Lesson Learned

Loss of Wind Turbines due to Transient Voltage Disturbances on the Bulk Transmission System

Primary Interest Groups
Balancing Authorities (BAs)
Transmission Operators (TOPs)
Generator Operators (GOPs)
Generator Owners (GOs)
Reliability Coordinators (RCs)

Problem Statement
Voltage disturbance events on the transmission system in Australia and Texas have highlighted concerns with voltage ride through and in some wind turbine control system parameters.

Details
South Australia Blackout Event[1]
On September 28, 2016, five transmission system faults occurred within a period of 87 seconds, leading to six voltage disturbances on the South Australian (SA) grid. The SA grid has one synchronous connection to the rest of the Australian National Electricity Market grid through a 275 kV double-circuit, single-tower ac transmission line (the "tie line"). At the time of the event, total load in SA was 1826 MW with 330 MW being provided by a few synchronous generators, 883 MW coming from wind, 114 MW being imported on a DC interconnector, and 499 MW being imported on the tie line. Investigations showed that there was a total sustained reduction of 456 MW of wind generation across nine wind plants, plus further transient reductions of 42 MW during each of the voltage disturbances. The sudden loss of 456 MW of generation increased import flows on the tie line, and the increased flow caused the protection system to disconnect the tie line to avoid damage, resulting in system separation from the rest of the Australian grid. The combined loss of the tie line and wind generation created a sudden supply deficit on the order of 50 percent of the pre-disturbance load. This large supply deficit resulted in very rapid system frequency decrease to below 47 Hz (Australia operates at nominal 50 Hz), causing the remaining generation and the DC interconnector to trip as expected. This resulted in the blackout of the South Australian grid.

ERCOT Events
Although outcomes have not been as severe as was observed in the Australian event, ERCOT has observed several situations where line faults or bus faults resulted in temporary loss of wind generation. These events provide additional understanding of the causes and recommended actions.

- Event 1: A 138 kV multiphase bus fault resulted in seven voltage disturbances within a ten-minute period. Investigations showed a total reduction of 475 MW of wind generation across nine wind plants during the event (approximately 56 percent of their pre-event output). The loss of generation,

[1] AEMO Report "Black System South Australia September 28, 2016" published March 2017

in addition to the loss of a static var compensator in the area, caused a low-voltage condition on the local transmission system. This resulted in the operation of under voltage load shed (UVLS) relays that disconnected 92 MW of firm load.

- Event 2: A 138 kV line fault caused a low-voltage excursion, resulting in the loss of 342 MW of wind generation across seven wind plants (a loss of approximately 36 percent of pre-event output). Five of these wind plants were connected to the 345 kV transmission grid. System frequency dipped to 59.905 Hz as a result of the loss of generation and recovered to 60 Hz in less than three minutes.
- Event 3: A 345 kV line fault caused a single-phase low voltage excursion (see Figure 1), resulting in the loss of 343 MW of wind generation across seven wind plants (a loss of approximately 48 percent of the pre-event output). Phasor measurement unit (PMU) data in the vicinity of the disturbance showed a voltage oscillation between 0.78 and 1.07 per-unit for less than 0.5 seconds. System frequency dipped to 59.864 Hz as a result of the loss of generation and recovered to 60 Hz in less than four minutes.

