NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Panhandle Wind Disturbance

Texas Event: March 22, 2022
Joint NERC and Texas RE Staff Report

August 2022

RELIABILITY | RESILIENCE | SECURITY




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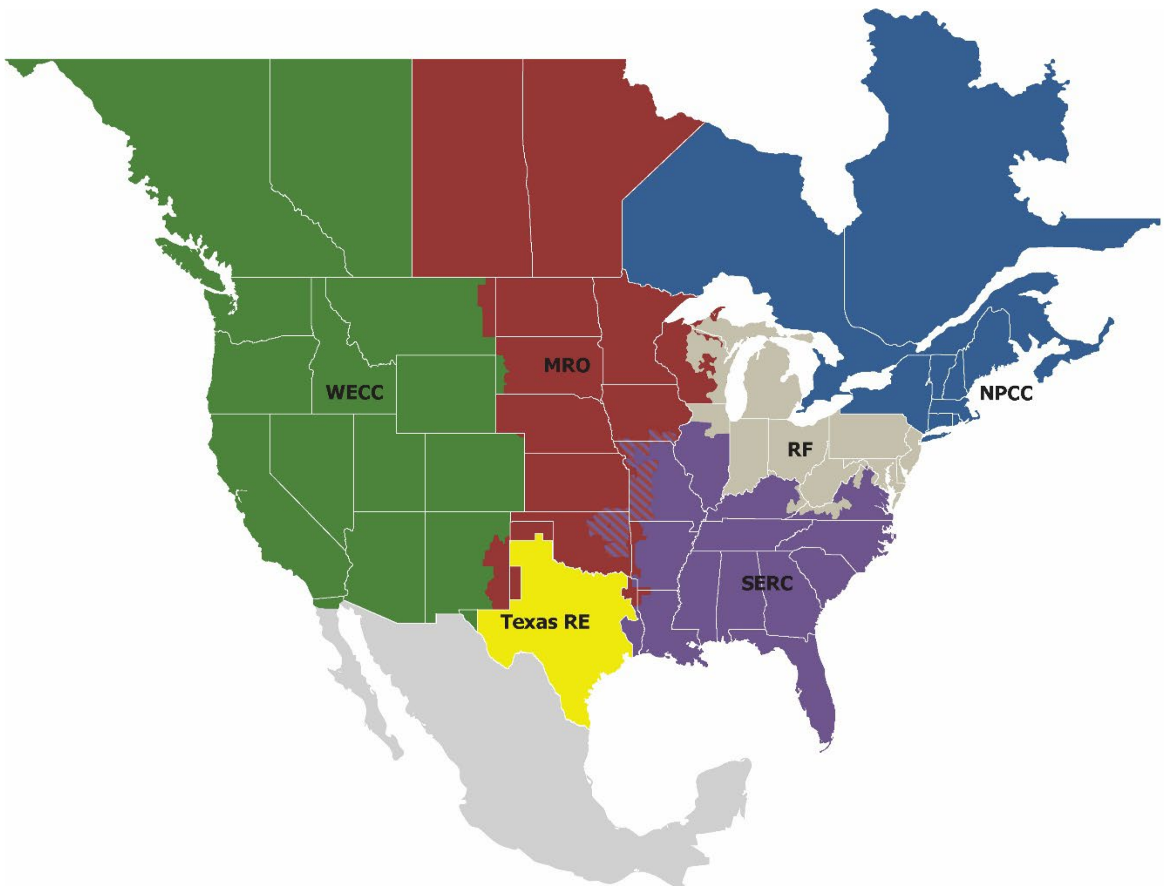
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of NERC and the six Regional Entities, is a highly reliable, resilient, and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six Regional Entity boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Regional Entity while associated Transmission Owners (TO)/Operators (TOP) participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	WECC

Executive Summary

The ERO Enterprise continues to analyze disturbances that involve widespread reduction of inverter-based resources to identify systemic reliability issues, support affected facility owners, and share key findings and recommendations with industry for increased awareness and action. Refer to NERC *Quick Reference Guide: Inverter-Based Resource Activities* for more details on all aspects of work in this area.[1] For instance, multiple disturbances that involve the widespread reduction of solar photovoltaic (PV) resources have occurred in California and Texas. The disturbance reports document the event analysis and recommended mitigating actions. This report focuses specifically on a reduction of wind resources across the Texas Panhandle area that occurred on March 22, 2022 (referred to herein as the "Panhandle Wind Disturbance"), up to around 200 miles from the initiating fault.

The event did not meet the qualified criteria for reporting in accordance with the ERO Event Analysis Process;[2] however, Texas RE requested a brief report from the Electric Reliability Council of Texas (ERCOT) as an event of interest given the breadth and magnitude of the reductions. ERCOT led the solicitation of requests for information (RFI), coordinated with affected entities, and collected data for analysis. NERC and Texas RE worked closely with ERCOT to analyze the data and RFI responses from affected Generator Owners (GOs) whose facilities experienced a notable reduction in power during the event. ERCOT collaboratively engaged the impacted TOs to gather additional information and corroborate data with other sources.

Overview of Disturbances

Concerning weather patterns started the evening of March 21, 2022, with severe conditions (freezing rain, snowfall, and high winds) occurring the early morning of March 22, 2022. Generator Operators (GOP) reported wind turbine icing and high wind speed cutoffs during this time period. Two BPS faults occurred the morning of March 22, 2022 (see **Table ES.1**):

- **Event 1:** At 4:16:26 a.m. Central, a phase-to-phase fault occurred on a radial 345 kV generator tie line that connects a wind plant to the ERCOT system. The fault cleared normally and consequentially tripped 273 MW of wind generation. Multiple additional wind plants in the area unexpectedly reduced power output by 492 MW. Therefore, the total active power reduction was 765 MW for this fault. Frequency dropped to 59.90 Hz, and 524 MW of responsive reserve service (RRS) were deployed. Frequency recovered to nominal in just under three minutes.
- **Event 2:** At 4:47:55 a.m. Central, another normally-cleared phase-to-phase fault occurred on a 345 kV transmission circuit nearby. Multiple wind plants again unexpectedly reduced power output, totaling 457 MW. Frequency dropped to 59.942 Hz and no RRS was deployed. Frequency recovered quickly in 29 seconds.

The MW reductions listed above are based on the best available information, combining supervisory control and data acquisition (SCADA) data, digital fault recorder (DFR) data, digital relay data, phasor measurement unit data, and any other relevant information from the analysis. Some plots throughout this report may show higher resolution information while others may show lower resolution information; the aggregate quantities reported throughout the document are based on the best available information.

Table ES.1: Overview of Disturbances

Fault	Initiating Fault Event	Description of Resource Loss
Event 1	A–B Fault on 345 kV Gen Tie Line	Loss of 765 MW of wind resources (10 facilities)
Event 2	B–C Fault on 345 kV Transmission Circuit	Loss of 457 MW of wind resources (8 facilities)

[1] https://www.nerc.com/pa/Documents/IBR_Quick%20Reference%20Guide.pdf
[2] NERC Event Analysis Program: https://www.nerc.com/pa/rrm/ea/Pages/EA-Program.aspx

Recommendations for Industry Action

The following are high-level recommendations from this report in the context of past disturbance analyses involving inverter-based resources:

- **Reiterated Need for Enhanced Inverter-Based Resource Ride-Through Requirements:** NERC has submitted a Standard Authorization Request (SAR) to overhaul PRC-024 with a performance-based ride-through standard to mitigate performance issues that continue to occur on the BPS for both inverter-based and synchronous generating resources.

  The March 2022 disturbance illustrates how multiple resources across a geographic area failed to ride through the disturbance but still generally met the minimum requirements established in PRC-024 regarding voltage and frequency protection, highlighting that PRC-024 is not serving its intended purpose nor is it performance-based to ensure reliable operation of the BPS. The types of issues observed in the March 2022 disturbance should fall within the scope of the standard and should be addressed in the future through ERO Enterprise compliance assurance activities.

- **Strengthened Need for Performance Validation and Abnormal Performance Mitigation Requirements for Inverter-Based Resources:** The March 2022 disturbance also illustrates that many of the abnormal performance issues observed in inverter-based resources are generally not modeled or identifiable during the interconnection process and will require effective post-commercial operation mitigation measures.

  NERC has previously recommended a "performance validation"[3] standard (i.e., validating that the performance of the installed equipment meets performance expectations and interconnection requirements). Many causes of tripping in the March 2022 disturbance fall in this category: plant controller interactions, pitch converter failures, abnormal subsynchronous control oscillation tripping, uninterruptible power supply failure, etc.

  NERC is strongly recommending a performance-based standard that addresses abnormal performance issue identification, analysis, and mitigation for all inverter-based resources to ensure that systemic risk issues specific to inverter-based resources are addressed in a timely manner before they reach a point that could result in instability, uncontrolled separation, or cascading outages. The GO should perform such validation with oversight and monitoring by the Reliability Coordinator and/or Balancing Authority (BA), either of which could identify and initiate such analysis and mitigation by the applicable GO.

[3] Performance validation is different from model validation, which focuses on comparisons of the modeled response versus the actual response. Performance validation focuses on comparisons of actual response to expected response based on interconnection requirements and performance expectations. NERC has highlighted systemic modeling errors for inverter-based resource facilities and difficulties in relying on models to predict plant performance, particularly during ride-through events.

Introduction

This Introduction provides details regarding the initiating event, the performance of the BPS-connected wind fleet during the event, and additional relevant details. **Chapter 1** provides a detailed review of the key findings and establishes the supporting evidence and technical basis for the recommendations that are laid out in **Chapter 3**. **Chapter 2** focuses on modeling and study findings that also support the recommendations in **Chapter 3**. **Appendix A** provides a detailed analysis of the affected facilities. **Appendix B** showcases additional wind-related performance and modeling issues occurring on another Interconnection.

Description of Analysis Process

ERCOT identified the March 2022 event and observed the reduction of wind plant power outputs across multiple facilities. While the event did not meet the qualified criteria for a Category 1i event per the ERO Event Analysis Process, ERCOT developed an in-depth report as an event of interest at the request of Texas RE due to the high risk of inverter-based resource performance issues. NERC, Texas RE, and ERCOT mutually agreed to develop an ERO disturbance report to share the key findings and recommendations from the analysis with industry. ERCOT solicited RFIs to affected entities and also held follow-up calls with those entities, Texas RE, and NERC to gather any additional information to perform a root cause analysis. Follow-ups focused primarily on facilities that reduced power output by more than 10 MW.

Predisturbance Operating Conditions

At the time of the disturbances, ERCOT net internal demand was 34.4 GW with wind producing nearly 21 GW (61%), synchronous generation producing 13.2 GW (38%), and imports at just over 200 MW; due to the early hours of the events, solar PV production was at zero (see **Table I.1**).

Table I.1: Predisturbance Resource Mix

BPS Operating Characteristic	MW	Percent
Internal Net Demand*	34,407	-
Solar PV Output	0	0%
Wind Output	20,977	61%
Synchronous Generation	13,212	38%

*ERCOT was importing 218 MW

Figure I.1 shows the total ERCOT wind power profile for March 22, 2022, as well as the times of the faults. The disturbance is visible in the total wind output plot; however, the magnitude of reduction is not the primary operational concern for this report; the unexpected reduction of power output across multiple wind plants is the primary focus of this analysis. All of the affected facilities were located in the Texas Panhandle area. The affected facilities included turbines and controllers from three different wind manufacturers.

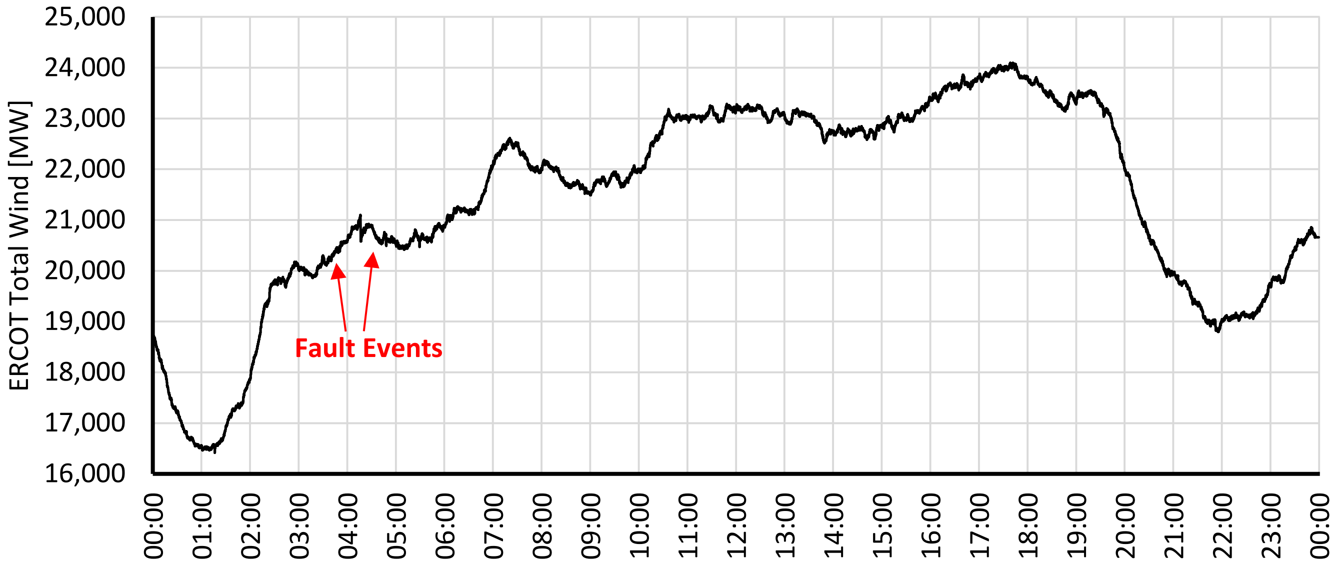


Figure I.1: ERCOT Total Wind Profile for March 22, 2022

Fault Analysis

The March 2022 disturbance involved two separate initiating faults that occurred at 4:16:26 a.m. Central and 4:47:55 a.m. Central.

