SYSTEM IMPACT STUDY
FINAL REPORT

Prepared for
Tri-State Generation & Transmission Association, Inc.

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SUMMARY
A system impact study for the Owaissa Wind Ranch has been commissioned by Tri-State Generation and Transmission Association (Tri-State). A previous report [1] examined power flow, dynamic and short circuit studies for the Owaissa Wind Ranch rated at 40 MW, and with the new Gladstone to Walsenburg 230 kV transmission line not in service. This second study includes the proposed Gladstone to Walsenburg 230 kV line\(^1\), and investigates the Owaissa Wind Ranch at the same location, but with 80 and 120 MW rating options in addition to the original 40 MW.

Acceptable steady state performance during contingencies for the three acceptance criteria of line/transformer overload, undervoltage deviations and maximum/minimum bus voltage limits was generally achieved in the North East Area of New Mexico (also known as the NEA) for the operation of the Owaissa Wind Ranch up to 120 MW. Marginal under voltage deviations exceeding 5% were observed on some 115 kV busbars for the following contingencies: Ojo-Taos 345kV line (or 345/115kV Taos transformer), Colinas-Rowe Tap 115kV line, and the Black Lake-Taos 115kV line.

Acceptable performance during stability analysis was generally achieved. A pre-existing problem in this part of the system was identified for a fault on the Gladstone to Walsenburg 230 kV line\(^2\). This fault causes the Bravo Dome compressor motors to trip on under frequency. When wind generation at Owaissa is added at levels of 80 MW or higher, the load at Bravo Dome is able to remain in service.

PSCAD studies were performed to determine short circuit current levels, determine the level of –ve sequence imbalance, study wind turbine and SVC interactions, determine the effect of the pulsations from compressor motors on the wind turbines, look for amplification of wind turbine harmonics and to study the transient impact of closing the breaker on the Gladstone to Walsenburg 230 kV line.

From steady state, short circuit, electromagnetic transients and also transient stability analysis considerations, the operation of the Owaissa Wind Ranch up to 120 MW still appears a realistic objective.

The facilities required to achieve operation of the wind ranch at 120 MW are minimal. These include replacing the current transformers on the 115 kV

\(^1\) At this time, the proposed Gladstone – Walsenburg 230 kV line is projected to be in service in mid 2005.

\(^2\) Although the Gladstone – Walsenburg 230 kV line does not currently exist, in terms of the Owaissa Wind Ranch, the potential to trip Bravo Dome load for underfrequency conditions exists today and was confirmed to be possible after the addition of the Gladstone – Walsenburg 230 kV line.
transmission lines that are presently limiting and to identify if conductors on the 115 kV transmission have to be raised. The facilities study will address these issues.
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ELECTRANIX
1 INTRODUCTION

A system impact study for the Owaissa Wind Ranch has been commissioned by Tri-State for the requestor; the wind ranch will be located in the North East area of New Mexico (also known as the NEA) and will tap onto the existing 115 kV transmission line that extends from Springer substation to Rosebud substation. The tapping point will be approximately half way between Clapham and Rosebud substations (see Figure 1).

A previous report [1] examined power flow, dynamic and short circuit studies for the Owaissa Wind Ranch rated at 40 MW, and with the proposed Gladstone to Walsenburg 230 kV transmission line not in service. This second study investigates the Owaissa Wind Ranch at the same location with the Gladstone to Walsenburg line in service, with 80 and 120 MW rating options in addition to the original 40 MW.

Figure 1: Single line diagram of the area under study showing the location of the proposed Owaissa Wind Ranch.
This is a final report of the power flow, transient stability and PSCAD electromagnetic transients study results. The cases run are summarized in Appendix I, the steady state results are summarized in Appendix II, and the complete transient stability results are shown in Appendix III. The PSCAD study results (Section 7) have been added since the Progress Report 3 dated March 30th, 2004.

2 BASIC ASSUMPTIONS
The assumptions that apply for the power flow study are summarized as follows:

2.1 Originating Case for Study
The originating case for this study is the 2008 hs2-sa case prepared by member organizations of the Western Electricity Coordinating Council (WECC). This case included the proposed Gladstone to Walsenburg 230 kV transmission line.

2.2 Representation
Significant detail was included in the representation of the wind ranch to include the main substation transformer, and an equivalent 34.5 kV feeder to each cluster of wind turbine generators (WTGs) connected to that feeder. The detail of the layout and information of the feeder was taken from single line diagrams SE-1, for the 40, 80 and 120 MW wind ranch options.

Each cluster of 12 to 15 WTGs was represented as a single WTG in the studies. There were 2 clusters and consequently 2 equivalent WTGs represented in the 40 MW option. The 80 MW option was represented by 4 lumped WTGs for its 4 clusters, and the 120 MW option by 6 lumped WTGs for 6 clusters. This information is shown in Figures 2, 3 and 4.

