs (typically re-dispatch) during the construction of the system reinforcements. Such costs cannot be estimated at this time, however, in accordance with applicable Federal Energy Regulatory Commission policy, PNM reserves the right to recover such costs from the Transmission Customer.

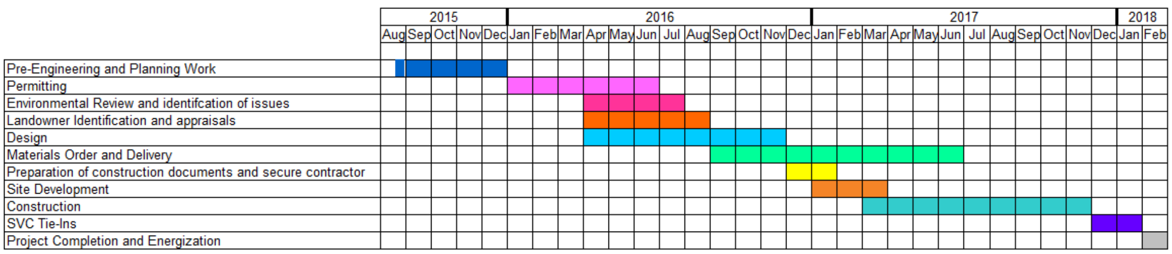
The following general assumptions apply to all PNM cost estimates and schedules:

1. For all estimates, pricing is based on 2015 unit costs. With likely fluctuations in the price of raw materials, fuel, and labor, actual costs may vary in future years.
2. Cost estimates are considered to be within +/- 10%.
3. Estimates include, rights-of-way, governmental permitting, design, materials, construction, construction management, and internal utility loads.
4. Project schedules are considered reasonably accurate but can be affected by permitting delays, equipment deliveries, weather, availability of workforce, and availability of outage clearance for construction.
5. Barring unforeseen complications with local permitting requirements, availability of land, strikes, resource limitations etc., the proposed schedule for final design and construction is estimated to take 30 months from an authorization to begin work.

Appendix A contains an itemized cost estimate as well as specific assumptions used in preparing the cost estimate.

Major activities are presented in the schedule below. Schedules are typical and will be revised as project details become firm. The anticipated in-service date required for the transmission system improvements is March 1, 2018.

Construction Schedule



Appendix A: Cost Estimate Detail

GUADALUPE STATION EXPANSION, SVC, WAVE TRAPS, & RAS			
GUADALUPE STATION IMPROVEMENTS	**Labor/Services**	**Material**	**Total**
ROW /SURVEYING	2,000		2,000
ENVIRONMENTAL	2,000		2,000
REGULATORY/PERMITTING	20,000		20,000
SITE DEVELOPMENT. SECURITY inc. STATION GRAVEL	900,000	150,000	1,050,000
345KV SURGE ARRESTORS AND INSTRUMENT TRANSFORMERS	20,000	130,000	150,000
345KV CIRCUIT BREAKERS 40KA 1300KVBIL	20,000	790,000	810,000
345KV CVTS METERING ACCURACY, 1300KV BIL	above	0	0
345KV DISCONNECT SWITCHES HOD 2000A 1300KB BIL	10,000	70,000	80,000
345KV DISCONNECT SWITCHES MOD 2000A 1300KV BIL	30,000	200,000	230,000
GROUNDING SYSTEM	25,000	36,500	61,500
RACEWAY / CONDUIT SYSTEM	70,000	65,000	135,000
CONTROL & POWER CABLE	50,000	100,000	150,000
PRIMARY CONDUCTORS & BUS MATERIAL	50,000	50,000	100,000
STATION STEEL AND FOUNDATIONS	250,000	148,500	398,500
STATION ENGINEERING	95,000		95,000
PROJECT MANAGEMENT	70,000		70,000
STATION CONSTRUCTION MANAGEMENT	130,000		130,000
FUNCTIONAL TESTING & MANAGEMENT	175,000		175,000
REMOVAL OF EXISTING STATION EQUIPMENT	30,000		30,000
SWITCHING SUPPORT	20,000		20,000
STATION GENERATOR FOR BACK UP POWER and UPGRADE TO STATION SERVIC	200,000	90,000	290,000
GUADALUPE STATION CONTROL, PROTECTION, & COMMUNICATION			
CONTROL & PROTECTION ENGINEERING	50,000		50,000
CONTROL & PROTECTION- CABLES, PANELS, EQUIPMENT, HOUSE EXPANSION	225,000	425,000	650,000
COMMUNICATION UPGRADES		50,000	50,000
SUB-TOTAL GUADALUPE STATION IMPROVEMENTS ONLY	**2,444,000**	**2,305,000**	**4,749,000**
GUADALUPE SVC (+250/-100)	**Labor/Services**	**Material**	**Total**
SVC SYSTEM STUDIES, MODELING, DESIGN, COMISSIONING & PERFORMANCE TESTING	3,070,736	Materials and equipment incl as part of services	3,070,736
VENDOR PROJECT MANAGEMENT & OVERSIGHT	2,864,684		2,864,684
SUPPORT STRUCTURES AND FOUNDATIONS	3,157,444		3,157,444
TRANSFORMERS inc appurtences and instal*	6,087,902		6,087,902
TSR & TSC & HARMONIC FILTERS *	2,736,745		2,736,745
SWITCHGEAR & SVC BUILDING & COOLING SYSTEM*	2,487,794		2,487,794
CONTROL AND PROTECTION SYSTEM*	1,757,181		1,757,181
LV ELECTRICAL SYSTEM	419,315		419,315
SPARE PARTS *	535,630		535,630
345kV TIE FROM RING TO SVC	125,573	150,000	275,573
PNM SVC PROJECT ENGINEERING & MANAGEMENT	100,000		100,000
PNM CONSTRUCTION OVERSIGHT	170,000		170,000
SUB-TOTAL - GUADALUPE SVC ONLY	**23,513,004**	**150,000**	**23,663,004**