- **Event 1:** The first fault was an A–B phase fault that cleared normally in 3.38 cycles. The fault occurred on a generator tie line about two miles from the 345 kV transmission substation (see **Figure I.2**) and subsequently tripped 273 MW of wind generation.

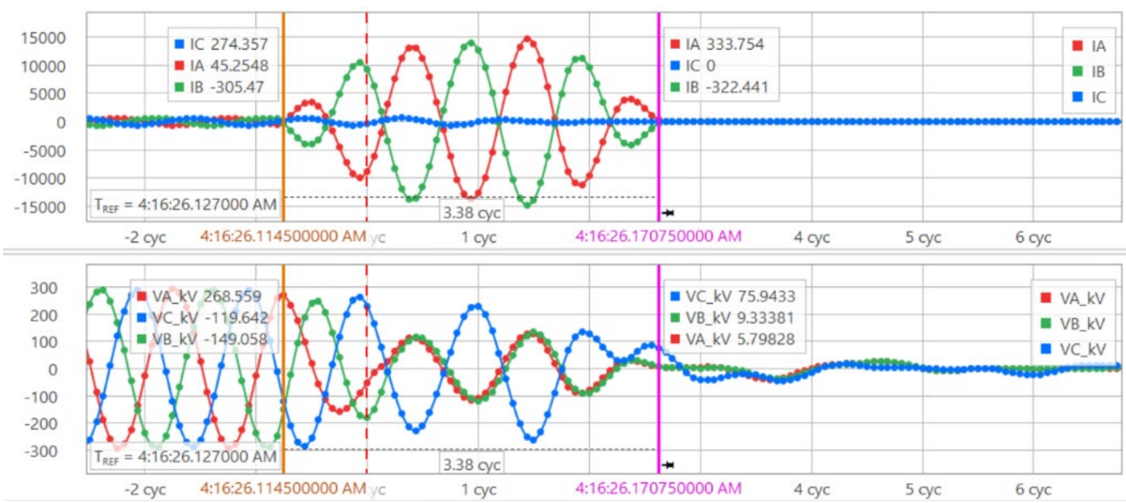


Figure I.2: A–B Fault on Generator Tie Line [Source: Oncor]

- **Event 2:** The second fault was a B–C phase fault that cleared normally in 2.88 cycles (see **Figure I.3**). The fault occurred on a 345 kV transmission circuit about three miles from the same substation in Event 1. ERCOT operations noted that the fault occurred due to galloping conductors.

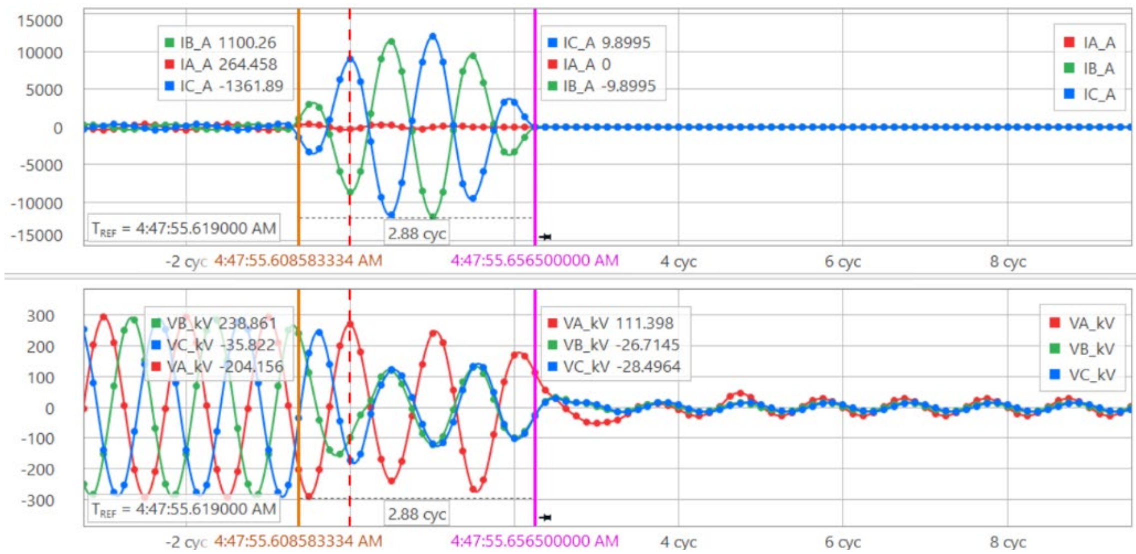


Figure I.3: B-C Fault on 345 kV Transmission Circuit [Source: Oncor]

The first fault involved consequential tripping of generation due to the tripped generator tie line; the second fault did not involve any consequential loss of generation. The additional loss of wind generation was due to the operation of protection systems and controls at these facilities. Solar power output was at zero due to the time that these faults occurred.

Location of Disturbance and Affected Facilities

The faults occurred in the Panhandle area of the ERCOT footprint. Figure I.4 shows the geographic location of the faults (orange), the wind plants that tripped (light blue), and other affected wind facilities that responded abnormally (dark blue). The circle size illustrates the magnitude of reduction. Wind plants identified as abnormally responding to the event were located up to about 170 miles away from the fault location.

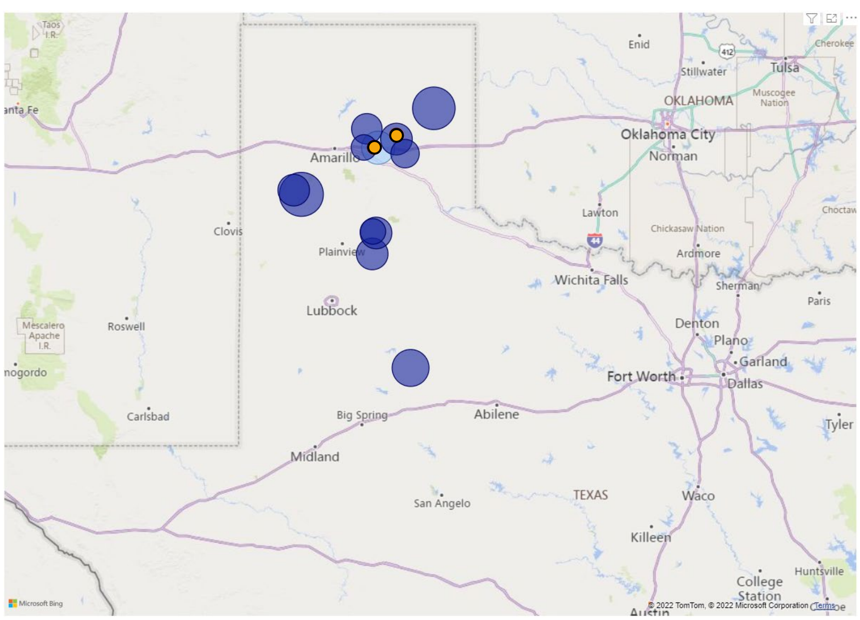


Figure I.4: Map of the Fault Location and Affected Facilities

Figure I.5 shows the reduction in wind resources reported by the ERCOT SCADA system. As with the past disturbance reports that involve fault-induced inverter-based resource reductions, the size of the active power reduction is determined by using SCADA data from the affected BA (i.e., ERCOT) in addition to analyzing data provided by individual facilities. Discrepancies may exist between the values due to SCADA scan rate limitations, meter resolutions, accounting practices, and other factors; however, the reductions in wind plant output provide a relative indicator of the impact of these reductions compared to past disturbances.

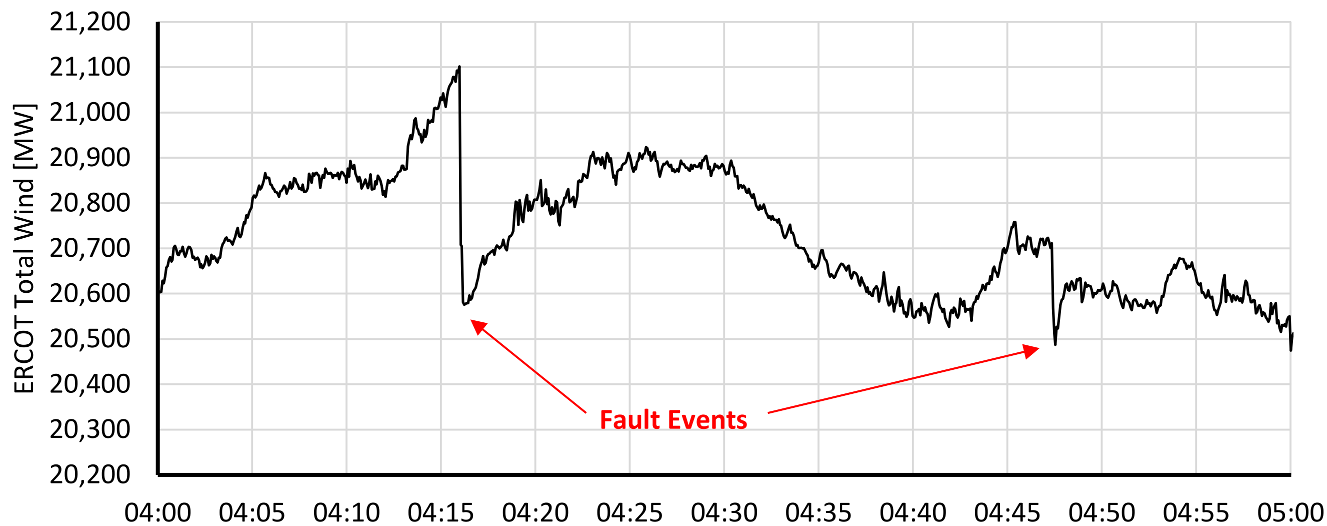


Figure I.5: ERCOT Wind Output during Disturbances

NERC has identified changes in net demand during BPS faults that are attributed to the tripping of distributed energy resources.[4,5] For the March 2022 event, the team reviewed net load quantities and did not identify any abnormalities in load response to the fault. There is no significant penetration of distributed energy resources in the Texas Panhandle area.

System Frequency Response

The first fault-induced generation loss event caused frequency to drop from 60.01 Hz to 59.9 Hz (see Figure 6). A total of 524 MW of generation responsive reserve service (RRS)[6] and 0 MW of load resources (LR)[7] were deployed in response to the frequency drop. Governor action and RRS deployment helped frequency recover within two minutes and 52 seconds. Calculated inertia at the time of the event was relatively low (130.4 GW-seconds) due to the high wind penetration at the time (over 61%). Measured maximum rate of change of frequency was 0.098 Hz per second, and the time from the event start to the frequency nadir was measured at 1.9 seconds (much lower than the average range of 5–6 seconds) due to the low-inertia conditions.

[4] *Palmdale Roost and Angeles Forest Disturbance* report, January 2019: https://www.nerc.com/pa/rrm/ea/Pages/April-May-2018-Fault-Induced-Solar-PV-Resource-Interruption-Disturbances-Report.aspx

[5] *June-August 2021 CAISO Solar PV Disturbance* report, April 2022: https://www.nerc.com/pa/rrm/ea/Documents/NERC_2021_California_Solar_PV_Disturbances_Report.pdf

[6] Responsive reserve service is an ancillary service that provides operating reserves to arrest frequency decay within the first few seconds of a significant frequency deviation and to help restore frequency to its scheduled value. Generation resources providing RRS are deployed automatically when frequency drops below 59.91 Hz.

[7] Load resources are interruptible loads capable of providing ancillary service to the ERCOT system and/or energy in the form of demand response. Load resources are required to deploy by underfrequency relay set at 59.7 Hz and to deploy within 10 minutes after a manual deployment instruction from ERCOT.

The second fault-induced generation loss event caused system frequency to drop from 59.998 Hz to 59.942 Hz. No RRS or LR were deployed in response to this event. System frequency recovered back to nominal values within 30 seconds.

Figure I.6: System Frequency Response for First Fault Event

Chapter 1: Detailed Findings from Disturbance Analysis

ERCOT facilitated data requests to all affected wind plant facilities and held follow-up calls with Texas RE, NERC, the affected GO and GOP, and the original equipment manufacturer (OEM) where possible. NERC, Texas RE, and ERCOT also engaged the OEMs directly to better understand the root causes of abnormal performance. This chapter describes the findings from this analysis. Refer to **Appendix A** for details regarding each affected facility.