The underground 34.5 kV cables applied for each feeder to its single equivalent lumped WTG consisted of two types of cables:

1000 MCM Aluminum between the main substation and the cluster.
4/0 Aluminum within each cluster.

The parameters applied for each type of cable for the power flow program in per unit of 100 MVA base for 1000 feet length were:

<table>
<thead>
<tr>
<th>Table 1: Parameters for Wind Ranch 33 kV collector system cables.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cable</strong></td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1000 MCM Al</td>
</tr>
<tr>
<td>4/0 Al</td>
</tr>
</tbody>
</table>
Figure 2: 2 Feeder Equivalent Model For 40 MW Wind Ranch used in Cases 1,2,5 and 6 of system impact study. All impedances on 100 MVA base.
Figure 3: 4 Feeder Equivalent Model For 80 MW Wind Ranch used in Case 3 and Case 7 of system impact study. All impedances on 100 MVA base.
Figure 4: 6 Feeder Equivalent Model For 120 MW Wind Ranch, used in Case 4 and Case 8 of system impact study. All impedances on 100 MVA base.
For each wind ranch rating option, the 34.5 kV cable feeders to the equivalent lumped WTG is summarized as follows:

### Table 2: Wind Ranch 33 kV feeder cable and unit transformer impedances

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Feeder Length (miles)</th>
<th>R (pu)</th>
<th>X (pu)</th>
<th>B (pu)</th>
<th>Unit Tfr Impedance (pu)</th>
<th>No. WTGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feeder #1</td>
<td>1.68</td>
<td>0.0315</td>
<td>0.0338</td>
<td>0.007</td>
<td>0.276</td>
<td>13</td>
</tr>
<tr>
<td>Feeder #2</td>
<td>1.50</td>
<td>0.0265</td>
<td>0.0190</td>
<td>0.006</td>
<td>0.257</td>
<td>14</td>
</tr>
<tr>
<td>80 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feeder #1</td>
<td>2.05</td>
<td>0.0368</td>
<td>0.0409</td>
<td>0.0082</td>
<td>0.2395</td>
<td>15</td>
</tr>
<tr>
<td>Feeder #2</td>
<td>1.44</td>
<td>0.0259</td>
<td>0.0238</td>
<td>0.0059</td>
<td>0.3</td>
<td>12</td>
</tr>
<tr>
<td>Feeder #3</td>
<td>3.08</td>
<td>0.0548</td>
<td>0.0597</td>
<td>0.0122</td>
<td>0.2395</td>
<td>15</td>
</tr>
<tr>
<td>Feeder #4</td>
<td>2.05</td>
<td>0.0361</td>
<td>0.0257</td>
<td>0.0084</td>
<td>0.3</td>
<td>12</td>
</tr>
<tr>
<td>120 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feeder #1</td>
<td>2.07</td>
<td>0.0369</td>
<td>0.0409</td>
<td>0.0082</td>
<td>0.2395</td>
<td>15</td>
</tr>
<tr>
<td>Feeder #2</td>
<td>2.79</td>
<td>0.05</td>
<td>0.0639</td>
<td>0.0109</td>
<td>0.276</td>
<td>13</td>
</tr>
<tr>
<td>Feeder #3</td>
<td>0.74</td>
<td>0.013</td>
<td>0.0111</td>
<td>0.003</td>
<td>0.3</td>
<td>12</td>
</tr>
<tr>
<td>Feeder #4</td>
<td>4.95</td>
<td>0.0884</td>
<td>0.1127</td>
<td>0.0192</td>
<td>0.2876</td>
<td>13</td>
</tr>
<tr>
<td>Feeder #5</td>
<td>2.41</td>
<td>0.0429</td>
<td>0.0511</td>
<td>0.0094</td>
<td>0.2764</td>
<td>13</td>
</tr>
<tr>
<td>Feeder #6</td>
<td>7.27</td>
<td>0.1302</td>
<td>0.1807</td>
<td>0.0278</td>
<td>0.2395</td>
<td>15</td>
</tr>
</tbody>
</table>

Each individual WTG is a GE Wind-VAR unit rated at 1.5 MW, and the reactive power range that can be applied for ac voltage control is +0.49 MVAR, and –0.73 MVAR.

### 2.3 SVC at Clapham

Only one ±25 MVAR is modeled to be in service at Clapham. Although a second ±25 MVAR is being planned at the same location, it was not considered in these studies.

### 2.4 Thermal Capacity of the Springer to Rosebud 115 kV Line

The thermal capacity of the 115 kV transmission line from Springer to Rosebud is applied at 146.6 MVA.

### 2.5 Power Flow Acceptance Criteria

For each of the power flow cases and each contingency, bus voltages and equipment ratings are to fall within the WECC and Tri-State system operation criteria. These include:

- Bus Voltages: 0.95 < V steady state < 1.05 during normal system conditions, and must be between 0.90 < V steady state < 1.10 during single contingency outage conditions.
• Steady state voltage deviations during contingencies must be less than 5%. This is a screening test for potential voltage collapse, where voltages that drop by more than 5% are flagged for further review.
• Line and Transformer Ratings in normal steady state conditions must not exceed 80% of the full load rating.
• Line and Transformer Ratings during contingencies must be within 100% of the continuous rating.
• Load tap changers, phase shifters, and switched shunt devices can operate during contingencies.
• Fixed area power flow interchanges are enforced during all contingencies.