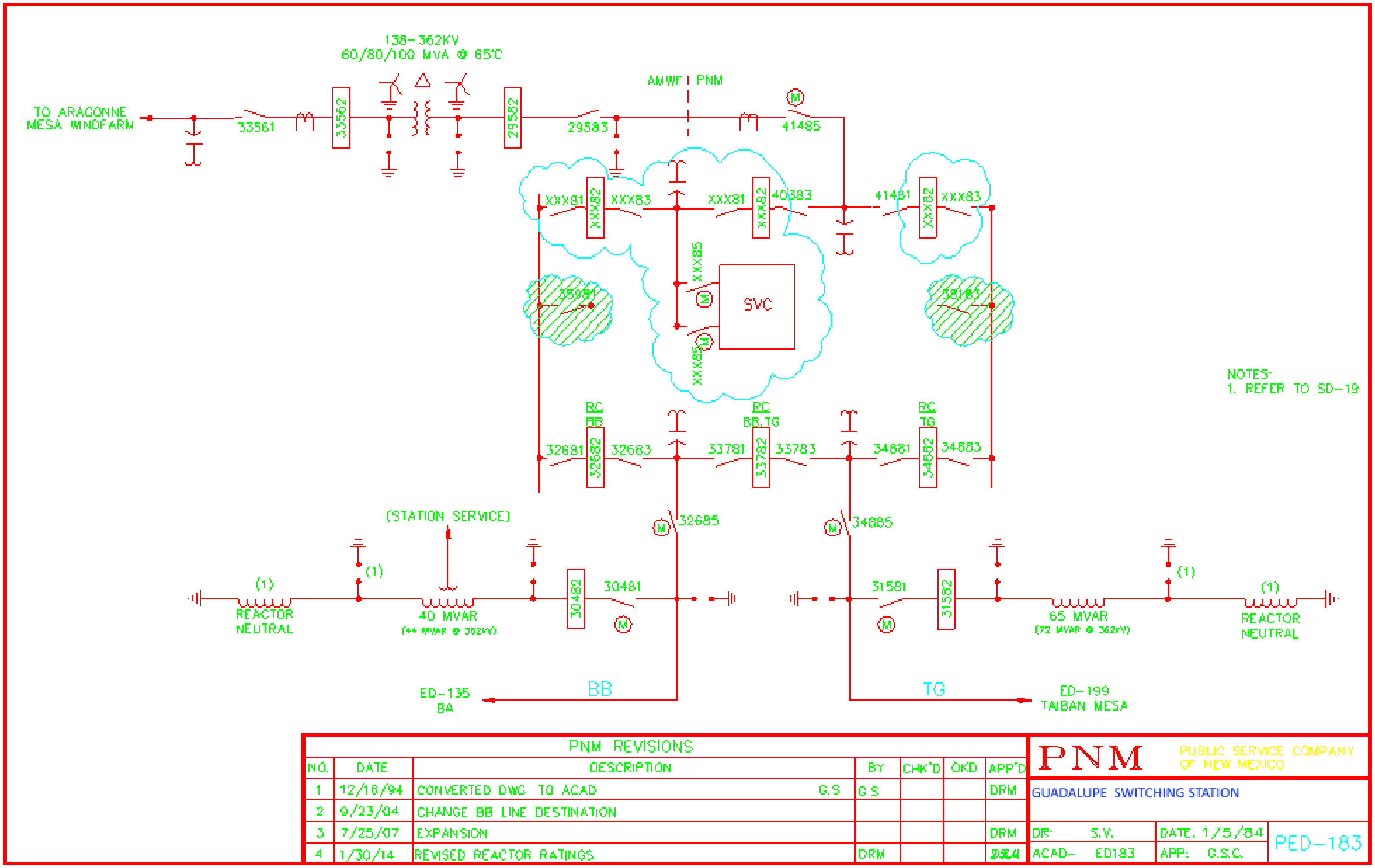
BLACKWATER & TAIBAN WAVE TRAP REPLACEMENT	Labor/Services	Material	Total
BLACKWATER - 3 WAVE TRAP/FILTER REACTOR & TAIBAN STATION - 1 WAVE TRAP REPLACEMENT	100,000	200,000	300,000
SUB-TOTAL - BLACKWATER & TAIBAN WAVE TRAP REPLACEMENT	**100,000**	**200,000**	**300,000**
REMEDIAL ACTION SCHEME (RAS)	**Labor/Services**	**Material**	**Total**
INSTALL REMEDIAL ACTION SCHEME	150,000	50,000	200,000
REMEDIAL ACTION SCHEME (RAS) ONLY	**150,000**	**50,000**	**200,000**
SUB - TOTAL COST (STATION, SVC, WAVE TRAPS, RAS)	**26,207,004**	**2,705,000**	**28,912,004**
A & G @ 2.80%	**733,796**	**75,740**	**809,536**
E & S @ 6%	**1,572,420**	**162,300**	**1,734,720**
AFUDC 7% ANNUAL	**1,834,490**	**189,350**	**2,023,840**
TAXES (NMGRT) @ 7%	**1,834,490**	**189,350**	**2,023,840**
LOADED TOTAL COST	**32,182,201**	**3,321,740**	**35,503,941**
CONTINGENCY @ 10%	**3,218,220**	**332,174**	**3,550,394**
TOTAL PROJECT COST	**35,400,421**	**3,653,914**	**39,054,335**

ESTIMATE NOTES
1. SVC PRICING BASED ON BUDGETARY QUOTE FROM VENDOR

Key Notes and Assumptions:

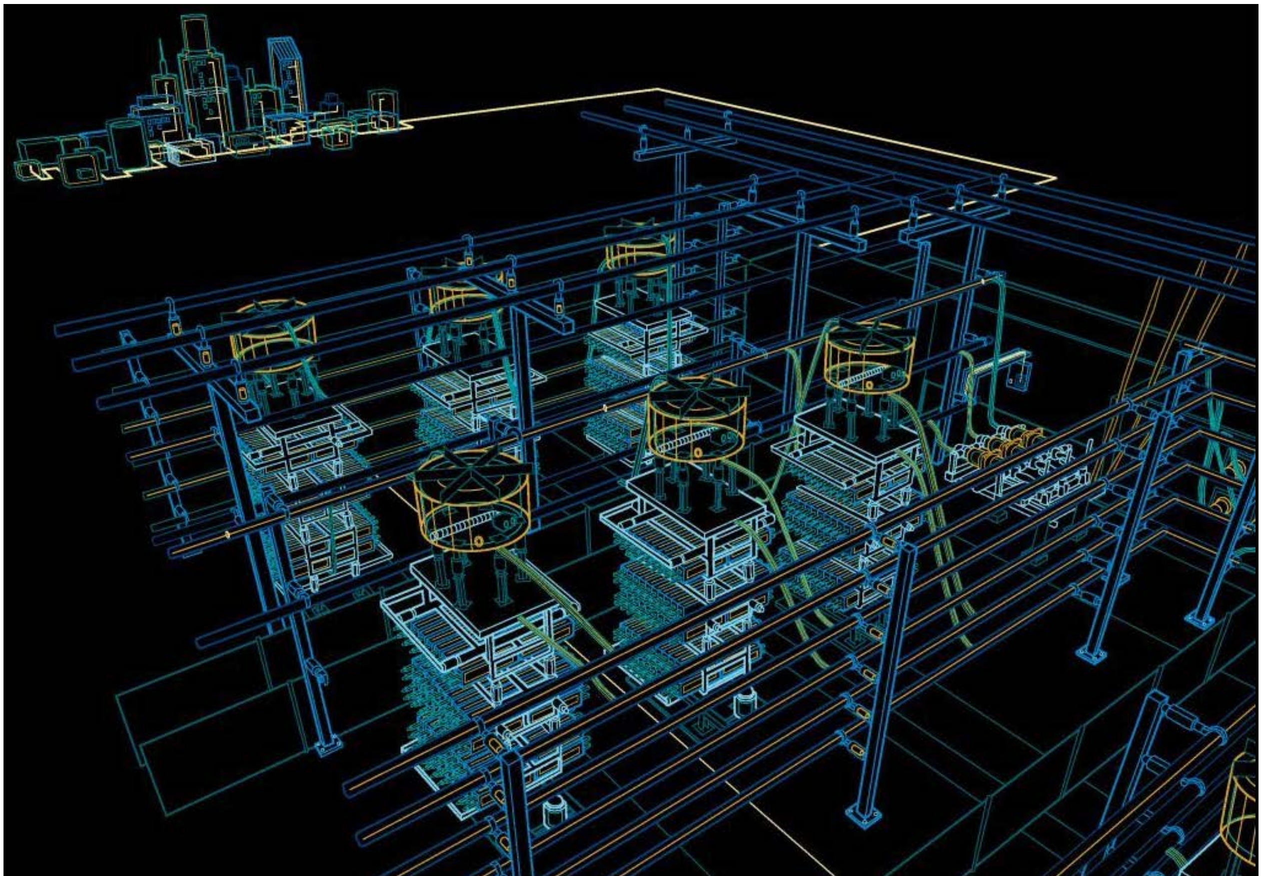
1. Mitigation for any environmental/cultural issues is not included.
2. All work is to be performed on existing PNM-owned land or easements.
3. AFUDC is not applied when customer payments are made concurrent with performance of work.
4. Assumes outages can be secured in timely manner and outages may be restricted to off-peak periods such as spring or fall.
5. PNM may elect to contract any or all parts of the project.
6. This design is in accordance with PNM's breaker configuration policy.
7. The project schedule is based on having all permits, agreements, and authorizations completed prior to initiation of construction work.
8. General station pricing based on current equipment standards and standard station design.
9. Right-of-way fees only include internal PNM labor.
10. Station grading based on flat site - No retaining walls.