Causes of Wind Plant Reduction

Table 1.1 show the causes and magnitudes of active power reduction in each March 2022 fault event. The consequential (second fault) tripping of wind resources was the largest reduction in output, but this was expected due to the first fault. The next most common reduction involved plant controller interactions impeding the ability of the plant to return to predisturbance output levels. AC overvoltage tripping at one facility also tripped a significant number of inverters. Dynamic active power reductions caused by the fault also were a notable cause of reduction. One plant tripped on detected subsynchronous oscillation tripping for both faults, and multiple facilities also tripped due to errors in their pitch converters. One plant had one turbine trip on failed uninterruptible power supply, and one plant was not analyzed in detail. **Figure 1.1** and **Figure 1.2** show a graphical representation of this information.

Table 1.1: Causes of Reduction for Fault 1 and Fault 2

Cause of Reduction	Fault 1 Reduction [MW]	Fault 2 Reduction [MW]
Consequentially Tripped	273	–
Plant Controller Interactions	138	144
AC Overvoltage Tripping	135	64
Dynamic Active Power Reduction	82	128
Subsynchronous Oscillation Tripping	64	55
Pitch Converter Faults	57	17
Not Analyzed	14	–
Uninterruptible Power Supply Failure	2	–

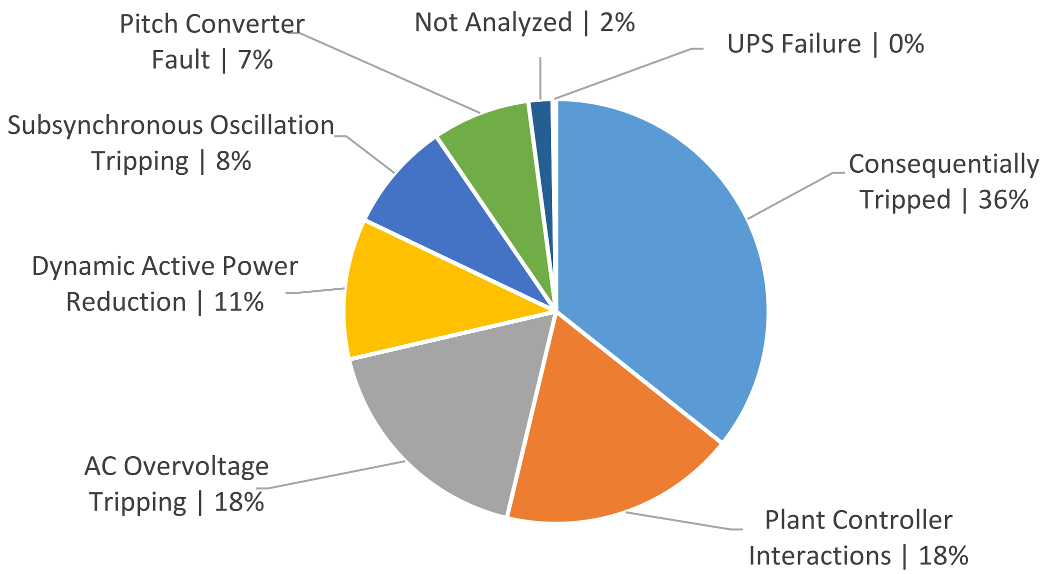


Figure 1.1: Causes of Wind Plant Reduction for Fault 1

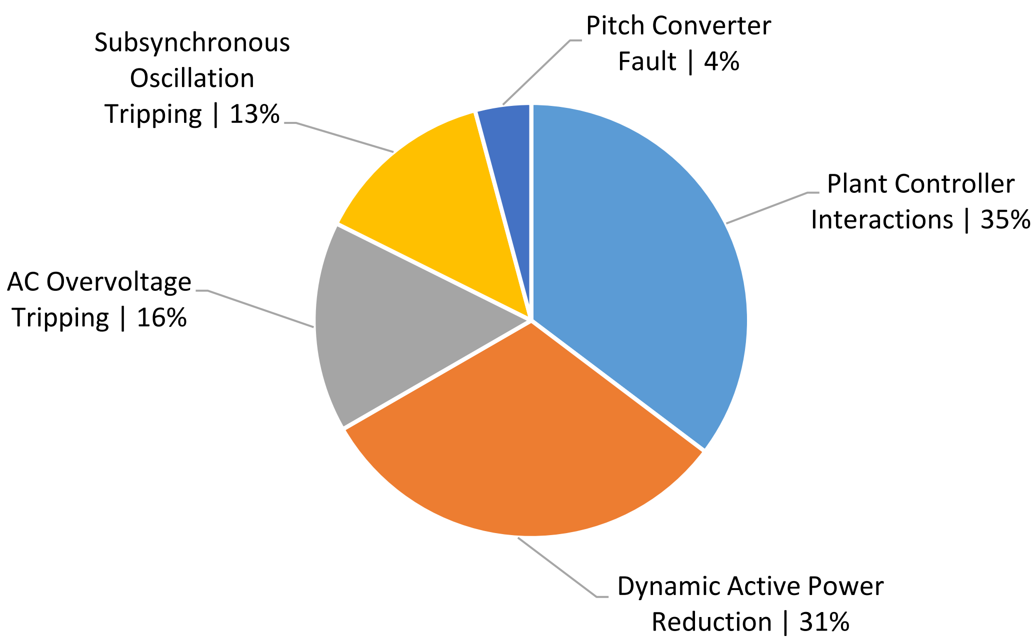


Figure 1.2: Causes of Wind Plant Reduction for Fault 2

Industry Awareness of Wind Turbine Response to BPS Faults

High-speed measurements from the point of interconnection (POI) were analyzed for multiple affected wind plants. The dynamic response varied across different turbine types and equipment manufacturers and is largely based on the controls programmed in the power electronics of the turbines. While different types of dynamic responses are acceptable, these responses differ greatly from synchronous generators that historically comprised the generation mix. Throughout this report, various plots of high-speed oscillography data show different responses from wind plants during and immediately after the faults.

NERC is not recommending a specific type of dynamic performance during faults for any technology; however, many BPS-connected inverter-based resources (and distributed energy resources) will significantly reduce active power for depressed voltages. The breadth and depth of the voltage depression is dependent on system strength and other factors. Regardless, this type of active power response to voltage will change grid dynamics and could have BPS reliability impacts over time. It is important, particularly in islanded systems, that the active power reduction is minimized to avoid degraded frequency response, any active power reduction is recovered quick and in a stable manner, and dynamic reactive power is provided throughout to hold BPS voltages stable throughout the event (including the appropriate injection of fault current).

The different types of response should be accurately modeled in simulations and studied during the interconnection process, during long-term planning studies, and during operational studies. **Appendix B** shows a clear illustration of how the dynamic model does not match the response of the actual plant to a BPS fault, and it is suspected that these issues are quite pervasive across the industry. One such example is shown in **Figure 1.3**, illustrating the dynamic response of a wind facility for this disturbance. The following annotations explain the response:

- **A:** The A–B-phase fault occurs, causing voltages to drop at the POI.
- **B:** The plant provides fault current at fault inception, a desired response from generating resources.
- **C:** Active power drops during the fault duration. The depth of reduction varies based on turbine type and specific turbine manufacturer control strategy.
- **D:** Active power recovers back to predisturbance output upon fault clearing within about 50 ms. This is a very quick recovery and supports grid frequency control but needs to be balanced with local grid voltage stability.
- **E:** After fault clearing and once voltages have recovered, active power quickly drops to near zero and begins an extended ramp back to predisturbance values. It is likely that the turbine low voltage ride through controls kick in, having the turbine return to predisturbance output on a ramped output. Prior NERC guidance has stated that resources should return to predisturbance values within one second; however, it is unclear why the resource recovers within 50 ms and then reduces output to near zero and begins a much slower recovery. Again, it is critical that these types of dynamics are appropriately modeled in positive sequence and electromagnetic transient (EMT) models. It is suspected that they are not in many positive sequence models.

Figure 1.3: Abnormal Dynamic Response of Wind Power Plant

The relatively significant reduction in active power is often caught by SCADA data depending on scan rates. Figure 1.4 shows an example of a plant that reduced output for both the first and second fault with active power dropping to near zero and recovering very quickly. SCADA data essentially missed the first fault and only picked up a partial reduction for the second fault. Figure 1.5 shows the high speed oscillography data capturing the plant going to zero output during the fault and recovering over a time period of 1–1.5 seconds.

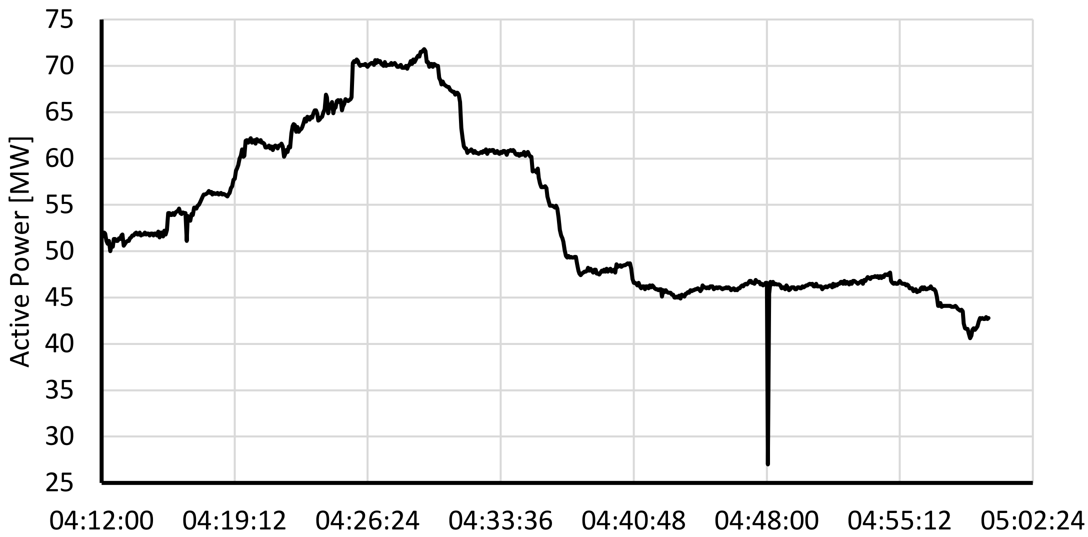


Figure 1.4: Reduction of Active Power during Fault Conditions

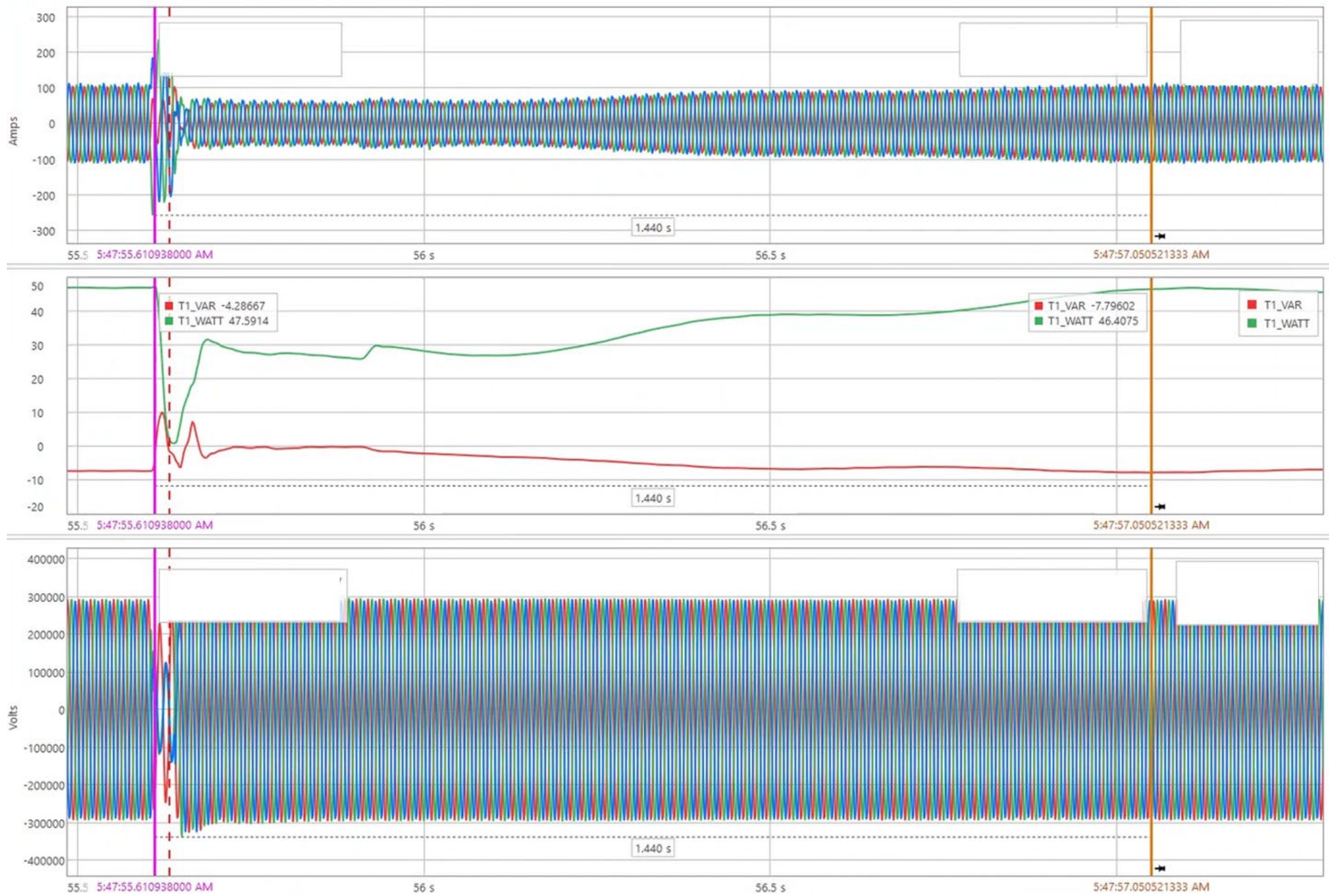


Figure 1.5: Dynamic Response of Plant to Second Fault

Wind Plant Controller Active Power-Frequency Response Interactions

Multiple plants from different manufacturers had plant controller interactions that resulted in an abnormal post-fault active power recovery to predisturbance output levels. The issue stems from the fact that these faults, which are not uncommon, caused plant voltage to go low (i.e., the turbines enter into low voltage ride-through (LVRT) mode) but the frequency also declined due to the loss of resources. When the LVRT condition occurs, the plant controller pauses and cedes control to the individual turbines. Once voltage recovers post-fault clearing, the plant controller regains control and resumes dispatch of the turbines. However, the handoffs between the plant controller and turbines are not properly coordinated.