2.6 Transient Stability Acceptance Criteria
For each of the base cases and each contingency, transient bus voltages and frequency deviations are to fall within the WECC and Tri-State system operation criteria. These criteria are summarized in Appendix IV, and include:

• Bus frequencies at a load bus must not fall below 59.6Hz for longer than 6 cycles.
• Voltage dip at a load bus must not exceed 25% at load busses, or 30% a non-load busses.
• Voltage dip at a load bus must not exceed 20% for longer than 20 cycles.
• Mechanical oscillations must be damped after 20 seconds.

2.7 Simulation Software
The simulation software used for this study is the GE PSLF V14.1 program. This version of the program includes the latest GE PSLF wind turbine dynamics models.

2.8 Load Sink
The power balance when wind power from Owaissa was being generated was achieved by reducing power generated by San Juan by an equivalent amount. This needs to be corrected to be load added at Hernandez.

3 LOAD FLOW STUDY METHODOLOGY
This interim report considers the steady state system impact of the power flow during single contingencies. In this particular study, outages within the NEA were simulated as listed in Appendix I.

For each contingency, Cases 1 to 4 are with the Bravo Dome compressor motors all in-service and fully loaded at 43.8 MW total.
• Case 1 is the base case with no wind power being generated.
• Case 2 is with 40 MW of WTG capacity in place and fully loaded.
• Case 3 is with 80 MW of WTG capacity in place and fully loaded.
• Case 4 is with 120 MW of WTG capacity in place and fully loaded.
Cases 5 to 8 are for the Bravo Dome compressor motors all out of service.

- Case 5 is the base case with no wind power being generated.
- Case 6 is with 40 MW of WTG capacity in place and fully loaded.
- Case 7 is with 80 MW of WTG capacity in place and fully loaded.
- Case 8 is with 120 MW of WTG capacity in place and fully loaded.

A summary of the results for each case studied is included in Appendix II.

4 RESULTS (Steady State)

The results of the power flow study in Appendix II consider the power flow acceptance criteria (Section 3.5 above) for the NEA area of interest (Zone 121 in the WECC base case). Output results are only shown if the power flow approaches violation conditions.

The conclusions are:

- There were no overload violations as a consequence of the wind farm, for any power level up to 120MW. The transformer at the Rowe Tap was overloaded in the base case and throughout the contingency cases at 0.84 per unit.

- Undervoltage deviation violations greater than 5% were observed when the wind power from Owaissa was both 80 and 120 MW for Contingency No. 5 (outage of the Black Lake -Taos 115 kV line), and for Contingency No. 8 (outage of the Colinas – Rowe Tap 115 kV line).

Additional undervoltage deviations exceeding 5% were observed at the Taos 115 kV busbar for outage of the Ojo – Taos 345 kV line (Contingency 12) and for the outage of the Taos 345/115 kV transformer (Contingency 15) when the wind farm was generating at 120 MW and the compressor motors at Bravo Dome were out of service.

- There were no bus voltage violations for contingency conditions.

The ±25 MVAR SVC at Clapham remained operational for the cases studied, and was sized sufficiently to prevent any voltage violations. Care was taken in coordinating the switching of the shunt capacitor banks at Clapham and Springer substations (What does this mean, “Care was taken…”).

5 STABILITY STUDY METHODOLOGY

Stability studies were performed with the goal of evaluating the voltage stability response of the NEA 115 kV power system, and dynamic stability of the Bravo Dome synchronous compressor motors.
Load flow base cases 1 to 4 (Appendix I) have the Bravo Dome compressor motors operating. These base cases were run with the disturbances listed in Table 3. These cases are not exhaustive, but have been selected to represent severe disturbances. Since disturbance S2 was not applicable to Case 1, a total of 19 simulations were run. For this study, results of the disturbance simulations were examined relative to the April 2003 *NERC/WECC Planning Standards*. These simulations represent disturbances based on the WECC 2008 heavy-summer configuration.

It is noteworthy to mention that the transient stability representation of the compressor motors does not include the pulsating torque effect on the compressor motors due to piston action. This effect was included in PSCAD models, but only for breaker energization studies (Section 7).

The cases were undertaken with the GE Wind -VAR wind turbine and generator model included in the PSLF program and with specific parameters provided by GE Wind. This model includes the reactive power control capability of the wind turbine.

### Table 3: Transient Stability Disturbance List

<table>
<thead>
<tr>
<th>Test</th>
<th>Stability Disturbance Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>3Ø permanent fault on the 34.5 kV Transformer bus, transformer clears after 6 cycles</td>
</tr>
<tr>
<td>S2</td>
<td>Sudden loss of Power from the Wind Ranch due to wind gust</td>
</tr>
<tr>
<td>S3</td>
<td>3Ø permanent fault on the Gladstone-Walsenburg 230kV line, clears after 6 cycles</td>
</tr>
<tr>
<td>S4</td>
<td>3Ø permanent fault on the Springer-Black Lake 115kV line, clears after 6 cycles</td>
</tr>
<tr>
<td>S5</td>
<td>3Ø permanent on the Ojo-Taos 345kV line, clears after 6 cycles.</td>
</tr>
</tbody>
</table>

6 RESULTS (Dynamic Stability)

6.1 Summary of Dynamic Stability Results

Results for all of the 19 disturbance simulations are shown in Appendix III, and met or exceeded the specified Category of the Planning Standards (See Appendix IV).