Appendix B: Proposed Guadalupe Switching Station Layout



Layout assumed for Facilities Study estimate purposes only. Actual design will be determined when project is transitioned to construction

Appendix C: Technical Study



Public Service of New Mexico
GA Solar Wind Farm PSCAD Study

Final Report

Report No.E15783A-R00

3 December, 2015

Power and productivity
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LEGAL NOTICE

Prepared for:	Public Service of New Mexico (PNM)
Report No.:	E15783A-R00
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ABB Inc.
Power Systems Division
Grid Systems Consulting
940 Main Campus Drive, Suite 300
Raleigh, NC27606

ABB Inc.	2015-E15783A-1.0.R00		
Public Service Company of New Mexico **GA Solar Wind Farm PSCAD Study**	**Dept.** **Consulting**	Date Dec. 3, 2015	Pages 1035

Executive Summary:

PNM requested consulting services from ABB related to a Transmission Customer requesting 170 MW of long-term firm transmission service ("TSR") on the PNM transmission system between PNM's Guadalupe 345 kV station point of receipt and the Four Corners switchyard 345 kV point of delivery ("Transmission Path"). This report describes a PSCAD study performed as a follow-up to a prior PSLF study described in Reference [1].

PNM's 216 mile 345 kV transmission line from BA 345 kV Station (north of Albuquerque) to PNM's Blackwater 345 kV Station (in the Clovis-Portales area of eastern New Mexico), known as the "BB line" is located in proximity to areas of New Mexico with very large wind generation potential.

Based on the previous power flow and stability study analysis[1], a +221 MVAr (capacitive) to -90 MVAr (inductive) Static VAR Compensator ("SVC") at the Guadalupe station was required to provide the necessary voltage support to accommodate the TSR.

PNM requested ABB to perform a technical study using 3-phase models (e.g., PSCAD) to evaluate the control interaction of the different voltage control devices in the area since the positive-sequence, reduced-order simulation model (PLSF) used in the stability analysis does not allow for this type of detailed analysis. In addition, this study also evaluate is there is sufficient synchronizing voltage strength (short-circuit capacity) for the existing and proposed windfarms and Blackwater HVDC.

Prior PSCAD studies of other TSR on the BB line have shown the need for a synchronous condenser at Blackwater station to maintain acceptable system performance. Because detailed designs of the proposed windfarm were not available for this study, the windfarm was represented as generic Type 3 and Type 4 turbines as described in this report. Protection schemes such as Low Voltage Ride Through (LVRT) were not implemented for the studied generic wind farm models.

The goal of the study was to determine whether, for the generic wind farm models described above, stable post-fault recoveries can be achieved after disturbances on or near the BB line, including three-phase and single-phase faults, equipment trips, and single-phase trip and reclose (SPTR) sequences. The present PSCAD study showed reasonable post-fault recoveries without adding synchronous condensers at Blackwater.

From the studies in this report, the following other conclusions are reached:

1. A suitable preliminary strategy (detailed in Section 5) for control of voltage along the

[1] http://www.oasis.oati.com/PNM/PNMdocs/TSR_72831217__170_MW_TSIS_Report.pdf

BB line, with coordination of the various voltage controlling devices (Statcom, SVC, wind turbines, and HVDC) has been developed in the study. The strategy is similar to that used in prior studies and has been tested for large scale dynamic disturbances and found to give adequate response during post-fault recoveries. The controls of the existing systems (Blackwater HVDC, Aragonne Mesa and Taiban Mesa wind farms) are left unchanged.

2. For all windfarm configurations (generic Type 3 and 4 wind turbine models), with the properly tuned SVC and project wind farm controller, reasonable post-fault recoveries are obtained under all studied cases. However, some concerns and recommendations are also listed below:
   - It is suggested that Aragonne Mesa Wind Farm should be transfer-tripped in the event that the Aragonne Mesa STATCOM trips.
   - Modifications may need to be developed for the HVDC control to address commutation failures seen during recovery from three-phase faults at B-A 115 kV.
3. The frequency scan results indicate the possibility of low-order resonance conditions near 2nd harmonic. The presence of active controls may introduce some damping to the resonance, but it is recommended that the project design studies for the generation interconnection studies and SVC include consideration of scenarios involving transient injection of large amounts of 2nd harmonic, such as transformer energization and clearing of faults.

Because the studies in this report are based on generic Type 3 and 4 wind turbine models, the above conclusions from the studies should be considered representative but not decisive. This means that the studies must be re-visited with actual (manufacturer-specific) wind farm models, including collector system, when generation interconnection studies are performed.

Rev #	Revision	Date	Author	Reviewed	Approved
DISTRIBUTION	Public Service Company of New Mexico				

Contents

1 Introduction

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PNM’s 216 mile 345 kV transmission line from BA 345 kV Station (north of Albuquerque) to PNM’s Blackwater 345 kV Station (in the Clovis-Portales area of eastern New Mexico), known as the “BB line” is located in proximity to areas of New Mexico with very large wind generation potential.

Based on the previous power flow and stability study analysis described in Reference [1], a +221 MVAr (capacitive) to -90 MVAr (inductive) Static VAR Compensator (“SVC”) at the Guadalupe station was required to provide the necessary voltage support to accommodate the TSR.

PNM requested ABB to perform a technical study using 3-phase models (e.g., PSCAD) to evaluate the control interaction of the different voltage control devices in the area (see Figure 1 below) since the positive-sequence, reduced-order simulation model (PLSF) used in the stability analysis does not allow for this type of detailed analysis. In addition, this study also evaluate is there is sufficient synchronizing voltage strength (short-circuit capacity) for the existing and proposed windfarms and Blackwater HVDC.

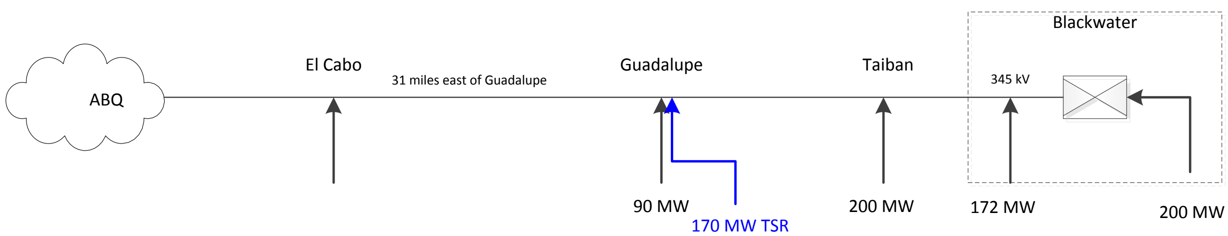

Figure 1: Transmission commitments on the Blackwater-BA 345kV Line

It is anticipated that the SVC previously investigated for installation at Guadalupe will need to be updated for conditions with the present TSR. Since the Guadalupe SVC is at a very preliminary stage, the design studied for the SVC will be preliminary. The Guadalupe SVC has a different size for the proposed study as compared to prior studies (221 Mvar capacitive versus 175 Mvar capacitive). In the PSCAD study described in this report, the SVC is modeled in detail including the TSC, TCR, transformer, filters, etc. Re-calculation of the main circuit parameters and component values has been performed for the 221 Mvar rating, and SVC gains have been re-checked for the new conditions with GA-Solar Wind Farm.

A technical study has been performed by ABB using a three-phase model in PSCAD to evaluate the control interaction of the different voltage control devices in the area. Because detailed designs of the proposed windfarm were not available for this study, the windfarm was represented as generic Type 3 and Type 4 turbines as described in this report. Protection schemes such as Low Voltage Ride Through (LVRT) were not implemented for the studied generic wind farm models at Blackwater 345kV. The goal of the study was to achieve stable post-fault recoveries following disturbances.