In the March 2022 disturbance, the plant controller active power-frequency response controls are incorrectly sending dispatch signals to the individual turbines immediately following the LVRT condition; this is partly caused by abnormal or unexpected response of the individual turbines after fault clearing. **Figure 1.6** shows one plant where the turbines provide fault current during the low voltage fault; however, turbine current then rapidly decreases post-fault, causing active power output to drop drastically from about 180 MW predisturbance down to a low of 116 MW. During this time, the plant controller is regaining control of the turbines' output and latches on to a plant power output of about 163 MW during the swing. That latched value becomes the new set point dispatch for the active power-frequency controller. So the turbines settle at a new output of 163 MW even though there is sufficient wind speed for 180 MW. Frequency remains low for a couple minutes and the new dispatched set point is held until frequency recovers and the erroneous dispatch from the controller is released. Once frequency returns to near nominal, the plant rapidly recovers back to predisturbance output (see **Figure 1.7**).

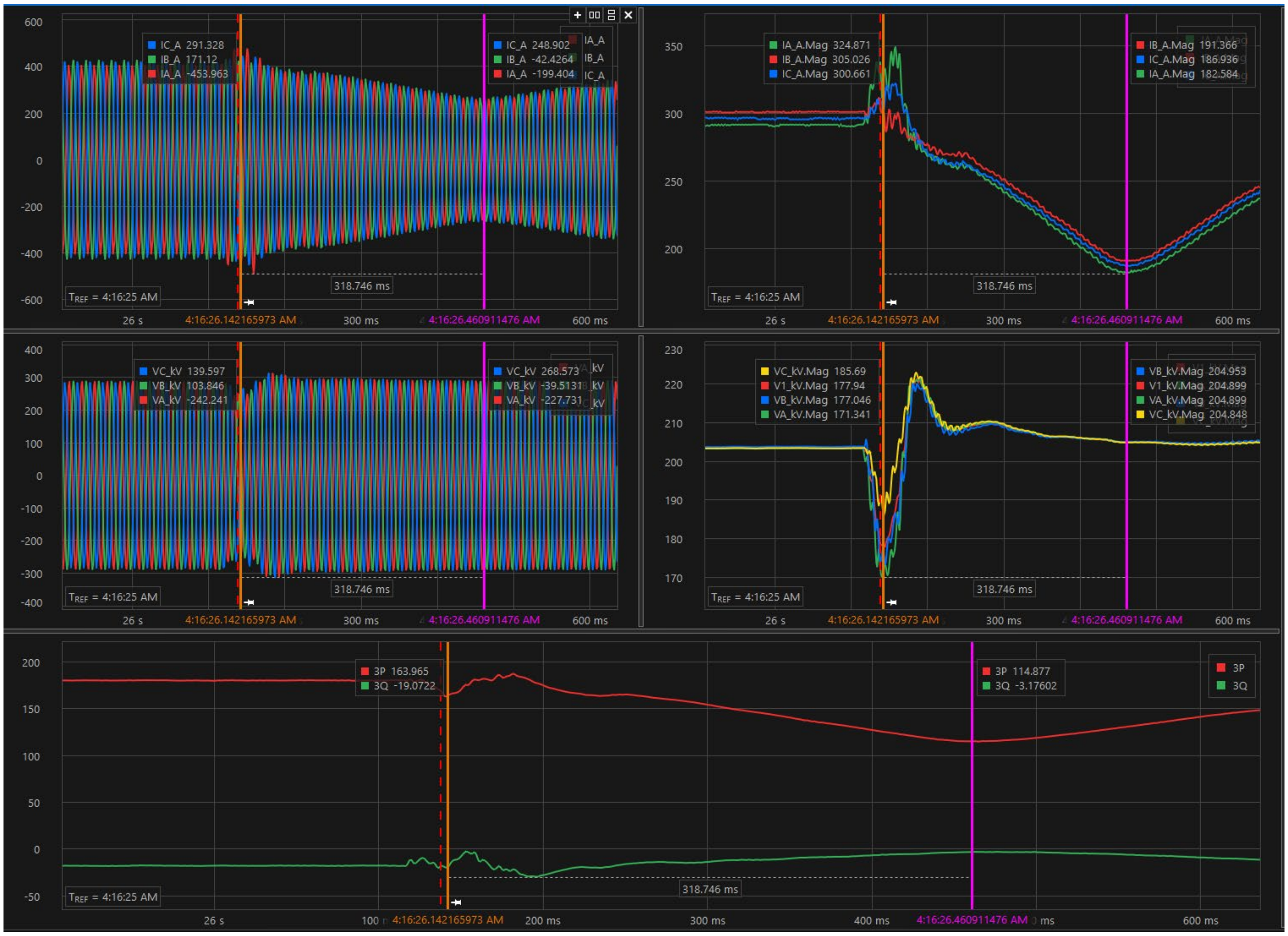


Figure 1.6: Plant Dynamic Response before Plant Controller Interactions

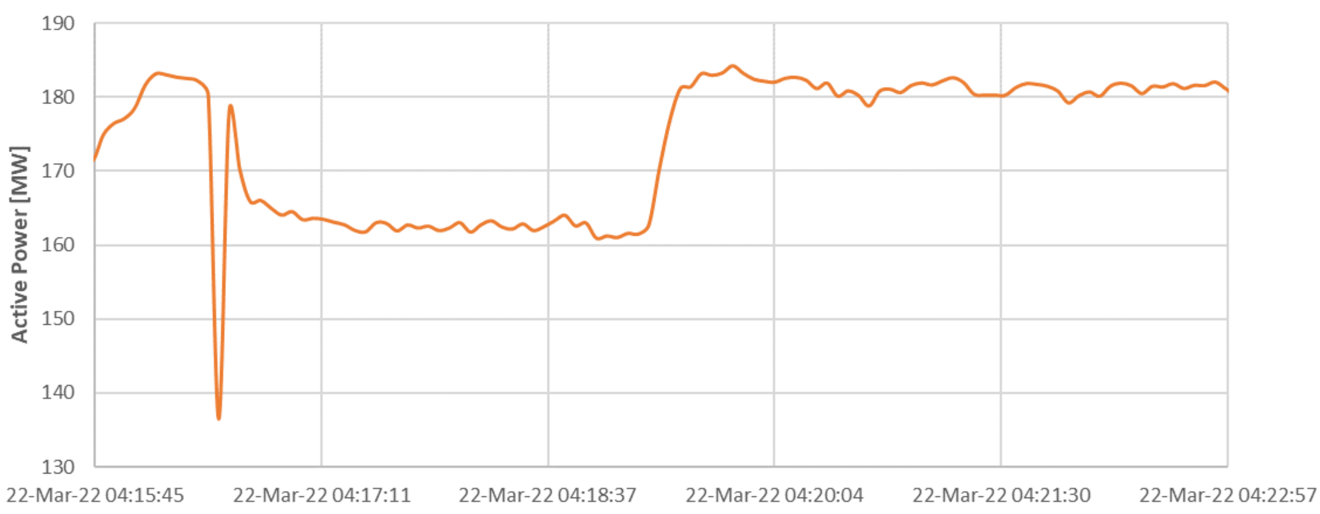


Figure 1.7: Plant Active Power-Frequency Controller Interactions

These issues are not identified in the dynamic models (positive sequence or EMT) the GO provided to ERCOT, so they will not be identified and corrected during interconnection studies or during long-term planning or operations studies.

Turbine Pitch Converter Faults

Multiple plants from one turbine manufacturer experienced wind turbine pitch converter faults that tripped multiple turbines at each facility. Each turbine blade (axis) is equipped with a turbine pitch converter that is controlled by a central controller. During the low-voltage conditions caused by the fault, some signals within the turbine may drop out for a short period to reduce the turbine power consumed to the greatest possible extent, a design choice made by the manufacturer. However, if the signals do not recover in a period of time (around 700 ms), the controller will issue a fault acknowledging that the pitch converter axis is not responding. The turbine then shuts down and goes off-line instantly and requires manual reset from a remote operator or a local technician. This pitch converter fault occurred on many of the turbines at each affected site, but not all of them were impacted.

It is unclear why specific turbines had this issue while neighboring turbines did not. The issue may depend on the age of the turbine or equipment as well as the pitch converter software and firmware. The turbine manufacturer is trying to make improvements to the affected sites, but specific corrective actions are not clear at this time. Recommended troubleshooting solutions from the turbine manufacturer include checking converter wiring, replacing the encoder, replacing the pitch axis module, and/or replacing the converter.

The turbines were off for different periods of time at each facility, and this was caused by the necessity of manual operator (remote or local) resetting of each affected turbine. At one site, some turbines were brought back on-line following the first fault before the second fault occurred. At another site, no turbines were returned to service between the two fault events. One site owner stated that the turbines are monitored by the turbine manufacturer that had remote control and reset capability of the fleet and was able to perform operator actions on the turbine to return them to service.

Subsynchronous Resonance Alarms and Tripping

One facility had multiple turbines trip for two anomalous reasons: subsynchronous resonance (SSR) and extreme ac overvoltage.

The concept of subsynchronous oscillations (SSO) is generally comprised of three phenomena: SSR, subsynchronous control interactions (SSCI), and subsynchronous torsional interactions (SSTI). The following contains more information specifically regarding SSR and SSCI:

- **SSR:** This generally refers to a phenomenon where one of the resonant frequencies of a synchronous turbine-generator shaft coincides with a natural resonant frequency of the electrical grid (commonly due to issues with series compensation).
- **SSCI:** This generally related to oscillations caused by resonances between inverter-based resource controls and the BPS; SSCI issues are most common in networks where the inverter-based resource may be connected to the BPS through a series compensated radial connection although this is not always necessary.

Regarding wind plants, SSCI type issues are most prominent in Type 3 doubly-fed induction generators. Resonances cause sustained and/or severe unstable exchanges of power between the turbine and the system that can cause damage to the shaft of the machine if not mitigated quickly. Although others have occurred, the Mohave generator incident that occurred in 1970 is one of the most well-known SSR events. In 2009, a fault occurred in South Texas area that resulted in wind farms being connected radially to a series compensated transmission line.[8] Consequently, this produced undamped SSCI oscillations at 22 Hz and doubled generator terminal voltages in about 150 ms, resulting wind generator and series capacitor damage.[9] This led ERCOT and its member TOs to significantly enhance their understanding and analysis of SSOs. SSOs are now a known risk in ERCOT and analyzed fairly extensively with

[8] J. Adams, C. Carter and S. Huang, "ERCOT experience with Sub-synchronous Control Interaction and proposed remediation," PES T&D 2012, 2012, pp. 1-5, doi: 10.1109/TDC.2012.6281678.

[9] https://www.ercot.com/files/docs/2018/05/02/10._South_Texas_SSR_ERCOT_ROS_May_2018_rev1.pdf

screening tools and EMT studies. As the system continues to evolve, ERCOT requires new and existing facilities to provide EMT models of facilities in the affected area so they can thoroughly conduct SSO studies.

Plants can be equipped with SSO[10] mitigation if required by ERCOT during the interconnection study process; however, the studies must present a risk of SSO for the mitigations to be deployed. All turbines are equipped with SSO monitoring and alarming, but turbines are not necessarily equipped with SSO mitigations unless required or requested of the manufacturer by the GO. Mitigation involves turbine controls (software) that can change the resonant frequency to avoid SSO from occurring at the turbine. The plant involved in this disturbance did have an SSO mitigation package, but the turbine manufacturer may need to analyze and possibly re-tune this controller to avoid unnecessary tripping. A total of 27 turbines tripped at the facility; however, it is unclear why only a portion of the turbines tripped. All turbines are the same type with the exact same converter make, model, and firmware installed.