6.2 Discussion of Bravo Dome Compressor Motor Tripping

Although the monitored system busses met the required stability criteria, several of the disturbance cases caused load tripping of the Bravo Dome compressor motors. During a three-phase fault applied to the middle of the Gladstone-Walsenburg 230 kV line (Test S3), Bravo Dome compressor motors tripped due to under-frequency for Cases 1 and 2 (0 MW and 40 MW of wind, respectively). As more wind
generation was added in Cases 3 and 4 (80 MW and 120 MW respectively), the compressor motors at Bravo Dome were able to remain on through the disturbance. For Case 2 the 40MW Owaissa wind ranch also tripped due to undervoltage.

If the 3-phase fault on the Gladstone-Walsenburg line is cleared after 4 cycles instead of 6 (a realistic scenario), the Bravo Dome motors do not trip in Case 2, which has 40 MW of wind generation. Additionally, the faster fault removal is sufficient to prevent the wind ranch from tripping during this disturbance. The reduced fault clearing time is not sufficient to prevent the Bravo Dome compressor motors from tripping during Case 1, where no power is available from wind. Further tests with simulated 1 phase faults instead of three phase faults with 6 cycle clearing time show there is no tripping of the Bravo Dome compressor motors.

It is worth noting that the under-frequency resulting from the Gladstone-Walsenburg 230kV line fault was reported in the WECC 2003 Study Program Annual Report – Case D0310, published Feb. 2004. This is an indication that the addition of larger amounts of wind generation in the immediate vicinity of the Bravo Dome compressor motors provides system support including offsetting the required power flow through the radial lines to the motors.

6.3 Discussion of Tripping of Owaissa Wind Ranch

During the 3 phase fault on the Walsenburg-Gladstone 230kV line, the turbines at the Owaissa wind ranch also trip off for the 40 MW case. As discussed in Section 6.2, this condition may be alleviated by reducing the fault clearing time to 4 cycles from 6. Additionally, a fault on the main substation transformer at the wind farm site causes the wind ranch to be islanded from the network, and the wind turbines to trip.

7 SHORT CIRCUIT AND TRANSIENTS STUDY

The following studies were performed with PSCAD:
- Short Circuit Current Calculations
- Measurement of –ve sequence voltage phase unbalance
- Interactions between the Clapham SVC and the Wind Turbines
- Impact of pulsating Bravo Dome compressor motors on the wind turbines
- Harmonic Studies
- Impact of Closing the Gladstone to Walsenburg 230 kV line

7.1 Model Development

All models were developed in PSCAD V4.0.3 (the latest release at the time of this study). The system representation is shown in Figure 5 (most objects in the single line diagram (SLD) in Figure 5 are page components, with detailed models on sub-pages).

The E-TRAN program is used to translate loadflow information into PSCAD and to initialize loads, transformer tap settings and to set machine initial conditions. Most
of the system 3 or 4 busses away from the study area is represented in detail, with multi-port system equivalents being calculated at San Juan 345 kV, Comanche 230 kV, Storrie, Walsenburg and Hernandez 115 kV busses. E-TRAN calculates system equivalents by re-creating the admittance matrix from the loadflow information and uses network reduction techniques to reduce the network to a size manageable in PSCAD. Data from the dynamics file (machine reactances) was imported and used to update the loadflow generator impedances so that accurate system equivalents can be created.

In addition:

- All transformers are represented using detailed 2 or 3 winding transformer models, including wye-delta transformations, neutral grounding, tap settings and non-linear saturation.
- The 115 kV transmission system from Rosebud back to Springer is represented with detailed phase-domain frequency dependent line models, whereas remaining transmission lines are represented based on loadflow RXB data (traveling wave Bergeron models for longer lines and pi-sections for short lines).
- The SVC at Clapham is modeled with a thyristor switching model of the TCR. The model was developed for a different project [2]. Although in the future there will be 2 - 25 MVAR SVC units, only a 25 MVAR single unit was included in this study.
- The compressor motors at Rosebud and York Canyon were also modeled in a previous study [2] and re-used here. They are represented with DQ0 machines, and include the multi-mass and piston torsional effects. The models were validated against site measurements.
- The wind farm units are modeled using the latest PSCAD model from GE Wind, with a recommended number of units lumped together as per Section 2.2.
7.2 Short Circuit Current Calculations

The wind farm manufacturer (GE Wind) specified that short circuit studies should be performed with a PSCAD simulation model (as opposed to traditional loadflow short circuit calculations).