Power injections used for this analysis are:

- Blackwater 345 kV: 172 MW (windfarm)
- Blackwater HVDC: 200 MW East to West
- Taiban Mesa: 200 MW (windfarm)
- Aragonne Mesa: 90 MW (windfarm)
- TSR: 170 MW (windfarm injected at Guadalupe)

PNM requested ABB to perform the following:

1. Modify the existing PSCAD model of the BB line, Blackwater HVDC, Taiban Mesa and Aragonne Mesa wind farms to represent the conditions shown in Figure 2.1.
2. Perform dynamic studies in PSCAD to confirm adequate dynamic performance for fault disturbance scenarios.

The studies requested by PNM have been performed by ABB and are described in this report, which is organized as follows. In Section 2, the updated model of the Blackwater HVDC, Taiban Mesa wind farm, Aragonne Mesa wind farm, and BB line, comprising an overall PSCAD model that served as the starting point to the study, is described. Section 3 presents the model of the +221/-90 Mvar Guadalupe SVC. Section 4 describes the modifications made to the generic representations of the Type 3 and Type 4 wind turbines in previous studies to be used in the Project wind farms. The overall strategy developed for coordination of the various voltage controlling systems along the BB line is given in Section 5. The PSCAD dynamic simulation configurations, case lists, and results are then given in Section 6. Low order harmonic impedance scan results are given in Section 7, and conclusions from the study are given in Section 8.

2 Existing PSCAD Model

The PSCAD model in previous study that formed the basis for the studies described in this report is shown as Figure 2.1. The model is based on PSCAD 4.2.1 with Compaq Fortran 6.6. The following PNM equipment is included in the model:

- B-A 345 kV
- B-A – Guadalupe 345 kV line
- B-A 345/115 kV transformer (for application of faults at 115 kV)
- Guadalupe 345 kV
- Shunt reactors at Guadalupe (44 and 65 Mvar)
- Guadalupe – Taiban Mesa 345 kV line
- Taiban Mesa 345 kV
- Taiban Mesa – Blackwater 345 kV line
- Blackwater 345 kV

The system west of B-A is represented as a simple Thevenin equivalent source at B-A. The short circuit calculations at B-A are updated, and the two new options are provided for the Thevenin equivalent source:

- Weak B-A Equivalent:
  - o SCC (Short Circuit Capacity) = 3911 MVA (minimum short circuit level)
  - o Z1 = 30.43 ohm, 82.94 deg
  - o Z0 = 30.79 ohm, 79.92 deg
- Strong B-A Equivalent:
  - o SCC = 5422 MVA (28 ohm)
  - o Using the same impedance angle and Zo/Z1 as above, this gives:
    - Z1 = 21.95 ohm, 83.37 deg
    - Z0 = 23.82 ohm, 78.59 deg

The SPS ac system representation (eastern side of Blackwater HVDC 230 kV station) is a simple Thevenin equivalent source representing minimum short circuit conditions at the SPS 230 kV station as follows:

- SCC = 1900 MVA (minimum short circuit level)
  - o Z1 = 27.84 ohm, 80.0 deg
  - o Z0 = Z1

The values in the above system equivalents were established in consultation with PNM in 2015.

The PSCAD model is compatible with the following PSCAD version platform and compiler:

- PSCAD version 4.2.1
- Compaq Fortran 6.6

The PNM system model also includes black-box models of the Taiban Mesa, Aragonne Mesa wind farms, a generic wind farm at Blackwater 345 kV station (100% Type 4) compatible with the above PSCAD software version. The system model also includes components to represent single phase and 3 phase faults at various locations.

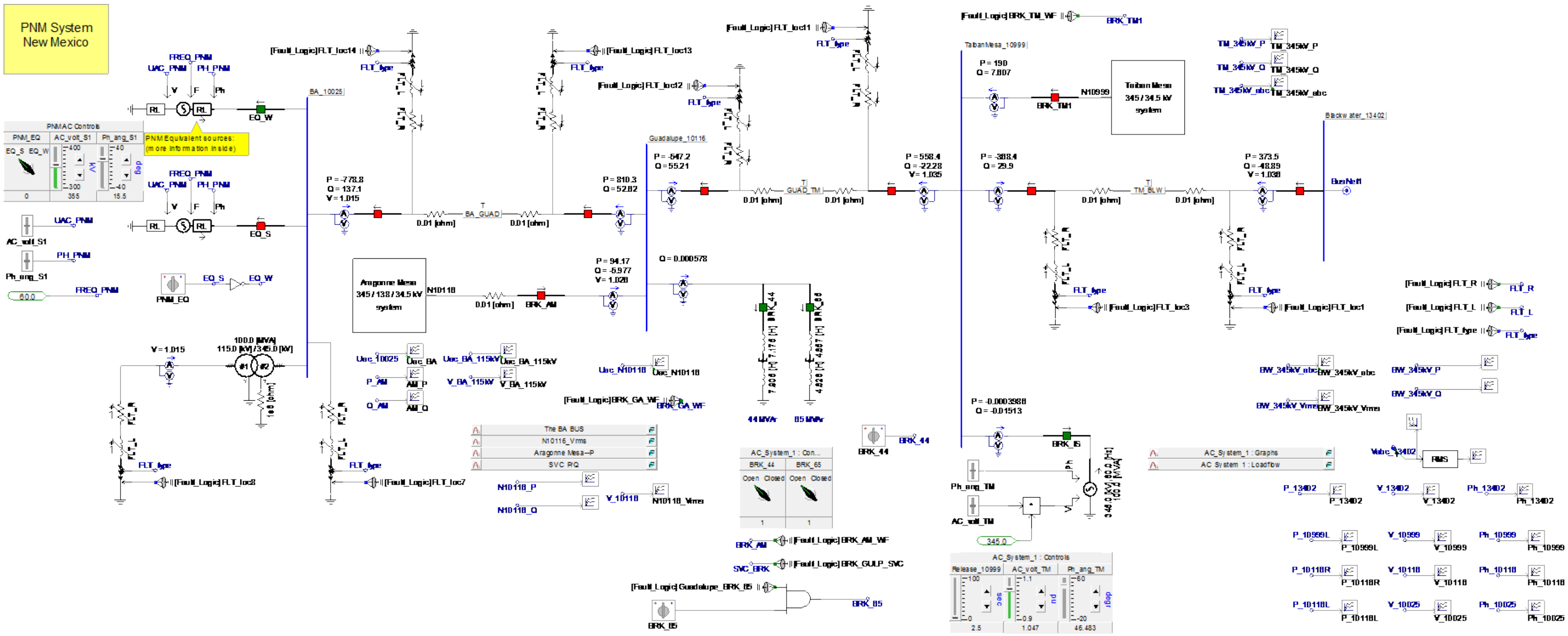

Figure 2-1: Original PSCAD Model (PNM System Shown)

3 Guadalupe SVC Model

The Guadalupe SVC model previously studied in PSCAD is updated in this study based on PSLF study results for the 170 MW GA Solar TSR. The new design for the SVC is given in the following sections.

3.1 Development of updated Main Circuit Parameters

The maximum capacitive and inductive ranges for the SVC as studied herein are +221 and -90 Mvar, respectively, as provided by PNM. The SVC is a conventional design with Vernier control. The design studied for the Guadalupe SVC in this report is preliminary, and the configuration of the SVC is similar to the previous study. It includes one TSC, one TCR, and two filters (5th and 7th). The preliminary main circuit parameters are given in Table 1.