The affected facility had extensive high-speed measurement data that provided the analysis team and the plant turbine manufacturer with the ability to perform detailed forensic analysis. **Figure 1.8** shows the plant dynamic response of the facility captured with oscillography data from a digital relay at the POI. The fault occurs and turbine power naturally drops and recovers back to pre-disturbance output within about 50 ms. After returning to predisturbance conditions, plant output starts dropping about 150 ms later; this is suspected to be the time that the turbines begin tripping on SSR protection. However, this response is not indicative of any SSO conditions occurring at the facility based on the data provided.

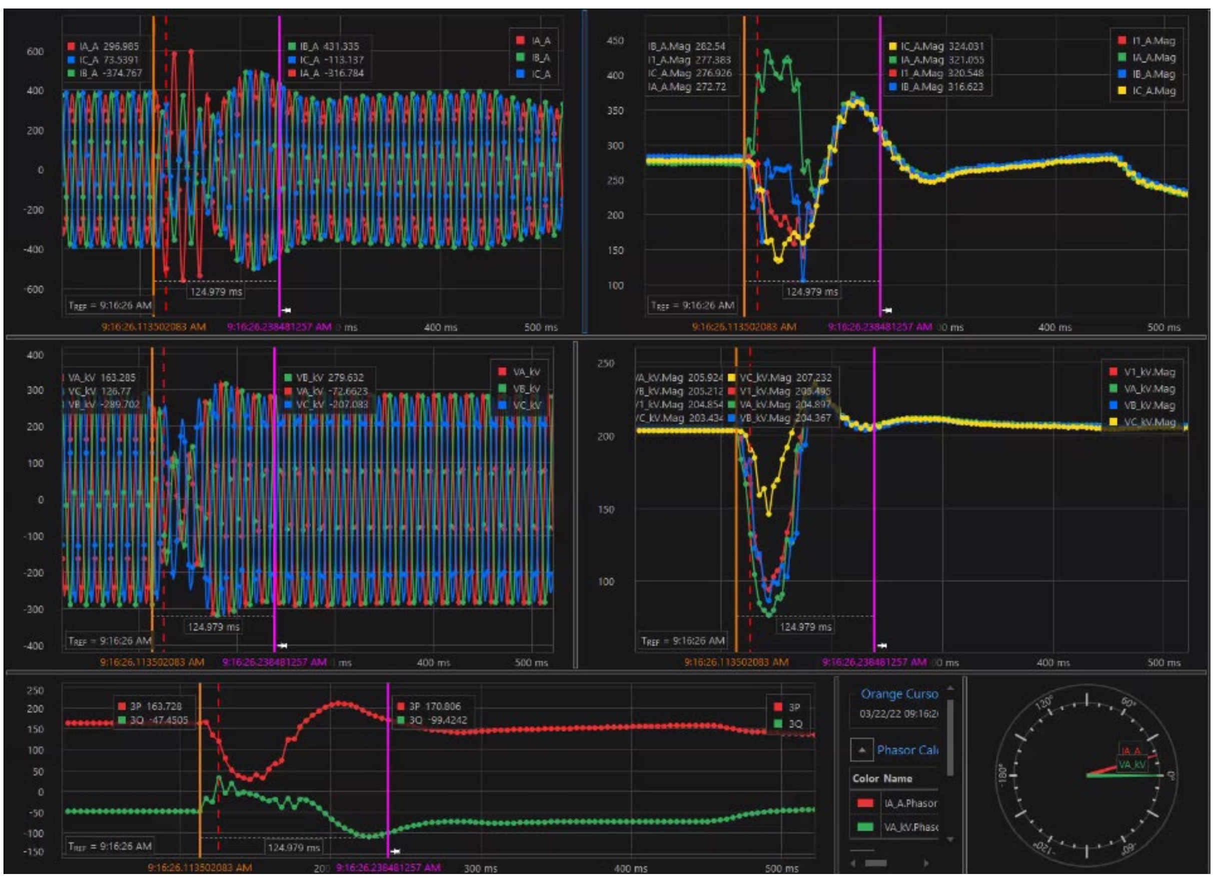


Figure 1.8: Affected Plant High Speed Measurement Data

[10] Note that SSR is sometimes used colloquially to refer to different types of SSO issues. In fact, the turbine manufacturer refers to this as SSR in their protection.

The area under consideration is not heavily series compensated unless under significant outage conditions. At the time of the faults, multiple transmission paths were fully in-service, posing minimal expected risk of SSCI. Furthermore, the turbine manufacturer explained that its SSR protection consists of logic monitoring instantaneous, cumulative, and summative energy counters in the turbines (i.e., looking at various calculated energies within the turbines). If any one of these calculations exceeds a threshold, then the turbines will trip very quickly to protect them from damage. Alarming (not tripping) uses a different set of parameters, but the turbine manufacturer has seen that these alarms at multiple facilities are tuned overly sensitive, and corrections are being made to the fleet over time; the turbine manufacturer speculates that the protection could also be set sensitively and may be able to be alleviated with firmware updates to the turbines after further investigation.

The turbine manufacturer with their ability to quickly remotely connect to the turbines at the affected facility informed NERC, Texas RE, and ERCOT that another fault-induced tripping of the turbines occurred a couple weeks later. Since this event was more recent, the turbine manufacturer was able to gather 10 kHz high resolution data from the turbine directly to observe what the turbine experienced immediately prior to tripping. **Figure 1.9** shows the active power (top), turbine voltage (middle), and turbine speed (bottom) during the fault. Note that the measurements are taken in front of the turbine filter capacitors and are unfiltered quantities, so they show more oscillations and noise in the data since they are not yet smoothed by the filter capacitors. As the plot shows, when the fault occurs, the turbine (rated at 2 MW) rapidly ramps up active power to about 3.2 MW and then quickly trips. No anomalous or abnormal data is observed in voltage or speed measurements at the turbine. The turbine manufacturer is continuing to investigate the cause of this tripping and will further determine if tripping may be attributed to SSO issues or some other cause. While sustained SSCI is not observed, it is plausible that the turbine tripped on the first unstable swing of an oscillation that could have been caused by SSO-related issues.

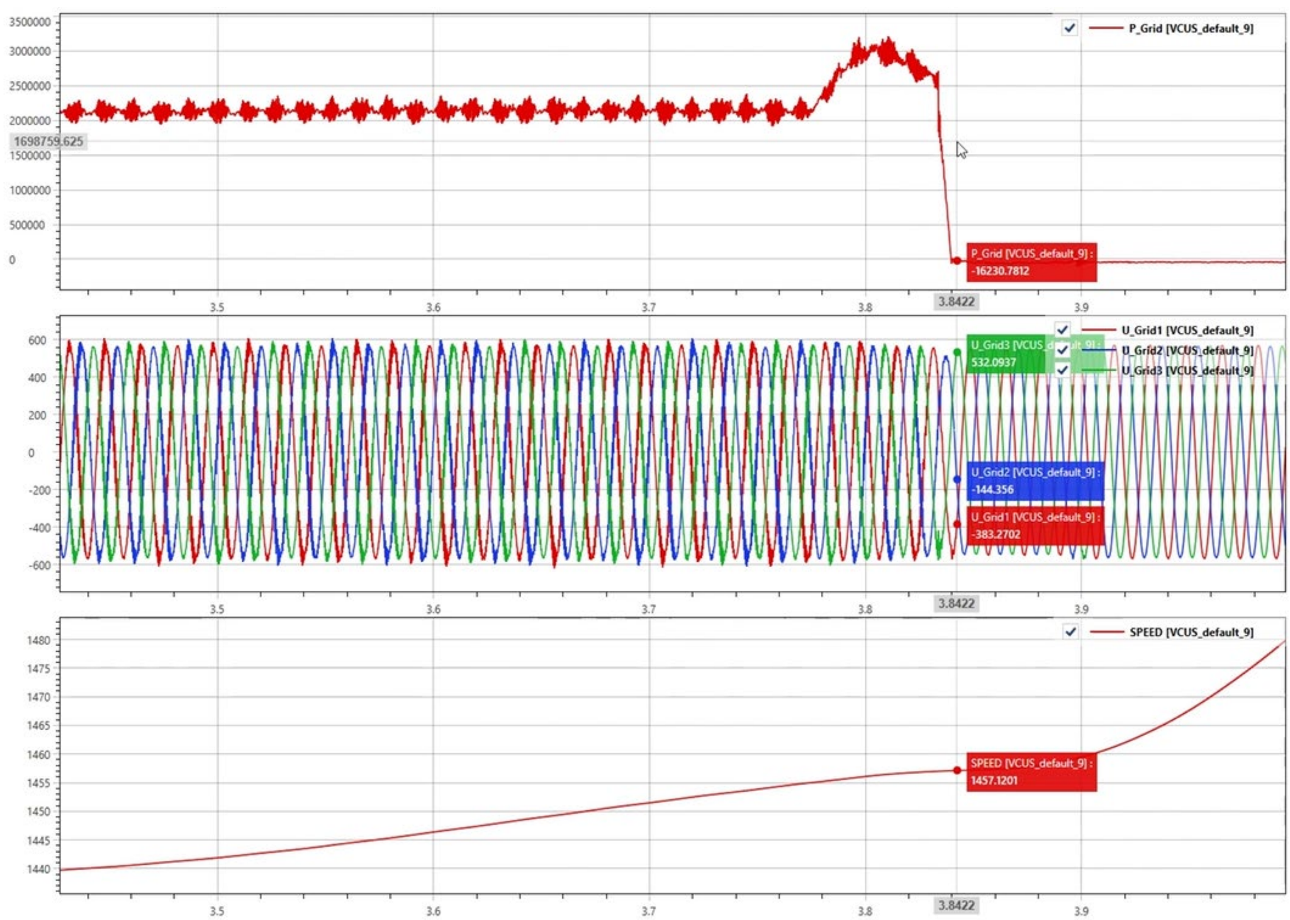


Figure 1.9: Turbine High Speed Data Capturing Turbine Tripping for Different Event

The turbines also alarmed on a 700% ac overvoltage condition. The turbine manufacturer explored this alarm in detail by using all available information at the facility and determined that the code used to alarm only (not control or protect the turbine) had a bug that resulted in an incorrect value reported to the turbine logger. NERC, Texas RE, and ERCOT also observed that plant POI voltage only reached a maximum of 1.2 pu, so 7.0 pu voltage is not feasible. This issue is being explored by the manufacturer in more detail and will be corrected with a firmware update.

Significantly Enhanced Data for Analysis at Wind Plants

Compared with past disturbance analyses that involved widespread reduction of solar PV resources, the March 2022 event had enhanced access to various types of data to perform comprehensive analysis at each individual site. This included high-resolution oscillography data at the POI coming from digital fault recorders or digital relay records. The Transmission Operator (TOP) in the Panhandle also had phasor measurement units measuring electrical quantities continuously at some of the wind plant POIs and on the 345 kV transmission network. All plants had SCADA data with sufficient resolution in addition to the SCADA data captured by ERCOT, which had excellent telemetry data regarding number of on-line turbines and other useful quantities that proved helpful during the analysis.

Multiple sites were able to access ultra-high resolution sampling data at the turbine level to further explore the electrical phenomena experienced. This was critically important in the analysis of SSR risks, and the turbine manufacturer was able to remotely connect to the affected sites and turbines to pull all relevant fault codes and high-resolution data quickly and effectively. NERC was able to leverage its contacts with the wind turbine manufacturers, and multiple affected GOs were able to pull in their manufacturer account managers for additional support, as needed. This led to a very collaborative engagement between all parties with relatively easy flow of information necessary to conduct a thorough analysis.

The necessity of high-speed measurement data to conduct adequate root cause analysis for abnormal performance issues cannot be overstated. Without this data, the analysis team and affected plant owner are unable to explore possible mitigating measures and the issues are expected to persist. When high-speed measurement data is available at the POI, within the plant controller, and at the individual turbine level detailed analyses can be conducted and performance issues can be properly explored and possibly mitigated.

Recommended Monitoring Equipment for Effective Event Analysis

NERC has observed industry confusion and inconsistencies regarding the monitoring requirements for newly connecting resources. NERC outlined recommended measurement data and their resolution and retention in Chapter 6 of NERC *Reliability Guideline: BPS-Connected Inverter-Based Resource Performance*.[11] To further support industry and provide clarifications, NERC recommends that all newly connecting inverter-based resources (e.g., wind, solar PV, battery energy storage systems, hybrid plants, co-located plants) have the following monitoring capabilities at a minimum:

- **High-resolution oscillography data at the plant POI and on collector feeders**
  This can be acquired from digital relays (most common), digital fault recorders, and plant-level controllers. Measurement quantities should include voltage and current phasors from power quantities that can also be calculated.
- **Plant SCADA data with 1–2 second resolution**
  A wide array of measurements and statuses should be collected and stored from throughout the plant.
- **Plant-level controller measurements, set points, control settings, and other quantities**
  This should include all input measurements and output signals coming from the plant-level controller regarding all controls, operating modes, and protections within the controller.