To verify the system representation in PSCAD, short circuit currents at the 34.5 kV bus were calculated using PSLF and were compared to those calculated in the PSCAD model. The base case system (without any wind represented) was used for this test case. The comparative results are summarized in Table 4.

Table 4 – Comparison of Short Circuit Current Calculations from Loadflow Programs Compared to PSCAD

<table>
<thead>
<tr>
<th>Case Description</th>
<th>SCC (3Φ Short Circuit Current Level, kA, RMS)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Loadflow (PSLF)</td>
<td>3.69</td>
<td>Traditional SCC Calculations.</td>
</tr>
<tr>
<td>2. PSCAD (detailed models not used)</td>
<td>3.69</td>
<td>Good verification of system equivalents.</td>
</tr>
<tr>
<td>3. PSCAD (detailed transformers used)</td>
<td>3.78</td>
<td>Some detailed transformer winding data had lower impedances compared to loadflow data.</td>
</tr>
<tr>
<td>4. PSCAD (detailed line models added)</td>
<td>3.80</td>
<td>Fundamental frequency impedance/admittance of detailed line models match the loadflow.</td>
</tr>
<tr>
<td>5. PSCAD (DQ0 machines added, SCC at first cycle)</td>
<td>3.79</td>
<td>SCC calculations in the loadflow use sub-transient reactance.</td>
</tr>
<tr>
<td>5. PSCAD (DQ0 machines added, SCC at 4th cycle)</td>
<td>3.5</td>
<td>SCC levels will be lower at the time of opening breakers due to frequency dependent effects in machines (i.e. XD'', XD'''...)</td>
</tr>
<tr>
<td>6. PSCAD (detailed SVC replaces SVC modeled as a generator)</td>
<td>3.2</td>
<td>In the previous cases, the SVC is represented as a generator, with an impedance that causes the SCC level to be higher.</td>
</tr>
</tbody>
</table>

The test cases show that the approach using the PSLF program for short circuit analysis will tend to exaggerate the short circuit levels. In particular:

- The short current levels will be lower 3 or 4 cycles into the fault (when the breakers have to interrupt the fault current) compared to the first cycle current levels. The loadflow program often uses subtransient reactance (Xd'') as a machine impedance, which is analogous to taking the first cycle fault current.
- The SVC will add short circuit current contribution if represented as a generator (with 0 MW output). The real SVC does not contribute to the short circuit current.
The PSCAD result is a time domain transient simulation program, so there will also be a decaying dc offset in the fault current waveforms. The fault currents are computed by taking the currents in the first cycle of the fault (maximum current minus the minimum current) / 2, and then converted to RMS. A typical short circuit current waveform is shown in Figure 6.

An additional test case was performed to approximate the short circuit impedance of the GE 1.5 MW wind turbines. The PSCAD model of the turbine was run feeding a 1 pu resistance on the 0.575 kV terminals of the turbine. The unit was then faulted (0 resistance 3 phase fault) and the fault current determined. From the first cycle fault current (averaged over 3 phases), the short circuit impedance is approximately 0.4 pu on a 0.575 kV and 1.5 MVA base.

If a fault is prolonged, the Rosebud compressor motors will slow down and the fault currents can exhibit pole-slipping beating characteristics. In reality these motors would trip on under-frequency for prolonged faults.

Table 5 shows the short circuit current results from the full PSCAD model with the dc offset ignored:
Table 5: AC Component of Fault Current (kA, RMS)

<table>
<thead>
<tr>
<th>Case</th>
<th>Fault Bus</th>
<th>Fault Description</th>
<th>SC Current (1st Cycle)</th>
<th>SC Current (3rd Cycle)</th>
<th>SC Current (6th Cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>12062</td>
<td>Rosebud 115kV</td>
<td>2.22</td>
<td>1.70</td>
<td>0.82</td>
</tr>
<tr>
<td>SC2</td>
<td>12063</td>
<td>Rosebud 13.8kV</td>
<td>14.90</td>
<td>11.37</td>
<td>4.24</td>
</tr>
<tr>
<td>SC3</td>
<td>10394</td>
<td><strong>Foresight 115kV</strong></td>
<td>2.65</td>
<td>1.82</td>
<td>0.92</td>
</tr>
<tr>
<td>SC4</td>
<td>12105</td>
<td><strong>Foresight 34.5kV</strong></td>
<td>8.31</td>
<td>3.34</td>
<td>4.69</td>
</tr>
<tr>
<td>SC5</td>
<td>12020</td>
<td>Clapham 115kV</td>
<td>2.96</td>
<td>2.17</td>
<td>1.31</td>
</tr>
<tr>
<td>SC6</td>
<td>12019</td>
<td>Clapham 69kV</td>
<td>2.38</td>
<td>2.34</td>
<td>2.05</td>
</tr>
<tr>
<td>SC7</td>
<td>12101</td>
<td>Gladstone 230kV</td>
<td>2.05</td>
<td>1.58</td>
<td>1.43</td>
</tr>
<tr>
<td>SC8</td>
<td>12100</td>
<td>Gladstone 115kV</td>
<td>4.04</td>
<td>3.25</td>
<td>2.52</td>
</tr>
<tr>
<td>SC9</td>
<td>12077</td>
<td>Springer 115kV</td>
<td>3.50</td>
<td>3.11</td>
<td>2.82</td>
</tr>
<tr>
<td>SC10</td>
<td>12076</td>
<td>*<strong>Springer 69kV</strong></td>
<td>1.77</td>
<td>1.74</td>
<td>1.74</td>
</tr>
</tbody>
</table>

** In some cases, beat frequencies due to machine speed changes cause the current to increase from the third cycle to the sixth cycles, or cause the two measurements to be very different.

