GEN-2002-019 Wind Farm Interconnection Study

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Summary

A study has been made of a 230 kV interconnection to the proposed GEN-2002-019 wind farm located in Carson County, Texas. This proposed wind farm would be interconnected to the Xcel Energy (SPS) transmission system, and will have a nominal rating of 160 MW. The proposed wind farm comprises a group of Mitsubishi MWT-1000a wind turbines, with nominal rating of 1.0 MW each.

A comprehensive range of fault cases defined by SPP has been run in the study. These cases have been augmented by other cases to determine the effects of operating the wind farm at lower power output levels.

The following conclusions are reached from the studies:

- Overall, the post-fault recoveries show stable system performance for all cases.
- The proposed wind farm trips due to low voltage for faults near the wind farm.
- This condition is not mitigated by reducing wind farm power output level.
- The assumed delay time for the undervoltage trip is a significant factor influencing the results.

Mitigation of the undervoltage trips by means such as an SVC is not likely possible for the wind farm trip cases, because the wind turbine undervoltage protection includes instantaneous tripping for phase voltage below 0.85 pu. This setting will generally result in a trip order during the fault (prior to fault clearing) for nearby faults.

A full description of the study, and results, are given in the report.

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1 INTRODUCTION

A study has been made of a 230 kV interconnection to the proposed GEN-2002-019 wind farm located in Carson County, Texas. This proposed wind farm would be interconnected to the Xcel Energy (SPS) transmission system, and will have a nominal rating of 160 MW. The proposed wind farm comprises a group of Mitsubishi MWT-1000a wind turbines, with nominal rating of 1.0 MW each.

Proper modeling of the wind farm is always a significant consideration for wind farm studies. Care has been taken in preparation of the equivalent model for the wind farm, and the assumptions in developing this model are presented in the report.

The cases run for the study were those defined in the SPP study scope document for the GEN-2002-019 wind farm. As per ABB's study proposal, cases have been run for conditions both with and without the wind farm in service.

A description of the model, assumptions, and case results are given in the report.

2 DATA SUMMARY, ASSUMPTIONS, AND MODEL DESCRIPTION

2.1 Powerflow Data

SPP provided a 2004 basecase loadflow (file name "lf04SP-ds.raw") as input to the study. In a separate effort, this base case was modified to add a proposed 102 MW wind farm (GEN-2002-024) near the Mooreland substation in northwest Oklahoma, and thus the results of this study reflect conditions with both wind farms in operation.

Addition of the GEN-2002-019 160 MW wind farm required redispatch of some generation. The conditions before and after addition of the wind farm are as follows:

Dispatch without GEN-2002-019 wind farm:
GEN-2002-019: 0 MW
51443 (TOLK31): 204 MW
50663 (MRG31): 48 MW
50696 (RVRV1): 0 MW (out of service)

Dispatch with GEN-2002-019 wind farm:
GEN-2002-019: 162 MW
51443 (TOLK31): 92 MW
50663 (MRG31): 0 MW (out of service)
50696 (RVRV1): 0 MW (out of service)

2.2 Wind Farm Powerflow Model

In the GEN-2002-024 wind farm near Mooreland, the generators are connected at numerous locations along unequal feeders. Thus it was appropriate to model explicitly 11 equivalent machines and the unequal feeders in the power flow case for the GEN-2002-024 wind farm.

The GEN-2002-019 wind farm, on the other hand, has a different layout, with all collector buses equidistant from the interconnection point. The typical plant layout was given in two drawings labeled E1 and E2 (Appendix E). The symmetry of the wind farm layout lends itself to modeling the entire plant as a single machine for simulating the plant's response to faults on the system. The detailed reasoning that went into development of the GEN-2002-019 wind farm model is as follows:

- Starting at the interconnection point, there are two identical 48/64/80 MVA, 230/34.5 kV substation transformers carrying identical power. Thus, these are grouped into a single equivalent transformer, which is modeled in the power flow case with 10% impedance on 2*48=96 MVA base and a rating of 2*80=160 MVA.
- Next, there are 2*3=6 identical 6000' 795 ACSR feeders that carry identical power. These are grouped into a single equivalent feeder that is modeled in the power flow case.
- Next, there are two junction points in the drawing E2 with no distance given between them. These are assumed to be the same node for modeling purposes.
- Coming off these junctions are 3*6=18 identical 7500' 477 ACSR feeders. These are grouped into a single equivalent feeder that is modeled in the power flow.