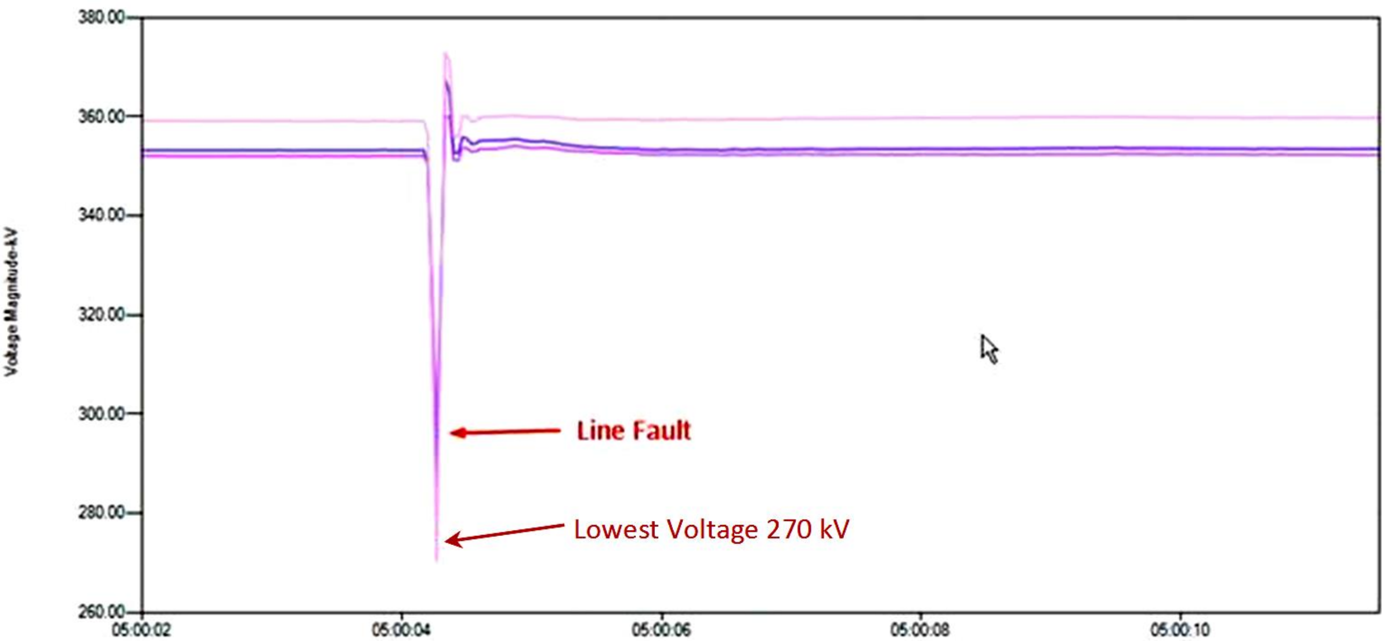

Figure 1 (Event 3)

- Event 4: A 69 kV bus fault caused a low-voltage excursion, resulting in the loss of 230 MW of wind generation across seven wind plants (a loss of approximately 85 percent of the pre-event output). All of these wind plants were connected to the 138 kV transmission grid. PMU data from the 138 kV system in the area showed a low-voltage magnitude of 0.86 per unit and recovery to pre-event magnitude in 0.2 seconds.
- Event 5: A 138 kV line fault caused a low voltage excursion, resulting in the loss of 404 MW of wind generation across six wind plants (a loss of approximately 53 percent of the pre-event output). Five of these wind plants were connected to the 345 kV transmission grid. PMU data from the 345 kV system in the area showed a voltage oscillation between 0.84 and 1.09 per-unit for approximately

0.2 seconds (see Figure 2). System frequency dipped to 59.902 Hz as a result of the loss of generation and recovered to 60 Hz in five minutes.