[11] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Inverter-Based_Resource_Performance_Guideline.pdf

- **Synchrophasor data at the POI**
  Synchrophasor data can be captured from standalone phasor measurement units or from digital relays. Quantities should include current, voltage, frequency, and angle along with digital status where needed.
- **Inverter-level fault codes**
  These fault codes should have very accurate resolution and should capture all protection and controls logic activated within the inverter for more detailed forensic analysis.
- **Inverter-level oscillography data**
  Multiple inverters at each facility should be equipped with the ability to capture triggered high-speed oscillography data to understand what is occurring at the individual inverters (or turbines). This could include at least one inverter on each collector string within the plant.
- **Time-synchronized measurements**
  This includes synchronizing the plant to a common time reference, such as coordinated universal time (UTC), and then disseminating that time with reasonable accuracy to the rest of the plant, such as over IEE 1588-2019 Precision Time Protocol.[12]
- **Sufficient retention**
  The identification and initial analysis of any given disturbance—along with the solicitation of requests for additional information across many assets—takes time for industry experts to conduct. Therefore, reasonable retention periods should be required on all necessary data within the plant. This should be 90 days at a minimum if not much longer.

NERC strongly recommends that FERC modify its pro forma interconnection agreements to reflect these changes for newly connecting inverter-based resources.

[12] https://standards.ieee.org/ieee/1588/6825/

Chapter 2: Modeling and Studies Assessment

This chapter provides a cursory review of the positive sequence and electromagnetic transient modeling practices for the affected facilities and the ability of those models to recreate the causes of reduction identified. Past disturbance reports related to widespread loss of solar PV resources have highlighted significant and systemic issues with model quality and accuracy. NERC has provided detailed assessments and ongoing recommendations for improved modeling practices across the industry in connection with the NERC FAC-001, FAC-002, MOD-032, and MOD-033 standards.

Availability of Dynamic Models

ERCOT confirmed that all affected wind plants submitted a positive sequence dynamic model and an electromagnetic transient model (see **Table 2.1**). Note that Plants A and J are not discussed in this chapter as they were not analyzed and were consequentially tripped during the fault.

Table 2.1: Availability of Dynamic Models

Facility ID	In-Service Date	Positive Sequence Model Available	EMT Model Available
B	December 2020	Yes	Yes
C	March 2015	Yes	Yes
D	January 2015	Yes	Yes
E	March 2014	Yes	Yes
F	November 2014	Yes	Yes
G	August 2015	Yes	Yes
H	November 2016	Yes	Yes
I	October 2015	Yes	Yes

Ability to Capture Causes of Reduction

Table 2.2 shows the ability of the positive sequence dynamic models available to ERCOT to capture or recreate the cause of reduction observed in this event. None of the causes of tripping in this event can be recreated in simulation since the dynamic models do not include these types of protections that tripped the turbines. The plant controller interactions are abnormal, should not be occurring, and cannot be recreated in positive sequence models.[13] The dynamic response resulting in deep reductions of active power may be able to be recreated, but it is unclear at this time due to the inability to conduct plant model validation activities.

[13] The issues should be corrected; an attempt at modeling them is irrelevant.

Table 2.2: Positive Sequence Model Ability to Recreate Disturbance			
Facility ID	**Cause of Reduction**	**Positive Sequence Model Able to Recreate Cause of Reduction**	**Explanation**
B	Anomalous turbine dynamic response; plant controller interactions	No: plant controller interactions Unclear: dynamic response	Abnormal plant controller interactions not modeled. Unable to conduct detailed model validation for affected plant.
C	Turbine pitch converter faults; plant controller interactions	No: pitch converter faults No: plant controller interactions	Pitch converters not modeled in positive sequence. Abnormal plant controller interactions not modeled.
D	Dynamic active power reduction	Unclear	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.
E	Turbine pitch converter faults; plant controller interactions	No: pitch converter faults No: plant controller interactions	Pitch converters not modeled in positive sequence. Abnormal plant controller interactions not modeled.
F	Uninterruptible power supply failure; instantaneous ac overvoltage tripping	No: UPS failure Unlikely: ac overvoltage	UPS not modeled. Sub-millisecond ac overvoltage not captured in positive sequence simulations. Model configured with tripping at 1.2 pu for 150 ms (not instantaneous).
G	Dynamic active power reduction	Unclear	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.
H	Turbine tripping on SSR alarms	No	SSR (SSCI) not able to be modeled in positive sequence.
I	Dynamic active power reduction	Unclear	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.

Table 2.3 shows the ability of the EMT models available to ERCOT to capture or recreate the cause of reduction observed in this event. As described in **Table 2.1**, the plant controller interactions are not represented in the EMT models since they are abnormal and should not be occurring.[14] Dynamic response causing deep reductions of active power may be able to be recreated, but it is unclear at this time due to the inability to conduct plant model validation activities. Lastly, none of the tripping causes in this event can be recreated in simulation since the dynamic models do not include these types of protections that tripped the turbines. This is due to the following reasons:

- Pitch converters and their protection systems are not modeled in EMT models.
- Uninterruptible power supply (UPS) systems are not modeled in EMT models.
- NERC and industry stakeholders have attempted to recreate the ac overvoltage phenomenon, and understanding it may be linked to very fast spikes in voltage during fault clearing; however, these require detailed point-on-wave sensitivities to identify that are not generally conducted during interconnection studies.
- The EMT model provided for the plant that tripped on SSR protection has the SSR mitigation package enabled and the SSR protection settings disabled. Therefore, ERCOT studies would never show SSR protection operating for this facility since they are enabled.

[14] The issues should be corrected; an attempt at modeling them is irrelevant.

Table 2.3: EMT Model Ability to Recreate Disturbance			
Facility ID	**Cause of Reduction**	**EMT Model Able to Recreate Cause of Reduction**	**Explanation**
B	Anomalous turbine dynamic response; plant controller interactions	No: plant controller interactions Unclear: dynamic response	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.
C	Turbine pitch converter faults; plant controller interactions	No: pitch converter faults No: plant controller interactions	Pitch converters not modeled in EMT. Abnormal plant controller interactions not modeled.
D	Dynamic active power reduction	Unclear	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.
E	Turbine pitch converter faults; plant controller interactions	No: pitch converter faults No: plant controller interactions	Pitch converters not modeled in EMT. Abnormal plant controller interactions not modeled.
F	Uninterruptible power supply failure; instantaneous ac overvoltage tripping	No: UPS failure Unlikely: ac overvoltage	UPS not modeled in EMT. Past research and experience shows difficulty in creating sub-cycle ac overvoltage in simulations.
G	Dynamic active power reduction	Unclear	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.
H	Turbine tripping on SSR alarms	No: model shows mitigations on and protection off	Model supplied to ERCOT shows SSR mitigations are turned on and SSR protections are turned off at plant.
I	Dynamic active power reduction	Unclear	ERCOT unable to conduct detailed model validation for affected plant due to time constraints.

Table 2.1 and **Table 2.2** illustrate that the majority of abnormal performance from wind plants in the March 2022 event cannot be accurately simulated in positive sequence studies nor in EMT studies most commonly performed by TPs and PCs. This aligns with the findings observed in past events involving solar PV resources. This is predominantly due to the fact that these models are not generally used to study a number of the causes of tripping and interactions (e.g., plant controller interactions, pitch converter faults) and because of the limitations of positive sequence simulations (RMS, quarter-cycle time step simulations), modeling simplifications associated with the inverter, and plant protection systems and controls. EMT simulations will also be challenged to study or recreate these tripping causes since many of these protections and interactions are not modeled in those models either. SSCI can be studied in EMT; however, accurate studies must rely on accurate models reflective of as-built facilities.

These findings reiterate recommendations from the ERO Enterprise in past disturbances that a performance validation feedback loop is necessary to mitigate abnormal performance issues in a timely manner. BES inverter-based resource owners should analyze abnormal performance events, such as these, and develop mitigating measures to eliminate these risks in the future if possible. The issues and their mitigations should be reported to the BA and RC for wide-area tracking of fleet performance and reported to NERC as a new classification of "IBR misoperations."

Overview of SSR Modeling and Studies in ERCOT Footprint

ERCOT has a relatively long history of studying subsynchronous oscillation risks and have published multiple studies related to this type of analysis.[15] ERCOT has requirements and processes related to studying subsynchronous oscillations that are specified in Section 3.22 of the ERCOT Nodal Protocols.[16] Assessments for generator interconnection are covered in section 3.22.1.2. At a high level, the interconnection assessments use the following concepts:

[15] https://www.ercot.com/files/docs/2020/11/27/2020_PanhandleStudy_public_final__004_.pdf
[16] https://www.ercot.com/mktrules/nprotocols/library

- Screening study to identify possible radial connections of generation (or energy storage) resources with series capacitors with up to 14 concurrent transmission outages used.
- Any resource identified in the screening will have an "SSR study" conducted, including frequency scan assessment and/or detailed SSR assessment to identify any vulnerabilities:
  - Studies are not needed if the interconnecting resource can prove they are not vulnerable to SSR.
  - If SSR is identified in studies for six or fewer concurrent transmission outages, the resource shall develop and implement a mitigation plan prior to commercial operation.

ERCOT has also posted a study scope guideline for when detailed studies are necessary to assess potential subsynchronous control oscillation interactions between generators and series capacitors.[17]

ERCOT Follow-Up on Model Quality and Model Validations

Due to high priorities related to summer operating conditions in Texas, ERCOT was unable to conduct any extensive model validation or model quality check activities during the analysis of the March 2022 event. ERCOT has committed to performing a more detailed analysis of these affected wind plants and working with the affected GOs to correct abnormal performance issues. ERCOT will also work with the GOs to ensure positive sequence and EMT models are updated to accurately reflect the equipment installed in the field. In multiple cases in both the ac overvoltage protection and the SSR protection situations, the model does not accurately reflect the as-built equipment. Additionally, model validation activities are likely to identify anomalous behavior between model and actual facilities for the post-fault dynamic current injection. This will require model validation for both positive sequence and EMT simulations as well as model benchmarking between both platforms. NERC would like to see these types of events used for system model validation events per NERC MOD-033 along with other events.

[17] https://www.ercot.com/files/docs/2021/01/20/ERCOT_SSR_Study_Scope_Guideline_10-27-2020-external.docx

Chapter 3: Recommendations and Actions Needed

Table 3.1 provides a list of recommendations and actions needed by applicable entities based on the key findings from this disturbance analysis and in the context of prior events analyzed by the ERO Enterprise.

Table 3.1: Recommendations and Actions Needed

Recommendation	Applicability
Improved Requirements and Processes	
Improvements to Interconnection Process: NERC has strongly recommended that the interconnection procedures and agreements administered by FERC need significant overhauls to align with current practices and risks posed to the BPS. These include gaps in the interconnection process particularly related to interconnection studies, model quality checks throughout, and commissioning testing. NERC has issues a notice of proposed rulemaking on this subject,[18] and NERC will be submitting comments regarding these reliability risks, and these risks are significant enough to highlight here as well. Accurate modeling and study information along with other necessary information to conduct sufficiently accurate reliability analyses should be a prerequisite to the "first read" queue approach. Without accurate information, TPs and PCs cannot conduct valuable studies to ensuring reliability. This includes accurate models of the protection and controls *of the actual equipment to be installed in the field (not default information)*. The necessary data should be prescribed in pro forma generator interconnection agreements or other interconnection requirements. Interconnecting customers should be held accountable for any situation in which model or equipment information provided to the Transmission Provider was inaccurate and/or resulted in studies that did not adequately represent the performance of the resource when connected to the BPS.[19]	FERC
NERC Standards Updates Needed to Address Performance Gaps in Inverter-Based Resources	
Strong Reinforcement of Need for Performance-Based Generator Ride-Through Standard: This event reinforces NERC's actions to submit a standard authorization request regarding overhauling and modernizing PRC-024 with a performance-based ride-through standard. Multiple wind turbines tripped in this event for causes that were avoidable and should be corrected through appropriate maintenance, testing, and firmware/software of the turbines. Furthermore, a number of plants reduced output and had plant controller interactions that precluded the plant from providing essential reliability services, which should be addressed appropriately in the performance-based standard. Corrective actions should be developed in all cases where power electronic controls or protection are interacting unnecessarily or abnormally within a plant or with other plants; this poses a significant risk to BPS reliability if not mitigated.	NERC Project 2020-02 Standard Drafting Team
Reinforcement of Need for Standard to Complement PRC-004 Focused on Analyzing and Mitigating Abnormal Performance Issues, Specifically for BES Inverter-Based Resources: This event further strengthens NERC's previous recommendation that the concept of a "misoperation" for inverter-based resources should be incorporated into either PRC-004 or (more ideally) in a new standard dedicated to this systemic risk. NERC continues to analyze inverter-based resources that are experiencing abnormal performance issues that should be identified and mitigated by asset owners in a timely manner. This includes issues observed related to inverter- and plant-level protections and controls. Unlike conventional protection systems, not all forms of these protections and controls necessarily trip an ac circuit breaker due to the flexibility of inverter power electronics, so a more applicable and appropriate standard is needed to ensure that these types of abnormal performance issues at inverter-based resource facilities are identified, analyzed, and mitigated. NERC has highlighted numerous times that this type of validation of expected performance, and GOs are not widely correcting performance issues. This appears to pose a significant and ongoing risk to BPS reliability since faint signal issues are not addressed in a timely manner, leading to more widespread and systemic performance risks on the BPS. This recommendation also highlights the need for inverter-specific requirements or standards where needed to address reliability issues presented specifically by inverter technology.	NERC RSTC and NERC IRPS

[18] https://www.ferc.gov/news-events/news/ferc-proposes-interconnection-reforms-address-queue-backlogs

[19] Note that this recommendation is using the terms of Interconnection Customer and Transmission Provider to ensure clarity with the terms used in the NOPR.