Table 3-1: Guadalupe SVC parameters

Parameter	Value
SVC Full capacitive output at 1 pu volt [Mvar]	221
SVC Full inductive output at 1 pu volt (Mvar)	-90
Number of TCR	1
Number of filters	BP5+BP7
SVC max reference voltage [pu]	1.05
Transformer rating [MVA]	221
Transformer voltage pri/sec [kV]	345/18
TCR_L [mH/D-ph]	8.268
TSC_C [uF/D-ph]	361.50
FC5 full capacitive output [Mvar]	35
FC7 full capacitive output [Mvar]	31

3.2 Development of Preliminary Controls

The control system model used in this study represents ABB's standard SVC controls and is compatible with the PSCAD 4.2.1/ Compaq Fortran 6.6 platform described earlier. The control parameters and limits are updated to compatible with the current rating.

3.3 Development of Main circuit Models

The main circuit of the Guadalupe SVC is updated based on the parameters defined in Section 3.1. Similarly to the previous study, only one TSC, one TCR and two filters (5^{th} and 7^{th}) are enabled in the model.

3.4 Testing and Preliminary Tuning of SVC Models

The developed Guadalupe SVC has been incorporated into the overall PSCAD model described in Section 2. Model testing has been performed with Blackwater HVDC operating at 200 MW E-W, with 172 MW of wind generation at Blackwater represented as 100% Type 4 with generic wind turbine models, and with Taiban Mesa at 200 MW and Aragonne Mesa at 90 MW. For initial SVC tuning, the 170 MW GA Solar TSR has been represented as 50% Type 3 and 50% Type 4 with generic wind turbine models.

Initial testing of the SVC controls was performed for the following types of disturbances:

- Voltage regulator step response
- 3 phase 4-cycle fault at B-A 345 kV
- 1 phase 12-cycle fault at B-A 345 kV

The detailed test cases are listed in Section 6.1.

The above tests were intended to establish a very preliminary tuning of the SVC controls to achieve a reasonable response time with appropriate gain margin. Plots for the test cases are available in Appendix A. It is seen that with the new control gain, the response time (the interval between initiation of the step and the output reaching within 10% of the desired output) is less than 40ms, the maximum overshoot is limited to be less than 10% of the desired output, and the settling time (The elapsed time required so that the output comes and remains within +/- 5% of the desired output) is less than 100 ms.

The SVC control gains were further optimized during execution of subsequent dynamic studies in order to have appropriate post-fault recovery behavior. The finalized parameters are presented in this report. The dynamic studies include large disturbances such as trip of wind farms and trip of the Blackwater HVDC as described further in Section 6.

4 Project Wind Farm Models

A PSCAD model of the 170 MW GA Solar TSR wind farm does not yet exist, and PNM has therefore requested ABB to include suitable generic wind farm models. Wind farms comprising 100% Type 3 or 100% Type 4 (or a combination) wind turbines are to be considered.

The Blackwater wind farm was used to develop the model at Guadalupe for the 170 MW GA Solar TSR. The controller for the Guadalupe wind farm was re-tuned and re-tested to confirm that all models are working together properly in this study.

Three types of PSCAD models for the windfarms have been developed:

- 100% Type 3 turbines
- 100% Type 4 turbines
- 50% Type 3 turbines plus 50% Type 4 turbines

The models for the 170 MW GA Solar TSR wind farm have been developed only for ABB's and PNM internal use.

The complete system model view is shown as Figure 4.1.

In the ensuing discussion of the Type 3 and Type 4 models, and the resulting dynamic simulations, it should be emphasized that the wind models are generic, meaning that they are generally representative of the main characteristics that can be anticipated for Type 3 and Type 4 turbines, but the models are not representative of any specific design presently available.

For this reason, it needs to be pointed out that conclusions from the resulting studies are representative but not decisive. This means that the studies must be re-visited with actual (manufacturer-specific) wind farm models and actual collector system models if the Project wind farm advances to detailed design and construction.

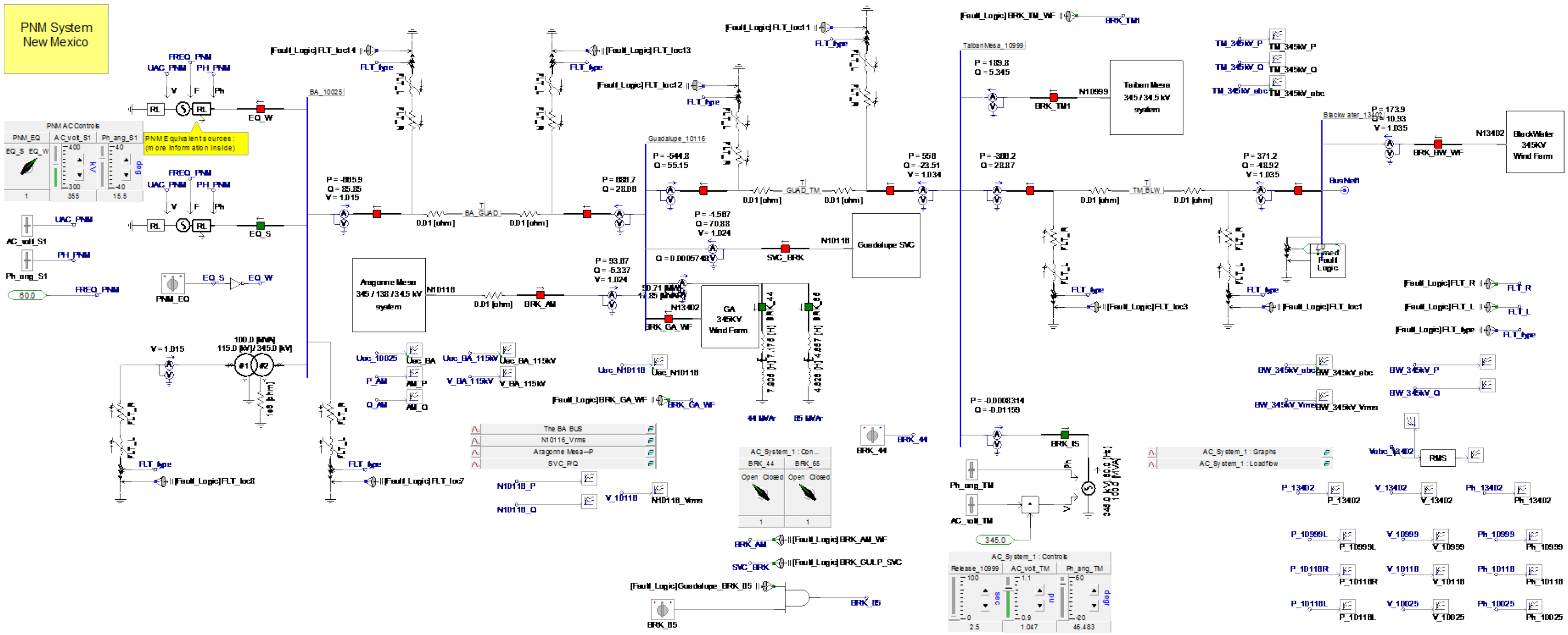

Figure 4-1: PSCAD Model With Project Wind Farm and Guadalupe SVC (PNM System Shown)

4.1 Wind Farm Model Based on Type 3 Wind Turbines

The Type 3 wind turbine from previous project has been modified to be used to represent the Project wind farms. The parameters assumed for the Type 3 wind farms are listed in Table 4.1.

Table 4-1: Generic Type 3 Wind Farm parameters

Parameter	GA Solar Wind Farm (170 MW)
Turbine rating, individual [MVA]	1.66667
Turbine rating, aggregate [MVA]	190
Wind farm step-up transformer MVA rating [MVA]	170
Wind farm step-up transformer impedance [pu]	0.08
Turbine step-up transformer MVA rating, aggregate [MVA]	170
Turbine step-up transformer impedance, aggregate [pu]	0.0575
Collector system voltage [kV]	34.5
Collector system impedance R/X/B/MVA Rating [pu/pu/pu/MVA]	0.011/0.043/0.08/170
Turbine power factor	0.95

Due the change in turbine rating, the main circuit parameters have been modified accordingly as shown in Figure 4.2 and 4.3.