- At the ends of these identical 477 ACSR feeders in drawing E2 are collector buses of 9, 9, and 8 machines. However, if we add up this power for the whole plant, we only get 156 MW from this typical layout. We need 160 MW at the interconnection point, and slightly more at the generator terminals to account for feeder losses. If we treat the 8-machine collector bus as 9 machines similar to the other two, we get a total of 162 MW at the generator terminals. This also gives approximately 160 MW at the interconnection point. This continues the symmetry in the plant.
- Thus, an equivalent of one 9-machine collector bus is made, and that is multiplied by 3 and 3 and 2 to get 162 MW at the equivalent generator terminals.
- This equivalent has an equivalent collector bus impedance followed by the impedance of the 100' of 1/0 shielded cable. Drawing E2 states that the Xc of the shielded cable is negligible, but this is not a good assumption. Shielded cables have higher charging than unshielded, over-head conductors. Therefore, a typical value for 1/0 shielded cable charging susceptance was used. The result for the 100' cable is a very small series R+jX, but a not insignificant Bc. Because of the Bc, this branch would not be treated as a zero-impedance line in the power flow solution and could cause solution problems. The Thevenin equivalent impedance of the 1/0 ACSR collector bus was then added to the 100' cable impedance. This combined impedance is modeled in the power flow case.
- The 162 identical GSU transformers are represented as a single equivalent with 5.65% impedance at 160 MVA.
- Finally, the 162 identical 1 MW wind turbine generators are modeled as a single 162 MW, 180 MVA generator.

It is important to note that of all the impedances in the plant model, the substation transformer is by far the most significant (18.8% on plant base), followed by the GSU transformer (6.3% on plant base). The three feeder impedances are much less significant (1.6%, 0.7%, and 0.2% on plant base). Small variations in the feeder impedances from the given typical values should not change the study results in any meaningful way.

The calculations for the wind farm system model are shown in Appendix E, along with a PSS/E drawing showing the final power flow model of the plant.

In developing the model, it was assumed that a zero net var interchange is desired at the point of connection to the system. To accomplish this, a 28 MVAR fixed capacitor was placed at the low side of the equivalent 34.5/230 kV substation transformer used in the model. Since this equivalent transformer actually represents two parallel 34.5/230 kV transformers for the two halves of the wind farm, the 28 MVAR capacitor in reality represents two banks of 14 MVAR each, located on the low sides of the two physical substation transformers.

It is also assumed that the conventional induction generators used in the wind farm are compensated to unity power factor, and therefore the generator vars for the equivalent wind farm generator are locked at zero in the powerflow case.

Appropriate tap settings were determined for the 34.5/230 kV substation transformer and the 0.600/34.5 kV generator step-up transformer, and they are shown in the PSS/E diagram shown in Appendix E.

2.3 Dynamics Data

A snapshot file corresponding to the 2004 loadflow case was provided by SPP for the study (file name "SPP04SP.dyr"). Prior to start of the study, the snapshot file was modified to include dynamics data for the proposed (GEN-2002-024) wind farm near the Mooreland substation in northwest Oklahoma.

Dynamics information for the GEN-2002-019 wind farm was incorporated into the snapshot file using the PSS/E CIMTR3 induction generator model. The data entered into this model corresponded to information for the Mitsubishi wind turbines as shown in Appendix E. The following observations are noted:

- In the Mitsubishi dynamics data, T' = T" and X' = X". This is taken to mean that the machine is a single cage induction machine. To model a single cage machine, T" and X" are set equal to zero in the PSS/E CIMTR3 model.
- The Mitsubishi dynamics data show H=128.5, which is unrealistic. H should be in the range of 4.0 to 6.0 for machines of this type. In the document "Mitsubishi Data Check Request.doc" on page 3, data is given for the calculation of H (Drive Train MOI and Induction Generator MOI). However, this data seems to be mislabeled (as "GD") and is not applicable to the equation provided at the bottom of the same page. The data seems to be mass moment of inertia. This assumption gives a value of H = 4.75. This is a very typical value. A value of H = 4.75 was used for the study.
- The Mitsubishi data show instantaneous tripping for 0.85 pu phase voltage. In the simulations, some non-zero delay must be assumed for this protection. The implications of the assumed trip delay are described in Section 4.

3 CASE LIST

The case list defined by SPP is as follows:

1. FLT13PH - 3-phase fault
   Fault on the Nichols (50915) - GEN-2002-019 Wind Farm (99950) 230 kV line, near the GEN-2002-019 Wind Farm (99950).
   a. Apply fault at the GEN-2002-019 Wind Farm bus (99950).
   b. Clear fault after 5 cycles by removing the line from 50915-99950.
   c. Wait 20 cycles, and then reclose the line in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip the line in (b) and remove fault.