Table 3.1: Recommendations and Actions Needed

Recommendation	Applicability
ERCOT Recommended Actions	
ERCOT Follow-Up with Affected Facility Owners for Corrective Actions: ERCOT is already actively following up with affected facility owners and NERC, and Texas RE strongly recommends this action in all cases where widespread and systemic performance issues are identified. ERCOT should follow up with NERC and Texas RE in a reasonable time period (e.g., 6 months) to provide a status update of the corrections that have been made to the affected facilities and how that information was disseminated to other ERCOT stakeholders who may have similar issues. NERC will ensure this information is also widely shared with other Interconnections and stakeholders in an anonymized manner.	ERCOT
ERCOT Detailed Model Quality Review: As stated in the Odessa disturbance report, ERCOT should conduct a detailed model quality review for all inverter-based resources connected to the ERCOT system. This should include both positive sequence and EMT model quality checks against as-built settings, specification sheets, one-line diagrams, and any other information provided to validate that the model is a suitable representation of the installed facility. Models should include any control or protection function that can trip the facility, including (but not limited to) all the protections identified in this disturbance report and all others published by NERC related to solar PV reductions.	ERCOT
ERCOT Model Validation Effort: ERCOT should conduct a thorough model validation effort by using both positive sequence and EMT models to identify model discrepancies between actual and modeled performance. Any identified discrepancies should be addressed by the applicable GOs in collaboration with ERCOT. In particular, the SSR mitigation/protection and ac overvoltage protections should be explored in more detail. Furthermore, these issues should be reviewed at other facilities that may have similar underlying model quality issues.	ERCOT

Appendix A: Detailed Review of Affected Facilities

This appendix provides a detailed review of the affected wind power plants that exhibited an active power reduction during the March 2022 event. Note that the reduction values in the tables are based on engineering judgment and a compilation of multiple data sources with different resolutions. These values may differ slightly from the total combined loss values.

Event 1 Analysis

Table A.1 provides an overview of the facilities involved in the first fault event and the subsequent subsections describe the analysis of each facility in more detail. All affected plants have a POI to the 345 kV transmission network.

Table A.1: Review of Affected Wind Plants								
Facility ID	**Capacity [MW]**	**Event 1 Reduction [MW]**	**Event 2 Reduction [MW]**	**In-Service Date**	**Number Turbines**	**Turbine Type**	**Highest Data Resolution**	**NERC-Texas RE Review**
A	150	14	0	October 2015	81	3	N/A	Plant not analyzed in detail.
B	243	64	64	December 2020	59	3 (48) 4 (11)	DFR	Anomalous turbine dynamic response and plant-level controller frequency response interactions.
C	300	40	79	March 2015	162	3	SCADA	Turbine pitch converter faults; plant-level controller frequency response interactions.
D	200	32	27	January 2015	100	3	N/A	Dynamic active power reduction.
E	288	91	38	December 2014	156	3	DFR	Turbine pitch converter faults; plant-level controller frequency response interactions.
F	191	137	138	November 2014	79	4	DFR	1 turbine tripped on uninterruptible power supply failure; many turbines tripped on instantaneous ac overvoltage above 1.2 pu.
G	150	3	19	August 2015	75	3	N/A	Dynamic active power reduction.
H	174	64	56	November 2016	87	3	DFR, turbine-level	SSR and high voltage tripping alarms; root cause under deeper investigation by turbine manufacturer.
I	200	47	36	October 2015	100	3	N/A	Dynamic active power reduction.
J	N/A	273	0	N/A	N/A	N/A	N/A	Consequentially tripped for fault 1.
TOTAL		**765**	**429**					

* Modified from ERCOT brief report

Plant A

This plant reduced power output by 14 MW during the first fault (see **Figure A.1**). A couple turbines tripped and recovered in about 15 minutes. The plant did not noticeably reduce output during the second fault. The analysis team did not perform a detailed analysis of this plant; therefore, the causes of reduction are not known.

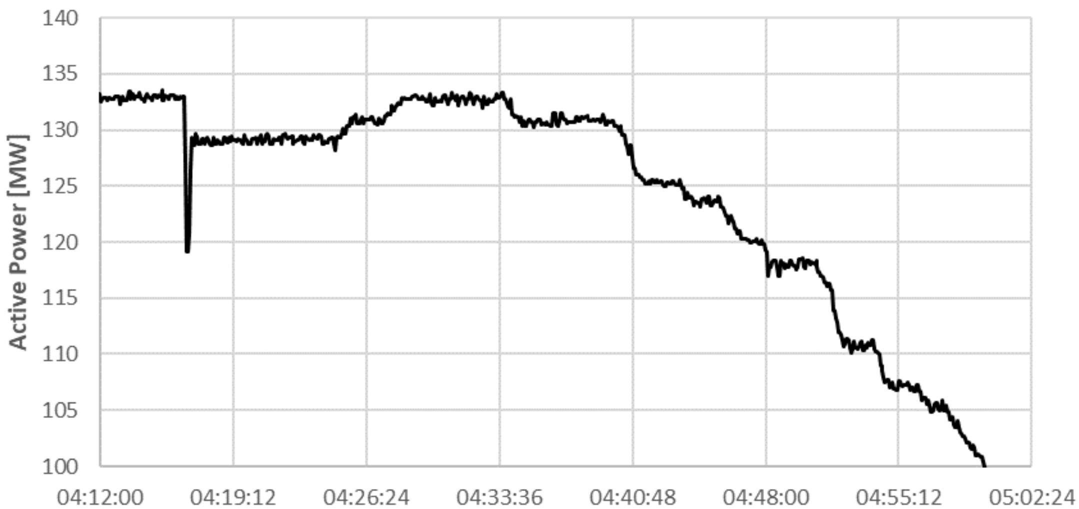


Figure A.1: Plant Active Power Output

Plant B

This plant reduced power output by 64 MW for the first fault and 64 MW for the second fault. The plant consists of multiple wind turbine types and manufacturers and has a master plant controller provided by one of the turbine manufacturers rather than a third-party controller or STATCOM master control. In both cases, the turbines appropriately responded to the LVRT condition, providing current injection during the fault. Active power reduced slightly and reactive power was provided to the grid. Active recovered very quickly within about 50 ms (see **Figure A.2**).

Upon the fault clearing, the active power rapidly ramped down from about 180 MW to 116 MW in about 275 ms. The rapid reduction of active power after fault clearing could not be attributed to any specific cause during the analysis. This is anomalous behavior for wind turbines during and immediately after faults and should be explored further. It may be involved with the subsequent plant controller interaction described below; however, this cannot be confirmed.

As the turbines responded to the LVRT condition, the plant controller paused control and the individual turbines took over local control. Upon the fault clearing, the plant-level controller latched on to a new active power set point in its frequency response controller. However, the turbines experienced an anomalous ramp down in power output so the plant-level frequency response controller latched on to an erroneous set point value that was then issued to the turbines. The uncoordinated latch of a new active power set point in the frequency response controller is what caused the plant to reduce output for an extended period of time. Grid frequency dropped and remained slightly depressed for a few minutes, and the erroneous set point was held for an extended period of time until frequency recovered, holding active power down near 163 MW (the erroneously latched power output) for that time.

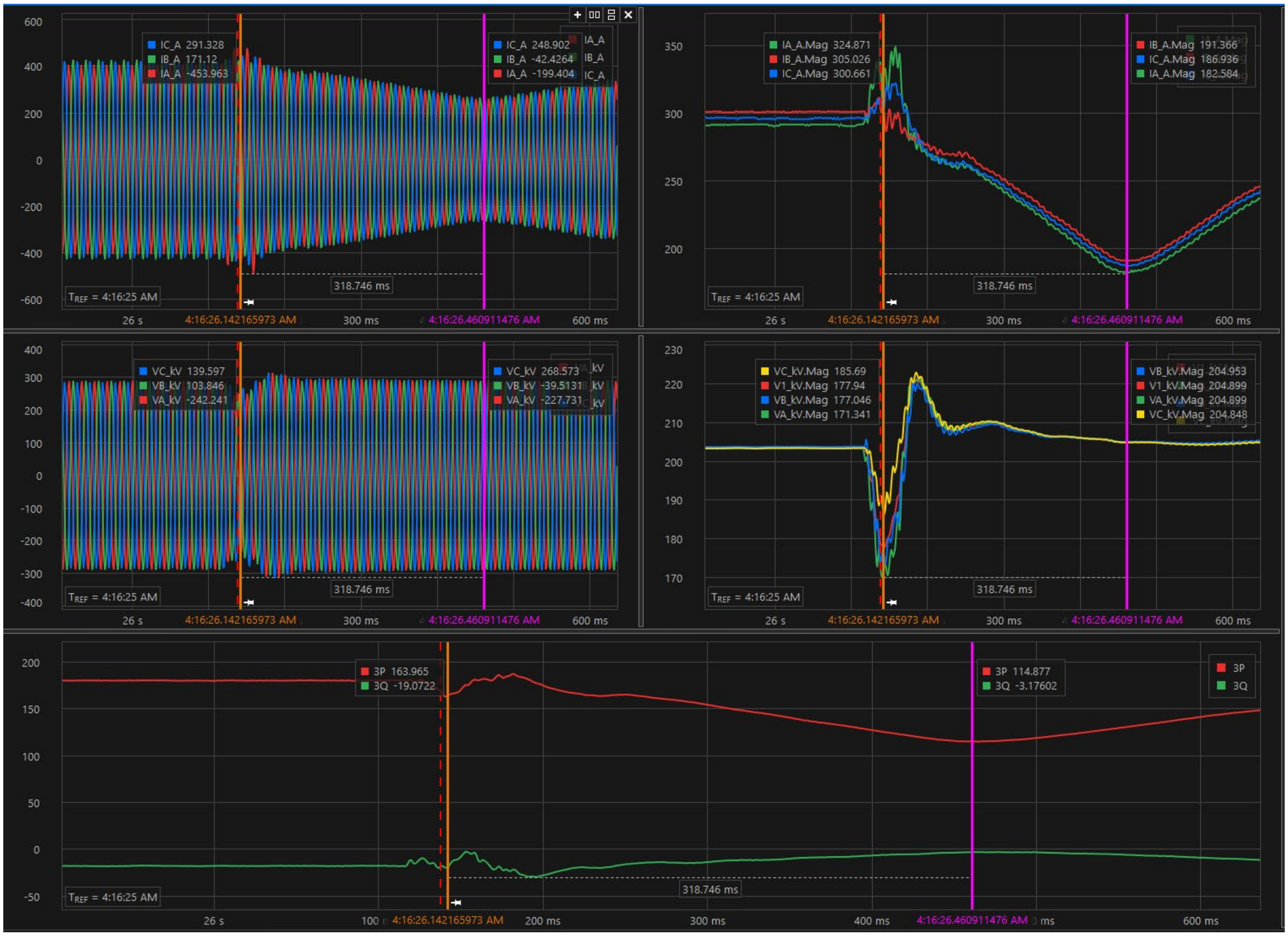


Figure A.2: Wind Plant Dynamic Response during Fault 1

NERC, Texas RE, and ERCOT held a follow-up discussion with the affected plant GO/GOP and the wind turbine OEM to understand these interactions. The OEM and GOP are exploring mitigation measures to eliminate this interaction in the future. In particular, the team discussed investigating the anomalous turbine dynamic response upon fault clearing and also coordinating the active power-frequency control set point latching with LVRT response of the turbines. This could involve using a total available power signal or other suitable measurement.

The anomalous response of the turbines upon fault clearing and the plant-level controller interactions are not represented in the dynamic models (positive sequence or EMT models) provided to ERCOT by the GO.

Plant C

This plant reduced output for 40 MW and 79 MW for the first and second fault, respectively (see **Figure A.3**). The reductions are attributed to two causes:

- **Turbine Pitch Converter Faults:** A total of 23 turbines tripped for the first fault and 10 turbines tripped for the second fault. These turbines all tripped for pitch converter faults that require manual reset. Pitch converter faults are described in detail in **Chapter 2**.
- **Plant Controller Interactions:** Limited data was available from the GO and turbine manufacturer for this site, which limited the ability to conduct adequate root cause analysis. No access to high resolution monitoring data at the POI and within the turbines severely limited the ability to determine which controls were interacting with each other. However, the analysis team, the GO, and the turbine manufacturer all agreed

that some form of plant controller interactions were precluding the turbines from returning to predisturbance output levels. It is suspected that the plant-level active power-frequency controller is interacting with turbine set points as identified at other nearby facilities with the same types of turbines.

This facility is equipped with a high speed digital fault recorder; however, that DFR was only configured to trigger oscillography data for low frequency events below 57.5 Hz, so it did not capture any high speed oscillography data useful for event analysis.

The GO has requested the turbine manufacturer to investigate the cause of pitch converter faults further, and those investigations are presently ongoing; no modifications have been made to the facility to mitigate this issue moving forward. The GO stated that they have reviewed relevant NERC guidelines and alerts and are in discussions with the OEM to potentially implement additional recommendations; however, a time line for additional performance improvements is yet to be determined. The plant owner stated that these specific pitch faults are not applicable to modeling activities conducted by TPs and PCs, so they are not included in any dynamic models (EMT or positive sequence) and no changes are being made to the models.