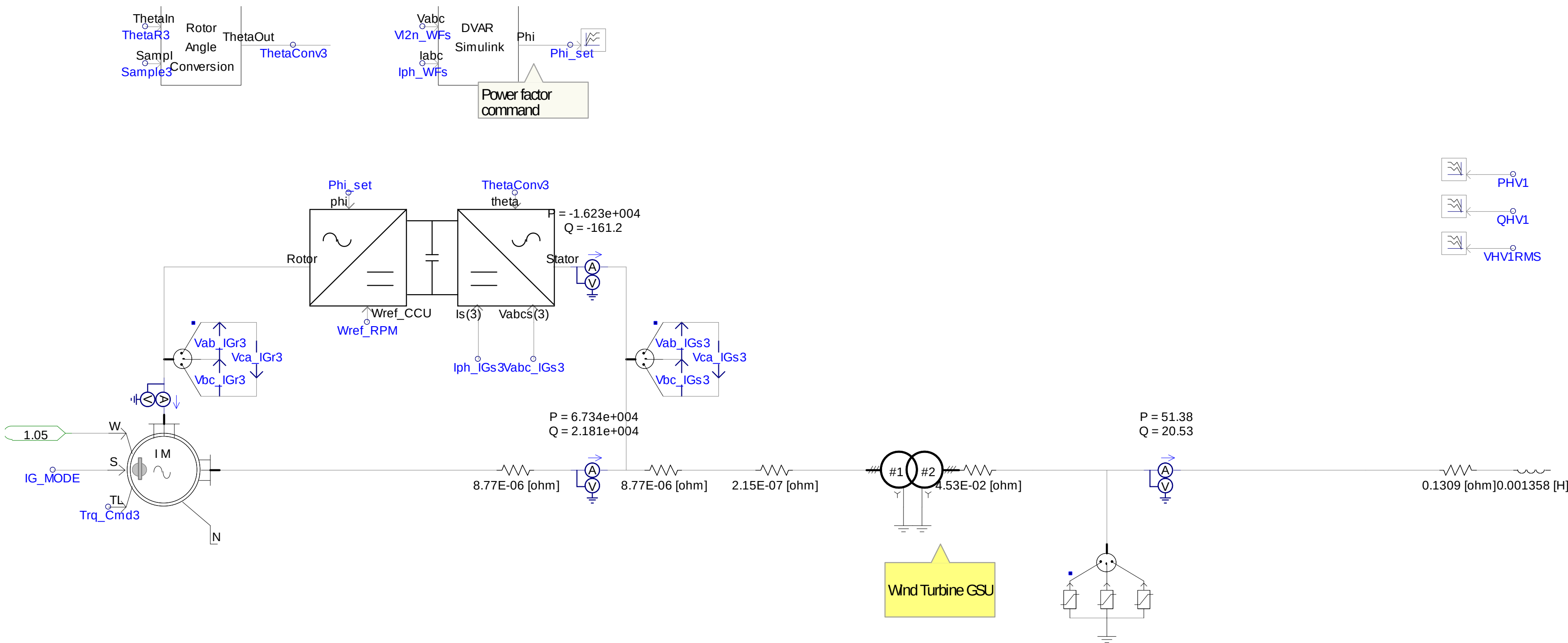

Figure 4-2: Type 3 wind turbine

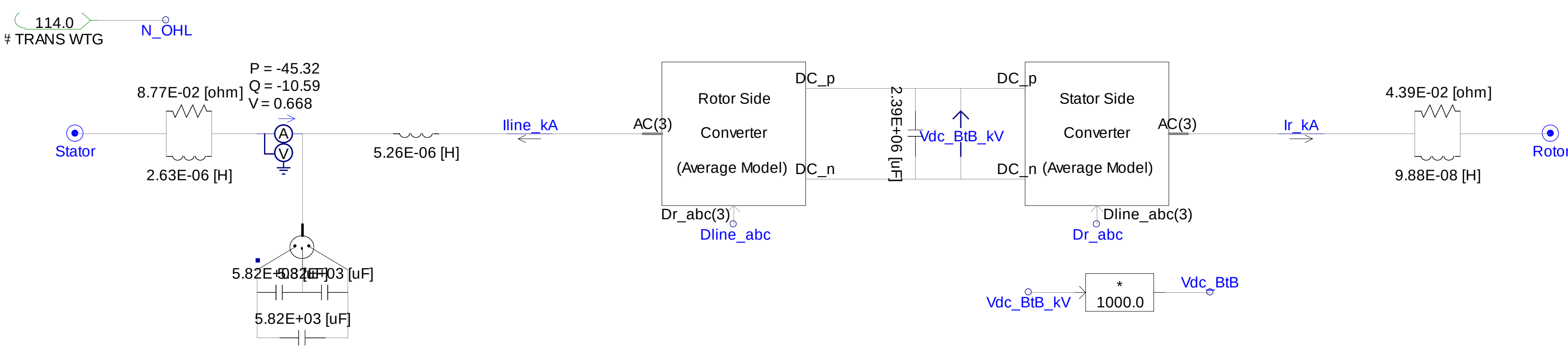

Figure 4-3: The Back-to-Back Converter of the Type 3 wind turbine

4.2 Wind Farm Model Based on Type 4 Wind Turbines

The Type 4 wind turbine model from previous PSCAD studies has been modified to be used to represent the Project wind farms. The parameters assumed for the Type 4 wind farms are very similar to the Type 3 parameters and are listed in Table 4.3.

Table 4-2: Generic Type 4 Wind Farm parameters

Parameter	GA Solar Wind Farm (170 MW)
Turbine rating, individual [MVA]-machine rating	1.5
Turbine rating, aggregate [MVA]	217
Wind farm step-up transformer MVA rating [MVA]	170
Wind farm step-up transformer impedance [pu]	0.08
Turbine step-up transformer MVA rating, aggregate [MVA]	170
Turbine step-up transformer impedance, aggregate [pu]	0.0575
Collector system voltage [kV]	34.5
Collector system impedance R/X/B/MVA Rating [pu/pu/pu/MVA]	0.011/0.043/0.08/170
Turbine power factor	0.985

Since the network strength is changed, the control parameters of the Type 4 turbines have been optimized accordingly as shown in Table 4.3.

Table 4-3: Generic Type 3 Wind Farm control parameters

Parameter	GA Solar Wind Farm (170 MW)
Reactive power loop proportional gain	0.5
Reactive power loop integral gain	0.8
Active power loop proportional gain	5000
Active power loop integral gain	0.4
PLL proportional gain	500
PLL integral gain	500

4.3 Wind Farm Model Based on 50% Type 3 and 50% Type 4 Wind Turbines

A third aggregated wind farm model based on a 50/50 split between Type 3 and Type 4 wind turbines was also developed. The 50/50 model was based on the same generic models as those used in the 100% Type 3 and 100% Type 4 wind farms, with scaling to represent the conditions for a 50/50 split.

The parameters used for the 50/50 split configuration were the same as those shown in Tables 2 and 3, with MVA ratings of the aggregate models adjusted for the 50/50 Type 3 / Type 4 split.

5 Coordination of Voltage Controls

A number of devices on the BB line are tasked with control of voltage along the line, including:

- The HVDC at Blackwater, which has an AC voltage control loop to regulate the 60kV tertiary (AC filter bus) voltage;
- The windfarm at Taiban Mesa, which regulates the voltage at Taiban Mesa 345kV bus using the existing GE Wind Volt-Amp-Reactive (WindVAR) system;
- The shunt reactors at Guadalupe;
- The STATCOM at Aragonne Mesa windfarm controlling power factor at the 345 kV PCC;
- The windfarm at Blackwater;
- The proposed SVC at Guadalupe;
- The proposed 170 MW TSR (GA Solar) wind farm at Guadalupe.