2. FLT21PH - 1-phase fault
   - Same as FLT13PH above.

3. FLT33PH - 3-phase fault
   Fault on the GEN-2002-019 Wind Farm (99950) -Grapevine (50827) 230 kV line, near Grapevine (50827).
   a. Apply fault at the Grapevine bus (50827).
   b. Clear fault after 5 cycles by removing the line from 99950-50827.
   c. Wait 20 cycles, and then reclose the line in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip the line in (b) and remove fault.

4. FLT41PH - 1-phase fault
   - Same as FLT33PH above.

5. FLT53PH - 3-phase fault
   Fault on the Grapevine (50827) - Elk City (54153) 230 kV line, near Elk City (54153).
   a. Apply fault at the Elk City bus (54153).
   b. Clear fault after 5 cycles by removing the line from 50827-54153.
   c. Wait 20 cycles, and then reclose the line in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip the line in (b) and remove fault.

6. FLT61PH - 1-phase fault
   - Same as FLT53PH above.

7. FLT73PH - 3-phase fault
   Fault on the Grapevine (50826) - Kirby (50932) 115 kV line, near Kirby (50932).
   a. Apply fault at the Kirby bus (50932).
   b. Clear fault after 5 cycles by removing the line from 50826-50932.
   c. Wait 20 cycles, and then reclose the line in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip the line in (b) and remove fault.

8. FLT81PH - 1-phase fault
   - Same as FLT73PH above.

9. FLT93PH - 3-phase fault
   Fault on the Kirby (50932) - Conway (50928) 115 kV line, near Kirby (50932).
   a. Apply fault at the Kirby bus (50932).
   b. Clear fault after 5 cycles by removing the lines:
      i. Kirby (50932) - Conway (50928)
      ii. Conway (50928) - Yarnell (50926)
      iii. Yarnell (50926) - Nichols (50914)
   c. Wait 20 cycles, and then reclose the lines in (b) into the fault.
   d. Leave fault on for 5 cycles, then trip the lines in (b) and remove fault.

10. FLT101PH - 1-phase fault
    - Same as FLT93PH above.

11. FLT113PH - 3-phase fault
    Fault on the Potter County (50888) - Finney Switch Station (50858) 345 kV line, near Finney (50858).
    a. Apply fault at the Finney bus (50858).
    b. Clear fault after 5 cycles by removing the line from 50888 to 50858.
    c. Wait 30 cycles, and then reclose the line in (b) into the fault.
    d. Leave fault on for 5 cycles, then trip the line in (b) and remove fault.

12. FLT123PH - 3-phase fault
    Fault on the Wolforth Interchange (51762) - Terry County (51830) 115 kV line, near Terry County (51830).
    a. Apply fault at the Terry County bus (51830).
    b. Clear fault after 5 cycles by removing the line from 51762 to 51830.
    c. Wait 20 cycles, and then reclose the line in (b) into the fault.
    d. Leave fault on for 5 cycles, then trip the line in (b) and remove fault.

13. FLT131PH - 1-phase fault
    - Same as FLT123PH above.

As described in ABB's study proposal, the above cases were run for conditions both with and without the GEN-2002-019 wind farm in service. Other cases were run based on observed results from the above cases. In particular, cases 1-3 were found to be of interest because of observed wind farm tripping for these cases.

The results of the above cases are described in Section 4.

4 CASE RESULTS

4.1 Identification of wind farm trip cases

Overall, the post-fault recoveries show stable system performance for all cases. However, wind farm tripping due to low voltage at the wind farm is indicated for cases 1-3. This can be seen in Figures A.1-A.3 (Appendix A), which show the first second of simulated time for conditions with the wind farm undervoltage protection disabled, meaning that the wind farm is intentionally not tripped.

In all of Figures A.1-A.3, low terminal voltage is seen at the terminals of the wind generator during the fault and after fault clearing. This low terminal voltage will be detected by the wind turbine undervoltage protection, and the wind turbine can be expected to trip on the 0.85 pu instantaneous phase undervoltage trip setting of the wind turbine protection for these cases.

As a further investigation of the low wind turbine terminal voltages observed in cases 1-3, these cases were repeated with the wind farm at half power (80 MW). The results are shown in Figures A.4-A.6.