*** Due to conflicting transformer impedance data, the load flow data was used for the Springer transformer for case SC10. This caused the short circuit current on this bus to rise slightly.

7.3 Measurement of Negative (-ve) Sequence Voltage Levels

The PSCAD model was run in steady state at 0, 40, 80 and 120 MW wind levels. The instantaneous A, B and C voltages were recorded, processed by Fourier analysis, and then expressed in terms of fundamental frequency sequence components.

The –ve sequence compensation in the SVC controls was turned off. The –ve sequence is predominantly caused by the use of non-transposed transmission lines through 115 kV system.

The results are shown in Table 6. Although the wind farm increases the –ve sequence unbalance, levels are quite small. The positive (+ve) sequence voltages are controlled (either by the SVC or by the excitation system on the compressor motors) so are constant.
Table 6: Measurement of Voltage Sequence Components (pu)

<table>
<thead>
<tr>
<th>Case</th>
<th>Clapham (SVC 115 kV Bus)</th>
<th>Rosebud (Compressor 13.8 kV Bus)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ve Seq</td>
<td>-ve Seq</td>
</tr>
<tr>
<td>1 (0 MW Wind)</td>
<td>1.02</td>
<td>0.0023</td>
</tr>
<tr>
<td>2 (40 MW Wind)</td>
<td>1.02</td>
<td>0.0038</td>
</tr>
<tr>
<td>3 (80 MW Wind)</td>
<td>1.02</td>
<td>0.0058</td>
</tr>
<tr>
<td>4 (120 MW Wind)</td>
<td>1.02</td>
<td>0.0074</td>
</tr>
</tbody>
</table>

Note that the loads in the PSCAD model are symmetrical on all 3 phases, whereas the loads in the real system can be unbalanced and will add to the levels shown in Table 6.

7.4 Interactions between the Clapham SVC and the Wind Turbines
The PSCAD models were run over a 10 second period to look for interactions between the SVC and the Wind Turbines units. In all cases (0, 40, 80 and 120 MW of wind) there were no apparent oscillations or control interactions. The SVC controls use Proportional-Integral controllers, but fortunately they are considered with a droop characteristic that prevents multiple operating points and minimizes hunting problems with other nearby fast-acting control devices such as the W TGs.

7.5 Impact of Pulsating Bravo Dome Compressor Motors on the Wind Turbines
The compressor motors at Bravo Dome (Rosebud) and York Canyon are piston driven, which generate pulsations and flicker into the electrical network. The concern is that these frequencies can coincide with mechanical modes of resonances on the wind turbine blades and shaft system.

The GE wind model in PSCAD does not include details on the mechanical modes of oscillation. To address this concern, the model was run in steady state and the instantaneous electrical power into a wind turbine unit was calculated. The frequencies that can appear on the shaft (due to the electrical system) were then computed by Fourier analysis.

The Fourier results are summarized in Table 7. The only significant interactions between the electrical grid and the wind turbine occurred near 5 Hz and at the 2nd harmonic (120 Hz). The 2nd harmonic component of electrical power is due to the presence of –ve sequence unbalanced voltages and currents (the –ve sequence transforms into the 2nd harmonic on the electrical torque of the machine). The 5 Hz component was much smaller (.16%) whereas the 2nd harmonic component was larger (up to .96%).

From system measurements and calculations, it is known that the mechanical modes of resonances on the compressor motors at Bravo Dome are 5.025 Hz and 5.4054
Hz. The Fourier analysis (reported in Table 7) was performed over a 1 second steady state period (which results in a frequency resolution of 1 Hz), so these two frequencies combine into the 5 Hz value. To provide more details, Case 4 was run for 100 seconds in steady state (which results in 0.01 Hz resolution in the frequency domain), and the Fourier analysis repeated. This time the electrical power showed clear 5 Hz and 5.45 Hz components (5 Hz: 0.001258 pu, 5.45 Hz: 0.0002174 pu, 120 Hz, 0.009649 pu). It was observed that the 5 Hz component was larger than the 5.45 Hz component.