All of these devices are regulating voltage at different points along the BB line. The voltage schedules at Blackwater and Guadalupe have been investigated in powerflow using the PSLF program. The Guadalupe SVC model in PSLF has been updated to the new 221 MVAr rating. Other voltage regulators, for example at Taiban Mesa and Blackwater HVDC, were also modeled using the existing PSLF models and powerflow solution methods.

The results of the PSLF investigation are given in Appendix I for various voltage schedules (1.050, 1.035, 1.000, 0.975, and 0.95pu). The powerflow results indicate that a voltage setpoint above 1.00 pu is needed in order to limit i^2X reactive losses on the BB line and make best use of the SVC vars. In the dynamic studies, a setpoint in the range of 1.035 pu was used at the Guadalupe and Blackwater 345 kV stations.

A preliminary coordination of the slopes, set-points, and response times of the various voltage regulation devices has also been developed during the course of the dynamic studies, with the objective to achieve reasonable post-fault recovery characteristics without adverse control interaction.

Following conclusion of the dynamics studies described in Section 6, voltage control strategies were established for the decisive conditions with maximum transfers on the BB line as follows:

- Controls of the Aragonne Mesa and Taiban Mesa are unchanged (same as in base case provided by PNM)
- Taiban Mesa voltage set point 1.054 pu in the existing GE WindVAR system, which results in approximately 1.035 pu on the Taiban Mesa 345 kV station. This setting was also used for the Blackwater HVDC Upgrade Dynamic Performance Study (DPS) in 2008.
- The 44Mvar and 65Mvar shunt reactors at Guadalupe are switched off for conditions with 300 MW of additional (wind) injection at Blackwater.
- The Blackwater HVDC converter firing control (CFC) includes a closed-loop control of the 60kV tertiary (AC filter bus) voltage; i.e. no change from present strategy

In the study, the proposed 172 MW windfarm at Blackwater is set to control the reactive output at the wind turbine terminals to capacitive power factor of 0.90 (100% Type 4), with the objective to maintain unity power factor at the Blackwater 345 kV station.

- The SVC controls the Guadalupe 345kV station voltage. The voltage set point was set at 1.035 pu, with 2% slope in the SVC voltage regulator.

This strategy decouples the control loops and was found to achieve reasonable post-fault recovery characteristics. During later detailed studies, the strategy can be re-checked after the wind turbine manufacturer is identified and the collector system designs are established.

6 Dynamic Simulations

6.1 Dynamic Simulations Configurations and Case List

The PSCAD model was set up for the configurations shown in Table 6.1. Note the following:

- Configurations A through D are the main configurations studied.
- Dynamic simulations were performed for configuration B, C and D.

Table 6-1: PSCAD Model Configurations Studied

Configuration	Blackwater HVDC (MW)	Taiban Mesa Wind Farm(MW)	Aragonne Mesa Wind Farm (MW)	Guadalupe SVC (Mvar)	Blackwater 345kV Wind Farm	Guadalupe Wind Farm
A	200 E-W	200	90	+221/-90	172 MW TYP 4 wind farm	NONE
B	200 E-W	200	90	+221/-90	172 MW TYP 4 wind farm	170 MW TYP 3 wind farm
C	200 E-W	200	90	+221/-90	172 MW TYP 4 wind farm	170 MW TYP 4 wind farm
D	200 E-W	200	90	+221/-90	172 MW TYP 4 wind farm	85 MW TYP 3 wind farm +85 MW TYP 4 wind farm

The wind farm at Blackwater 345 kV was represented using generic Type 4 turbines. This is based on information from PNM that the developer of this wind farm plans to use Type 4 turbines.

Dynamics cases were run in PSCAD to evaluate the behavior of the above system configurations. The cases included selected cases from the Blackwater HVDC Dynamic Performance Study (DPS) and other cases related to the Project as follow:

Table 6-2: Dynamics Case List

Case	Description of Contingency	Config. A	Config.B	Config. C	Config. D
Case 0a	SVC Test: voltage regulator step response	X	NA[1]	NA	NA
Case 0b	SVC Test: 3 phase 4-cycle fault at B-A 345 kV	X	NA	NA	NA
Case 0c	SVC Test: 1 phase 12-cycle fault at B-A 345 kV	X	NA	NA	NA
Case 1	Disconn./conn. of largest shunt reactor, 65 Mvar, at Guadalupe	NA	X	X	X
Case 2	Disconn./conn. of shunt capacitor, 54 Mvar, at SPS converter bus	NA	X	X	X
Case 3	Disconnection/connection of filter FA2 on PNM side	NA	X	X	X
Case 4	1PhG, 100 ms, Blackwater SPS side, ≤10% rem. volt. on converter bus	NA	X	X	X
Case 5	1PhG, 100 ms, Blackwater PNM side, ≤10% rem. volt. on converter bus	NA	X	X	X
Case 6	3PhG, 100 ms, Blackwater SPS side, ≤10% rem. volt. on	NA	X	X	X

	converter bus				
Case 7	3PhG, 100 ms, Blackwater PNM side, ≤10% rem. volt. on converter bus	**NA**	**X**	**X**	**X**
Case 8	1PhG, 300 ms, Blackwater SPS side, ≤10% rem. volt. on converter bus	**NA**	**X**	**X**	**X**
Case 9	1PhG, 500 ms, Blackwater PNM side, ≤10% rem. volt. on converter bus	**NA**	**X**	**X**	**X**
Case 10	1PhG, 100 ms at Blackwater PNM side, SPTR[2] on the line BW - Taiban	**NA**	**X**	**X**	**X**
Case 11	1PhG, 100 ms at Taiban Mesa, SPTR on the line Taiban - Guadalupe	**NA**	**X**	**X**	**X**
Case 12	1PhG, 100 ms at Guadalupe, SPTR on the line Guadalupe – GA Solar	**NA**	**X**	**X**	**X**
Case 13	1PhG, 100 ms at GA Solar, SPTR on the line GA Solar - BA	**NA**	**X**	**X**	**X**
Case 14	Trip of Project wind farm	**NA**	**X**	**X**	**X**
Case 15	Trip of Blackwater wind farm (172 MW)	**NA**	**X**	**X**	**X**
Case 16	Trip of Taiban Mesa wind farm	**NA**	**X**	**X**	**X**
Case 17	Trip of Aragonne Mesa wind farm	**NA**	**X**	**X**	**X**
Case 18	Trip of DSTATCOM at Aragonne Mesa	**NA**	**X**	**X**	**X**
Case 19	Trip of Guadalupe SVC with RAS[3]	**NA**	**X**	**X**	**X**
Case 20	Trip of Blackwater HVDC	**NA**	**X**	**X**	**X**
Case 21	3PhG, 100 ms, ≤10% rem. volt. at 115 kV bus at B-A	**NA**	**X**	**X**	**X**
Case 22	1PhG, 100 ms, ≤10% rem. volt. at 345 kV bus at B-A	**NA**	**X**	**X**	**X**
Case 23	3PhG, 100 ms, ≤10% rem. volt. at 345 kV bus at B-A	**NA**	**X**	**X**	**X**

[1] Dynamic simulation not performed for this configuration

[2] SPTR = Single Phase Trip and Reclose

[3] RAS = Trip GA Solar project wind farm

The dynamics cases listed in Table 6.3 include a subset of the cases in the 2008 Dynamic Performance Study (DPS) for the Blackwater HVDC Upgrade project.