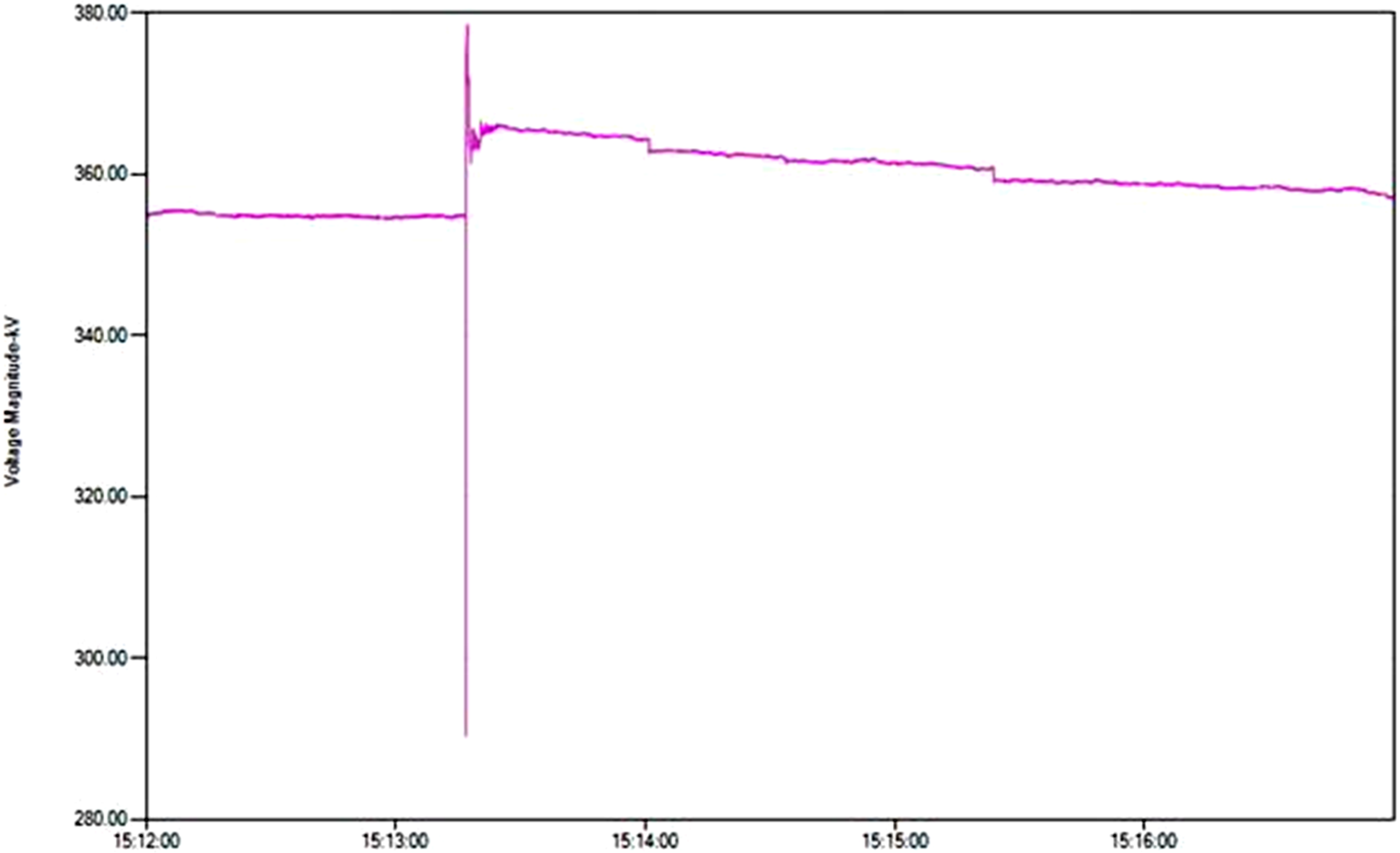

Figure 2 (Event 5)

Corrective Actions

The following corrective actions were taken by the Australian Energy Market Operator (AEMO) after the September 28, 2016 event:

- Of the 13 wind plants that were on-line, nine did not ride through the six voltage disturbances during the event. In the days following, AEMO identified this issue and reclassified the simultaneous trip of these wind plants as a credible contingency.
- AEMO then worked with each of the operators of these wind plants and determined that their voltage ride-through settings were set to disconnect or reduce turbine output when between three and six voltage ride-through events were detected within a given time frame. The investigations also found that information on the control system and these parameter settings were not included in the information provided to AEMO during the registration process prior to interconnection.
- The wind plant operators and the turbine manufacturers proposed improved voltage ride-through settings for consideration by AEMO. As the wind plants were reconfigured with these new settings, the plants were removed from the contingency group and returned to normal operation.