It is observed from Figures A.4-A.6 that wind farm tripping will still occur at the lower wind farm power output, due to the 0.85 pu instantaneous phase undervoltage setting. No reasonable means to correct this can be envisioned, as the trip condition is detected during the fault. Since the proposed plant trips instantaneously for voltages below 0.85 pu, dynamic voltage support devices (such as SVCs) will not help in keeping the plant on-line for three-phase faults near the plant as the voltages would instantaneously dip below 0.85 pu anyway thereby tripping the plant. No such mitigating means, however, can be realistically envisioned to improve the wind farm voltage during the fault, and thus the 0.85 pu instantaneous phase voltage trip setting remains a major factor influencing the study results.

4.2 Effects of wind farm tripping on system

The available information from Mitsubishi defines 0.9 pu delayed and 0.85 pu instantaneous undervoltage trips. The information available from Mitsubishi does not specify the pick up delay time for the 0.9 pu delayed trip, so a delay of 100 milliseconds was assumed. Both the 0.9 pu delayed and the 0.85 pu instantaneous settings were considered to determine which cases would result in wind farm tripping. The 0.85 pu instantaneous trip turned out to be the most relevant setting for the cases in this investigation.

To investigate the result of wind farm tripping on the remainder of the system, cases 1-3 were repeated with wind farm tripping, with an assumed tripping delay of 6 cycles (100 ms) after detection of the 0.85 pu phase voltage condition. These cases are shown in Appendix B, along with the remaining cases 4-13.

In cases 4-13, the voltage at the wind turbine generator terminals does not indicate wind farm tripping due to undervoltage, and the wind farm is kept online throughout the simulation. Note that positive sequence voltage is shown in the simulation plots, while the wind turbine undervoltage protection actually considers the individual phase voltages. Therefore, fault calculations were made in a separate PSS/E short circuit case provided by SPP (case name

"SC04.SAV") to determine the phase voltage at the wind turbine generator terminals during remote single phase faults. These calculations confirmed that the wind farm does not trip in case 4 (single line fault at Grapevine 230). As the other single phase faults are more remote than the Grapevine fault, it is inferred that wind farm tripping does not occur for the other single phase fault cases.

The information available from Mitsubishi does not specify the actual delay time (pick up delay plus breaker or contactor opening delay) for the undervoltage tripping. Cases 1-3 were therefore repeated with SPP-provided values of 50 ms pickup delay and 500 ms breaker (or contactor) delay, giving a total of 550 ms trip delay after detection of the undervoltage condition. These cases are shown in Appendix C. It is observed from the results in Appendix C that this delay results in an extended period of low voltage before the wind farm trips. After the wind farm trips, the system recovery is stable.

In addition to the above settings, SPP requested ABB to consider possible use of an improved undervoltage trip scheme. This improved trip scheme for the Mitsubishi wind turbines has the following settings provided to ABB by SPP:

0.6 pu voltage and below:	Instantaneous trip
0.6 pu to 0.95 pu:	Trip after 200 ms delay

Inspection of Figures A.1-A.3 (Cases 1-3) with consideration to the above settings leads to the conclusion that the wind farm will also trip for these three cases with the improved settings. The time instant of the trip will change slightly, but will fall between the values simulated in Cases 1-3 of Appendix B (100 ms delay) and the corresponding cases in Appendix C (550 ms delay). Since the studied cases in Appendices B and C bracket a range of values that includes the improved trip settings, the improved trip settings do not lead to any changes in the findings of the study.

In Appendix D, all of cases 1-13 are repeated with the GEN-2002-019 wind farm offline (out of service). These cases thus show reference conditions for the existing system prior to addition of the wind farm.

In Appendices B-D, six pages of plots are given for each case, with two plots per page. The information in the plots is described on the cover sheet of each appendix.

5 CONCLUSIONS

A comprehensive range of fault cases defined by SPP has been run in the study. These cases have been augmented by other cases to determine the effects of operating the wind farm at lower power output levels.

The following conclusions are reached from the studies:

- Overall, the post-fault recoveries show stable system performance for all cases.
- Wind farm tripping due to low voltage is indicated for faults near the wind farm.
- This condition is not mitigated by reducing wind farm power output level.
- The assumed delay time for the undervoltage trip is a significant factor influencing the results.

Mitigation of the undervoltage trips by means such as an SVC is not likely possible for the wind farm trip cases, because the wind turbine unddervoltage protection includes instantaneous tripping for phase voltage below 0.85 pu. This setting will generally result in a trip order during the fault (prior to fault clearing) for nearby faults.