6.2 Dynamic Simulation Results

Dynamic simulation results are presented in the appendices as follows:

- Appendix A: SVC step response tests described as in Section 3.
- Appendix B: 100% Type 3 wind farm under weak network strength.
- Appendix C: 100% Type 4 wind farm under weak network strength.
- Appendix D: 50% Type 3 and 50% Type 4 wind farm under weak network strength.
- Appendix E: 100% Type 3 wind farm under strong network strength.
- Appendix F: 100% Type 4 wind farm under strong network strength.
- Appendix G: 50% Type 3 and 50% Type 4 wind farm under strong network strength.

It is seen from the Appendix B to G that for all configurations, in general the Guadalupe SVC, the post-disturbance recoveries of the project wind farm, Blackwater HVDC, Blackwater Wind Farm, Taiban Mesa Wind Farm, and Aragonne Mesa Wind Farm are generally reasonable for the studied dynamics cases. Stable post-fault recoveries are generally achieved for the dynamics cases under weak and strong network conditions. It can be concluded that the developed control tunings for the project wind farm and Guadalupe SVC achieve stable recoveries for all cases. However, observations that may need special attention are listed below:

- For several cases (Cases 11, 12, 13) the Taiban Mesa wind farm trips following the disturbance. The Taiban Mesa wind farm model provided by PNM is a black box model in PSCAD and the internal settings and signals are not accessible. The reason for the trip of the wind farm cannot be determined. It is worth noting that all these three cases are faults with SPTR. Tripping of the Taiban Mesa wind farm also occurred for a few cases in the 2010 Blackwater HVDC dynamic performance study and in PSCAD studies conducted in 2014 by ABB. This condition thus occurs for both pre- and post-Project conditions and is unrelated to the addition of the Project wind farm.
- Case 18 (Trip Aragonne Mesa STATCOM) has been run to 10 seconds for all configurations because the dynamics are not fully settled after four seconds (the simulation time for other cases). In this case, it is seen that the Guadalupe SVC, the project wind farm, Blackwater HVDC, Blackwater wind farm, and Taiban Mesa wind farm are acting as anticipated for the conditions. However, the trip of the Aragonne STATCOM in this case results in low voltage at the Guadalupe bus, and the Aragonne Mesa wind farm cannot maintain normal operation even with Guadalupe SVC gradually increasing its reactive power output. It is suggested that consideration should be given to transfer-trip of the Aragonne Mesa Wind Farm for loss of the Aragonne Mesa STATCOM.
- It is also seen for strong network conditions and with three-phase faults at the B-A 115 kV bus, the HVDC recovery is normal (Appendices F and G), but in the other configurations one or more commutation failures are seen during the HVDC recovery. PNM will need to review these observations to determine whether the results are acceptable or whether deeper investigation of the HVDC control settings is preferred.

It should be emphasized that the cases given in the appendices will need to be re-investigated during detailed design of the wind farms, when the wind turbine manufacturer(s) are identified and collector system impedances are calculated. The above studies must be re-visited with actual (manufacturer-specific) wind farm models, windfarm collector system, and detailed synchronous condenser models when the windfarm seeks generation interconnection to the PNM transmission system.

7 Low Order Harmonic Resonance

The installed amount of ac filtering shunt capacitors at Blackwater HVDC is large relative to the short circuit capacity of the Blackwater 345 kV station, and the installed shunt capacitors will be increased further by the addition of the Guadalupe SVC. Thus, the possibility of parallel resonance at low harmonics between the capacitive shunt compensation and the ac network may be increased in the post- Project system as compared to the present system. Investigation of the low order harmonic conditions in the post-Project system is therefore of interest.

An additional effect for both post- and pre-project conditions that has not been considered until now is the damping effect that the power electronic control systems can introduce at harmonic frequencies. This effect is not possible to capture using passive network equivalents that have been studied to date, but can be assessed for the active condition (with power electronics at the wind farms and HVDC in operation) by injection of harmonic currents into the network during time simulations in PSCAD. The system response (harmonic voltage) is then extracted by Fourier analysis and the resulting driving point impedance at the injection frequencies is calculated.

Low order harmonic resonance has been assessed for pre-and post-Project conditions by injection in PSCAD of harmonic currents at frequencies of 80Hz through 220 Hz, in steps of 20 Hz, during time-domain simulations. Two scan locations have been selected: Blackwater 345 kV bus (HVDC Bus) and Guadalupe 345 kV bus (Project Wind Farm Bus). Both weak and strong network conditions are considered. The resulting calculations of harmonic impedance are presented in Appendix H.

Case 1 in Appendix H is a benchmark case of existing conditions with the Blackwater HVDC operating at 200 MW E-W, with 172 MW of wind generation at Blackwater represented as Type 4 with generic wind turbine models, and with Taiban Mesa at 200 MW and Aragonne Mesa at 90 MW. A low-order resonance near 2nd harmonic is seen but appears to be well-damped (phase angles within ±50 degrees over the range from 100 Hz to 140 Hz).

In Case 2, the Guadalupe SVC is online but the Project wind farm is left offline. The resulting resonance shifts lower in frequency, to around 100 Hz, with relatively higher harmonic impedance. However, the harmonic resonance appears to be well damped.

Cases 3-6 in Appendix H show variations on Post-project conditions with the Project wind farm as follows:

- Case 3: 100% Type 3 wind farm, 1.2 pu rotor speed
- Case 4: 100% Type 3 wind farm, 0.8 pu rotor speed
- Case 5: 100% Type 4 wind farm
- Case 6: 50% Type 3, 50% Type 4 wind farm

The results from case 3-6 indicate the possibility of low-order resonance conditions near 2nd harmonic. The presence of active controls may introduce some damping to the resonance, but it is recommended that the project design studies for the generation interconnection studies and SVC include consideration of scenarios involving transient injection of large amounts of 2nd harmonic, such as transformer energization and clearing of faults.

8 Conclusions

From the studies in this report, the following conclusions are reached:

1. A suitable preliminary strategy (detailed in section 6) for control of voltage along the BB line, with coordination of the various voltage-controlling devices (Statcom, SVC, wind turbines, and HVDC) has been developed in the study. The strategy has been tested for large-scale dynamic disturbances and found to give adequate response during post-fault recoveries. The controls of the existing systems (Blackwater HVDC, Aragonne Mesa and Taiban Mesa wind farms) are left unchanged.
2. For all windfarm configurations (generic Type 3 and 4 wind turbine models), the Guadalupe SVC, the project wind farm, Blackwater HVDC, Blackwater Wind Farm, Taiban Mesa Wind Farm, and Aragonne Mesa Wind Farm show reasonable post-fault recoveries for the studied dynamics cases. In general, all devices reach stable post-fault recoveries for the studied dynamics cases under weak and strong network strength. However, some concerns and recommendations are also listed below:
    - It is suggested that Aragonne Mesa Wind Farm should be transfer-tripped in the event that the Aragonne Mesa STATCOM trips.
    - Modifications may need to be developed for the HVDC control to address commutation failures seen during recovery from three-phase faults at B-A 115 kV.
3. The frequency scan results indicate the possibility of low-order resonance conditions near 2nd harmonic. The presence of active controls may introduce some damping to the resonance, but it is recommended that the project design studies for the generation interconnection studies and SVC include consideration of scenarios involving transient injection of large amounts of 2nd harmonic, such as transformer energization and clearing of faults.

The PSCAD studies showed acceptable system performance for post-fault recoveries. However, because the studies in this report are based on generic Type 3 and 4 wind turbine models, the above conclusions from the studies should be considered representative but not decisive. This means that the studies must be re-visited with actual (manufacturer-specific) wind farm models, when generation interconnection studies are performed.

9 References

[1] ABB Consulting Technical Report 2015-E14906-1.0.R02, “GA Solar PSLF Study”, May 5, 2015. http://www.oasis.oati.com/PNM/PNMdocs/TSR_72831217__170_MW_TSIS_Report.pdf