- During a subsequent event on March 3, 2017,[2] the failure of a 275 kV capacitor voltage transformer resulted in a series of three transmission voltage disturbances within a 1.6 second period. All of the wind plants in the South Australia grid rode through the transmission faults with no identifiable reduction in output, indicating that the changes made since the September 28, 2016, event were successful in improving the ride-through characteristics of the wind plants.

The following issues were noted by wind plant owners following the ERCOT events:

- During Event 2, one wind plant owner noted that 12 turbines tripped due to the failure of the wind turbine auxiliary uninterruptible power supplies (UPS) devices. UPS devices provide clean power and ride-through power for critical wind turbine auxiliary controls such as blade pitch, nacelle yaw, and brake control. UPS devices may also provide power for SCADA, metering, and other controls. The most frequent UPS failures are battery failures and environment-related (humidity, temperature, vibration) circuit board failures. The owner is investigating the cause of these particular UPS failures.
- One wind plant owner noted that 11 turbines tripped due to failed crowbar components in the wind turbine during Event 2. (See Attachment 1 for an explanation of crowbar circuit use in wind turbines). The facility owner updated the wind turbine semiannual maintenance process to add inspections of the "Smart Crowbar" circuits. During Event 5, 29 turbines tripped that did not have functioning "Smart Crowbar" hardware, meaning that they will only ride through voltage excursions within +/-10% of nominal voltage.
- During Event 1, wind plant owners noted that 130 turbines tripped due to the repeated voltage fluctuations during a particular event. The magnitude of the individual voltage disturbances were within the "no trip zone" of regional low-voltage ride-through requirements; however, the turbines tripped due to voltage ride-through parameters that were set to disconnect or reduce turbine output when a specified number of voltage excursions were detected within a given time frame (note that Figure 3 on the next page comes from four-second data sampling, so the actual magnitude of fluctuations may be greater than indicated). The rationale for this setting was to prevent damage to the turbine when there was insufficient recovery time between the voltage excursions. This is similar to the experiences reported by AEMO during the September 28, 2016, South Australia event.

[2] AEMO Report "Fault at Torrens Island Switchyard and Loss of Multiple Generating Units on 3 March 2017" published March 2017