Table 7: Effect of Pulsating Motor Load on Wind Turbines (WTG #1)

<table>
<thead>
<tr>
<th>Case</th>
<th>Harmonic Frequencies Present on Wind Turbine Electrical Power (pu on Total WTG Rated Power (N*1.5MW))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (40 MW Wind)</td>
<td>5 Hz: 0.00163</td>
</tr>
<tr>
<td>3 (80 MW Wind)</td>
<td>5 Hz: 0.00154</td>
</tr>
<tr>
<td>4 (120 MW Wind)</td>
<td>5 Hz: 0.00149</td>
</tr>
</tbody>
</table>

Note: FFT (Fourier analysis) performed over 1 second period, so frequency resolution is 1 Hz.
The electrical power that appears at the WTG terminals will result in an electrical torque with similar frequency components. The frequencies on the electrical power match those of the Rosebud motors (5.025 Hz and 5.4054 Hz).

7.6 Harmonic Studies

The GE wind model for PSCAD is not a detailed switching based model (it is possible to represent the Voltage Sourced Converter used in the double wind generator and thereby model the switching of the electronic devices) so it cannot inherently reproduce the level of harmonics in the system. However, GE provided a table of measurements of voltage and current harmonic magnitudes. This information can be used to estimate how the addition of the wind turbine units will affect the Total Harmonic Distortion (THD) levels in the nearby system.

To study this, it was assumed that the harmonics that appear on the 115 kV system at the GE wind turbine can be represented as a current injection onto the 115 kV bus (this is reasonable because these harmonic currents must pass through the inductance of the 115/34.5 kV transformers and 34.5 kV unit transformers, thus approximating a current source). The harmonic currents (measured from the 575 volt terminals of a single GE wind turbine) were output to a text file, and then read in by a custom-developed component in PSCAD. The harmonic currents on each phase were then reconstructed (essentially an inverse Fourier transform) and injected onto the 115 kV system (scaling factors were applied for the number of wind turbines in service and the different voltage level). A validation test of the new model was made by performing a Fourier analysis from the time domain current injections and comparing them to the original measured harmonics in the frequency domain (with excellent results).
The resulting THD levels are shown in Table 8 and graphically in Figure 7 for varying levels of wind output.

### Table 8: THD Level of 115 kV Bus (%)

<table>
<thead>
<tr>
<th>Wind MW</th>
<th>Phase A (without wind harmonics)</th>
<th>Phase B (without wind harmonics)</th>
<th>Phase C (without wind harmonics)</th>
<th>Phase A (with wind harmonics)</th>
<th>Phase B (with wind harmonics)</th>
<th>Phase C (with wind harmonics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.476</td>
<td>1.404</td>
<td>1.435</td>
<td>1.476</td>
<td>1.404</td>
<td>1.435</td>
</tr>
<tr>
<td>40</td>
<td>1.327</td>
<td>1.26</td>
<td>1.291</td>
<td>1.321</td>
<td>1.258</td>
<td>1.288</td>
</tr>
<tr>
<td>80</td>
<td>1.278</td>
<td>1.212</td>
<td>1.239</td>
<td>1.247</td>
<td>1.196</td>
<td>1.223</td>
</tr>
<tr>
<td>120</td>
<td>1.316</td>
<td>1.257</td>
<td>1.254</td>
<td>1.229</td>
<td>1.19</td>
<td>1.218</td>
</tr>
</tbody>
</table>

Maximum Individual Harmonic: 1.064 (phase B of 0 MW case, 65 Hz)
(all other cases had all individual harmonics below 1%)

![THD Levels at Foresight 115 kV](image)

**Figure 7: THD Level of 115 kV Bus (%)**

It is interesting to note that the largest single component of frequency in these cases was a 65 Hz component (+/- 1 Hz), which was 1.064%. This occurs because of the pulsation effect of the compressor motors (the 5 and 5.4 Hz mechanical mode of oscillation appears on the electrical grid as 65 and 65.4 Hz as seen on the instantaneous voltage waveshape, and which reflects through in the RMS measurement as an approximate 5 Hz component). This 65/5 Hz component of 115 kV voltage can possibly be minimized with flicker reduction controls on the SVC (this was not represented in the SVC model).
The THD levels increase as wind power levels increase, however this is compared to a “theoretical” wind generator that does not produce harmonics (ie the table shows the results with the wind turbine harmonic currents on and off). The results also show that the base case (without any wind production) has higher THD levels.

The representation of the wind turbine harmonics as a current source (as seen from the 115 kV side) is an approximation. If THD levels are at high levels, a more detailed GE wind model for PSCAD is required which represents the VSC as switching devices.

Another test was done using linear harmonic impedance scanning. A graph showing the harmonic impedance as a function of frequency (as seen from the 115 kV bus) is shown in Figure 8. In this case, 120 MW of GE wind turbines are in service and are approximated with a 0.4 pu inductive source impedance.