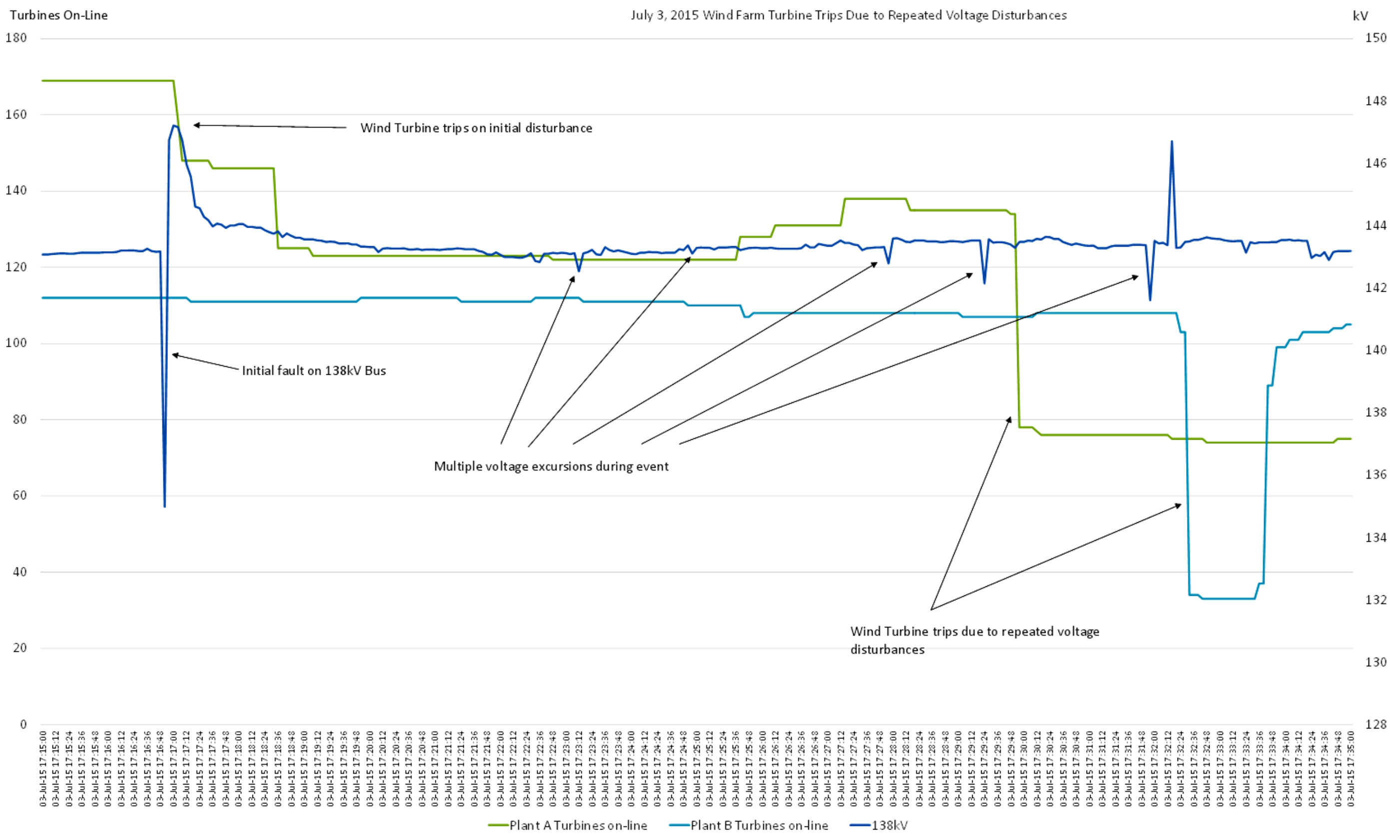

Figure 3

- During Event 4, multiple wind plant owners indicated that the voltage ride-through tolerance for their turbines was insufficient for the magnitude of the voltage disturbance. Those ride-through capabilities ranged from:
  - Less than 0.80 per-unit for 0.08 to 0.2 seconds
  - Between 0.80 and 0.90 per-unit for up to 60 seconds

As noted above, ERCOT Event 1 shows similarities to the South Australia event in that it was related to repeated, rapid voltage fluctuations. The other ERCOT events, while more general in nature, provide additional support for the Lessons Learned that follow.

Lesson Learned

- Wind generation owners should review and verify the voltage ride-through capabilities of their equipment, clearly communicate those capabilities to their BA and connected TOPs, and ensure that the models provided to the BA and TOPs correctly reflect those capabilities.
- If BAs and TOPs are notified by the wind generation owners that units lack ride through capability, BAs and TOPs should communicate to their RC and BAs, TOPs, and RC should consider in their daily resource plan the potential for the loss of these resources during transmission faults on the power system. BAs, TOPs, and RCs should take appropriate mitigating measures.

- Wind generation owners should review and verify that UPS and "Smart Crowbar" systems within the wind turbines are maintained and functioning properly.
- High speed PMU data is critical for visibility into the magnitude of voltage disturbances related to the loss of wind turbines (or grid resources of any type).