![Figure 8: Harmonic Impedance at 115 kV Bus (120 MW Wind Case 4)](image)

**7.7 Impact of Closing the Gladstone to Walsenburg 230 kV line**

When the new 230 kV line from Gladstone to Walsenburg is out of service, a large phase shift will exist between the systems on either side of the breaker (from PSLF loadflow studies, the phase shift was more then 35 degrees in the base case). The concern was that closing the line breaker could cause a large transient effect on the compressor motors at Rosebud or on the Wind Farm units.
To investigate this, loadflow cases were run with this line open at Gladstone but energized at Walsenburg. The case was then translated to PSCAD (using E-TRAN) and multiple runs were performed which closed the breaker sequentially every 20 degrees of one cycle (all three phases closed at the same time). The over-frequency and under-frequency protection systems of the compressor motors were modeled (the GE Wind model already had protection systems included in the model). The state of each compressor motor (Rosebud 1, Rosebud 2 and York Canyon) as well as each wind turbine unit was monitored to look for trips due to the breaker closing.

The breaker closing times were chosen to occur at the maximum frequency of the smallest Rosebud compressor motor (the steady state motor frequency will change with a 5 Hz and 5.4 Hz component due to the piston pulsating effect) and then varied every 20 degrees over a full cycle (19 runs). This was repeated for the minimum frequency swing, and was repeated for all 4 wind turbine output levels (0, 40, 80 and 120 MW).

In all cases the compressor motors and the wind turbine units did not trip. However, it is conceivable that a larger phase angle across the contacts of the open circuit breaker at Gladstone could occur for a particular power flow condition, and a greater deviation of frequency of the compressor motors will result when the circuit breaker is closed. The open circuit phase angles observed in the models for the respective power flow conditions for this study were as shown in Table 9:

Table 9: Phase angles across open circuit breaker at Gladstone for different generation levels at the Owaissa Wind Ranch.

<table>
<thead>
<tr>
<th>Power Generated at the Owaissa Wind Ranch</th>
<th>0 MW</th>
<th>40 MW</th>
<th>80 MW</th>
<th>120 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase angle across the open Gladstone 230 kV breaker</td>
<td>55°</td>
<td>40°</td>
<td>28°</td>
<td>17°</td>
</tr>
</tbody>
</table>

The increase in generated power from the Owaissa Wind Ranch reduces the phase angle across the open Gladstone 230 kV circuit breaker, and lessens the impact on the frequency swing of the Bravo Dome compressor motors when the circuit breaker is closed.

It is noteworthy that site measurements (and PSCAD models) indicate the compressor motor frequencies change significantly due to the pulsating piston effect. Fault analysis is typically conducted in transient stability algorithms, but the pulsation effect of the compressor motors is not included in the WECC models. If future motor-trip protection studies are to be undertaken, the steady state pulsating effects of the motors should be included (either in transient stability models or in PSCAD).
8 CONCLUSIONS

Acceptable steady state performance during contingencies for the three acceptance criteria of line/transformer overload, undervoltage deviations and maximum/minimum bus voltage limits was generally achieved in the NEA for the operation of the Owaissa Wind Ranch up to 120 MW. No violations of the WECC/Tri-State operational standards were observed except for undervoltage deviations exceeding 5% when the wind power from Owaissa was both 80 and 120 MW for Contingency No. 5, outage of the Black Lake - Taos 115 kV line and for Contingency No. 8, outage of the Colinas – Rowe Tap 115 kV line.

The undervoltage deviations were more severe when the Bravo Dome compressor motors were out of service and all the power generated from Owaissa had to flow west instead of some of it displacing power to the compressors. Thus when the Bravo Dome compressors were out of service, Contingencies No. 5 and 8 result in more severe violations than when the compressors were in service. In addition, undervoltage deviations exceeding 5% were observed at the Taos 115 kV busbar for outage of the Ojo – Taos 345 kV line (Contingency 12) and for the outage of the Taos 345/115 kV transformer (Contingency 15) when the Owaissa was generating at 120 MW.

Additionally, a marginal undervoltage condition was observed at the York Canyon 115 kV bus during the base (n-0) case while 120 MW was being generated at the Owaissa site.

The transient stability analysis indicated that during a three phase fault and loss of the proposed Gladstone to Walsenburg 230 kV line, the compressor motors at Bravo Dome would trip due to underfrequency for cases with 40 MW of wind generation or less. During this contingency (Case2, fault S3), the 40 MW of Owaissa wind turbines also tripped due to undervoltage at the generator busses. For 80 MW or more, both the load at Bravo Dome and the new wind turbines were able to remain in service. This indicates that the addition of large amounts of wind generation in the vicinity of the Bravo Dome load provides system support in the region by offsetting the required power flow through the radial lines to the motors.

PSCAD studies were performed to determine short circuit current levels, determine the level of –ve sequence imbalance, study wind turbine and SVC interactions, determine the effect of the pulsations from compressor motors on the wind turbines, look for amplification of wind turbine harmonics and to study the transient impact of closing the breaker on the proposed Gladstone to Walsenburg 230 kV line.

From steady state, short circuit, PSCAD electromagnetic transients and also transient stability analysis considerations, the operation of the Owaissa Wind Ranch up to 120 MW still appears a realistic objective.

The facilities required to achieve operation of the wind ranch at 120 MW are minimal. These include replacing the current transformers on the 115 kV...
transmission lines that are presently limiting and to identify if conductors on the 115 kV transmission have to be raised. The facilities study will address these issues.

9 REFERENCES