References:

- AEMO Report "Black System South Australia September 28, 2016"
- AEMO Report "Fault at Torrens Island Switchyard and Loss of Multiple Generating Units on 3 March 2017"

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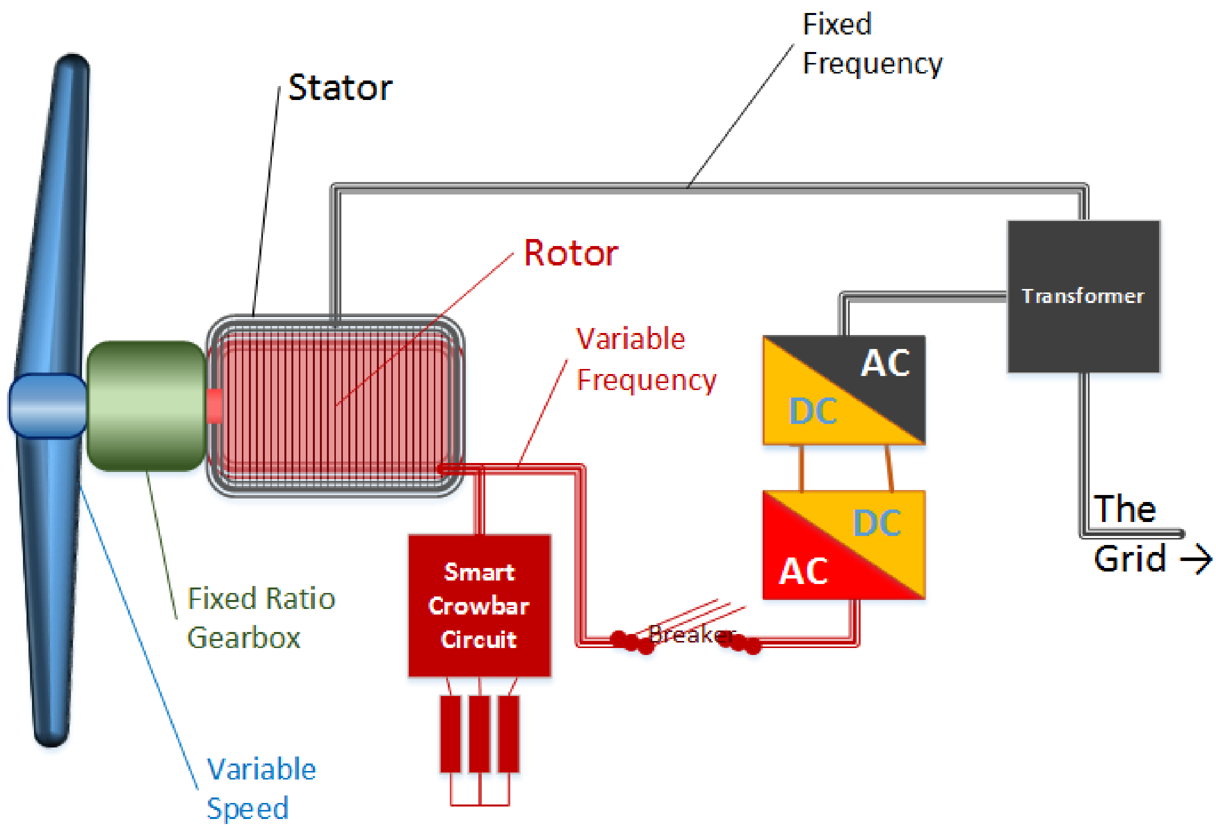
Attachment 1:
Simplified DFIG Wind Turbine diagram for explaining Crowbar Circuit use

Most recently built wind turbines use Doubly Fed Induction Generators (DFIG) that have their stator windings connected directly to the grid, making the rotor winding susceptible to high currents induced during grid faults. The back-to-back converter subsystem (variable-AC to DC to fixed-AC) is very sensitive to over-currents.



Various methods have been used to provide low voltage ride-through capability and some ability to contribute to voltage support during and after grid faults. One method is to dump excess energy with a crowbar system, which intentionally shorts out the rotor windings through large resistors when predetermined thresholds of measured parameters are reached, usually based on the DC-link voltage level in the back-to-back conversion system. In addition, a combination of blade pitch control and braking is typically used to quickly reduce the mechanical energy input.