The analysis team also requested details regarding why the responses look significantly different; however, the plant owner was unable to provide any additional details regarding this question.

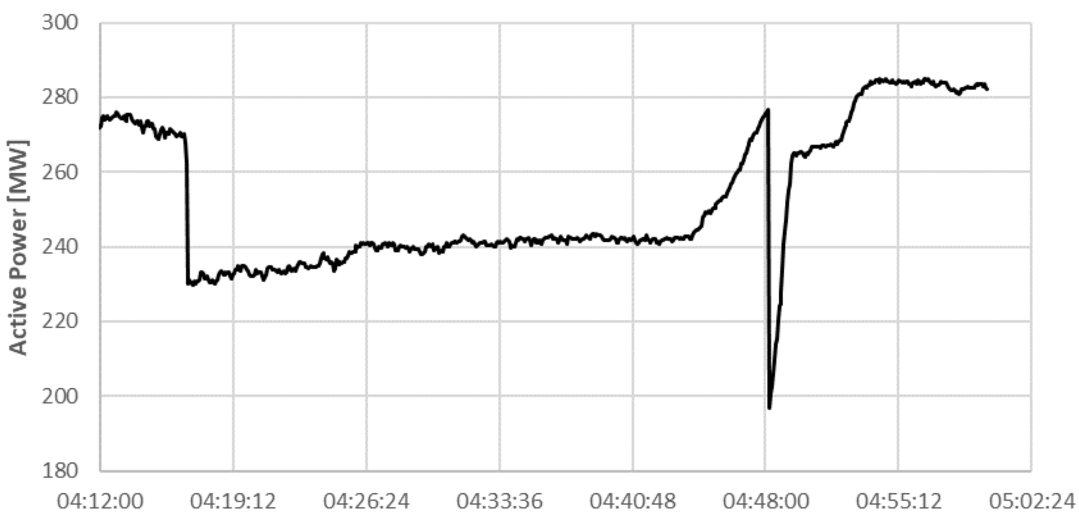


Figure A.3: Plant Active and Reactive Power Output

Plant D

This facility reduced power output by 32 MW during the first fault and 27 MW during the second fault and restored power output to predisturbance values very quickly in both cases (see **Figure A.4**). This reduction is noted here due to the depth of the active power reduction captured with SCADA data; however, no further analysis was conducted.

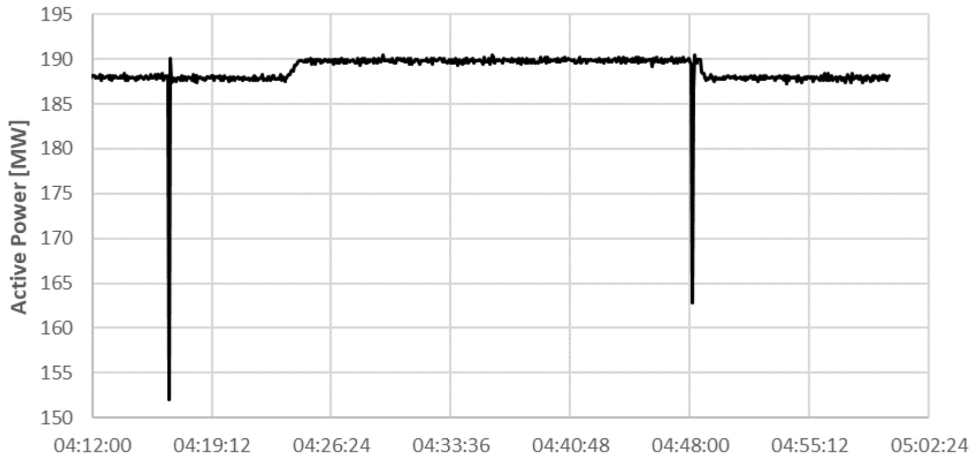


Figure A.4: Plant Active Power Output

Plant E

This plant reduced output by 91 MW for the first fault and 38 MW for the second fault, which is attributed to two primary causes:

- **Plant Frequency Controller Interactions:** During the fault, the plant frequency response controller sends a command to the individual turbines to reduce power output. However, frequency is lower than nominal at this time; therefore, this is not the correct operation of this facility. The root cause of this abnormal performance is unclear, but both the plant owner/operator and the turbine manufacturer have acknowledged that this response is unacceptable and should be investigated and a corrective action developed to avoid this in the future. This interaction causes the delayed ramped recovery of active power that is observed in Figure A.5.

Figure A.5: Unit 1 and Unit 2 Active Power Response to Fault 2

- **Turbine Tripping on Pitch Converter Faults:** Nine turbines tripped on the first fault and four turbines tripped on the second fault due to pitch converter faults. Turbines that tripped during the first fault were not restarted prior to the second fault occurring, resulting in cumulative power reductions (see Figure A.6).[20]

[20] These faults require manual turbine reset either from a remote operator or from a local technician.

Figure A.6: Plant Active Power Output

The plant owner stated that no modifications or changes to protection settings have been made to this plant; however, they are investigating both the pitch converter fault and plant controller interactions more closely with the turbine manufacturer. ERCOT will be following up with the GO to ensure that mitigating measures are put in place. The GO also stated that they have reviewed relevant NERC guidelines and alerts and incorporated recommendations where possible; no further performance improvements are planned at this time.

Plant F

This facility reduced power output by 137 MW during the first fault and 138 MW during the second fault. These values were derived from using high speed oscillography data provided by the GO (see **Figure A.7** for an illustration). SCADA data did not capture the rapid drops in active power immediately following fault clearing (see **Figure A.8**); rather, SCADA data only captured the reductions caused by the turbine tripping. The response of the turbines to reduce active power to a very low value immediately after fault clearing is noted across multiple turbine manufacturers and noted as a finding in this report.

One turbine tripped on uninterruptible power supply failure and many other turbines tripped on ac overvoltage conditions. The plant consists of Type 4 power electronic-interfaced turbines that were purchased in 2013 and installed in 2014. The turbines have a 1.2 pu instantaneous ac overvoltage trip setting that was deemed to be an equipment limit and cannot be modified unless some power electronic equipment is swapped out. The tripped turbines automatically restart after a five-minute timer. High-speed oscillography data showed the plant responded dynamically to both faults with a deep active power reduction that recovered in about a second so the response was not explored any further.

ERCOT will follow up with the affected GO to better understand if any equipment changes can be made to mitigate the protection that is prone to tripping during normal BPS faults. ERCOT has also recommended to the GO to minimize the automatic restart time to the extent feasibly possible within equipment limitations (without bypassing any necessary safety or equipment checks).[21]

[21] Due to the large rotating mass of the turbine-generator, wind turbines require some time to automatically restart. Since solar PV and battery energy storage systems have no moving parts with power electronic controls, they are able to restart much quicker.

Figure A.7: Plant Dynamic Response to Fault 1

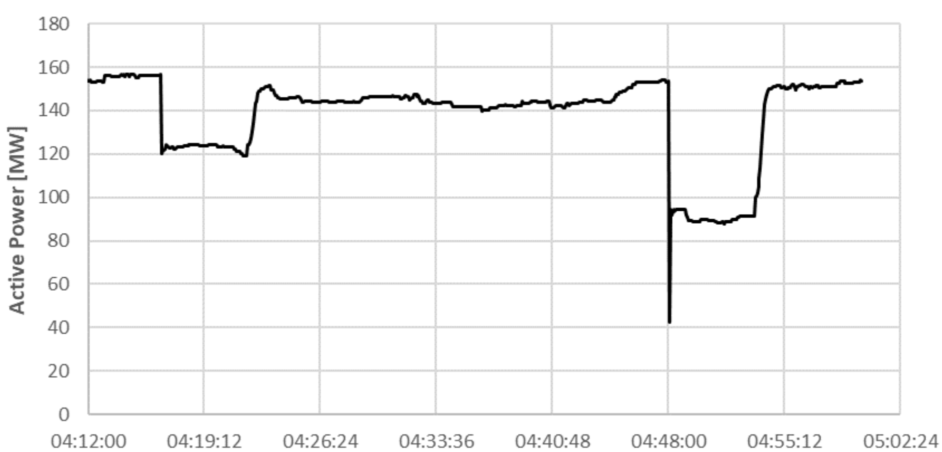


Figure A.8: Plant Active Power Output

Plant G

This facility reduced power output by 19 MW during the second fault and restored power output to predisturbance values very quickly (see **Figure A.9**). This reduction is noted here due to the depth of the active power reduction captured with SCADA data; however, no further analysis was conducted.

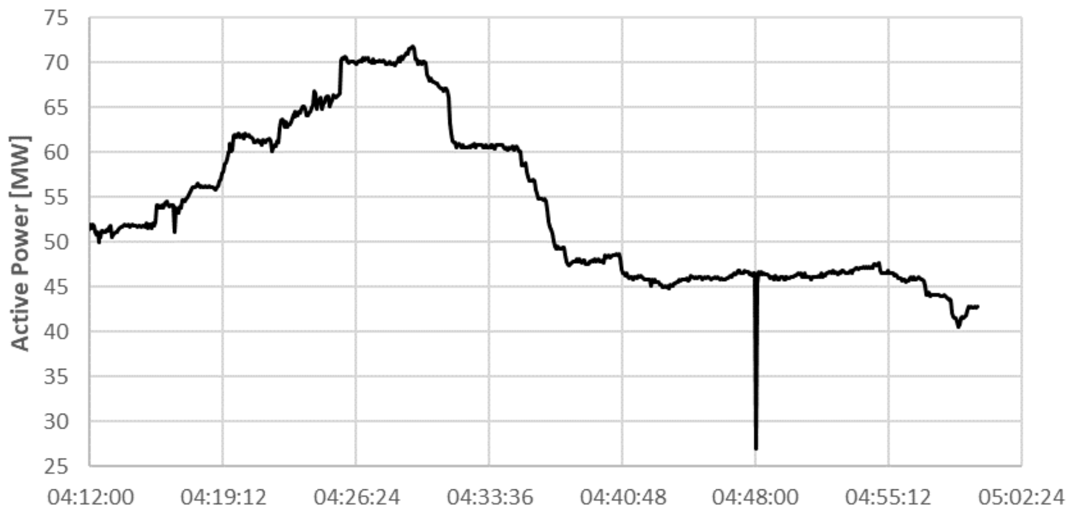


Figure A.9: Plant Active Power Output

Plant H

This plant trip involved multiple turbines that tripped with fault codes identifying SSR and extreme ac overvoltage conditions. The plant reduced power by 64 MW and 56 MW for the first and second fault, respectively (see **Figure A.10**). In both cases, the turbines underwent an automatic restart in about 3–4 minutes, and the turbines recovered in about 12 minutes. A couple turbines tripped on the first fault and remained off-line until after the second fault.

Chapter 1 provides details regarding the SSR and ac overvoltage alarms. The turbine manufacturer is currently performing extensive analysis of the response of the turbines to the BPS faults; however, the cause of tripping is unknown at this time. The response of the turbines to the fault are not indicative of classical SSR conditions or response, but the manufacturer is not ruling out some related issue. Another event occurred a couple weeks later that caused the turbines to experience a significant injection of active power beyond the turbine rating, demonstrating some form of unexpected energy transfer between the turbine and the system. The turbines at this site are Type 3 turbines, which are prone to subsynchronous oscillation issues. These turbines have SSR protection as well as an SSR mitigation package that may need to be revisited by the plant owner in coordination with the turbine manufacturer.

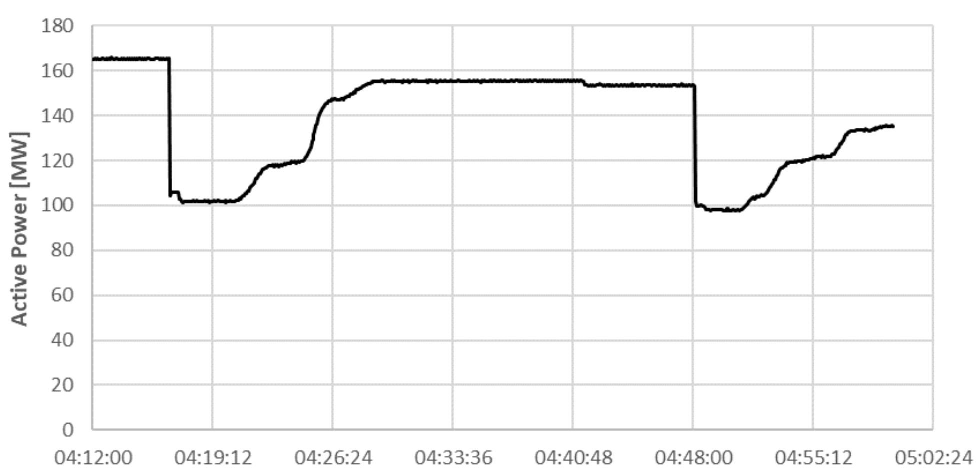


Figure A.10: Plant Active Power Output

Plant I

This facility reduced power output by 47 MW during the first fault and 36 MW during the second fault and restored power output to predisturbance values very quickly in both cases (see **Figure A.11**). This reduction is noted here due to the depth of the active power reduction captured with SCADA data; however, no further analysis was conducted.

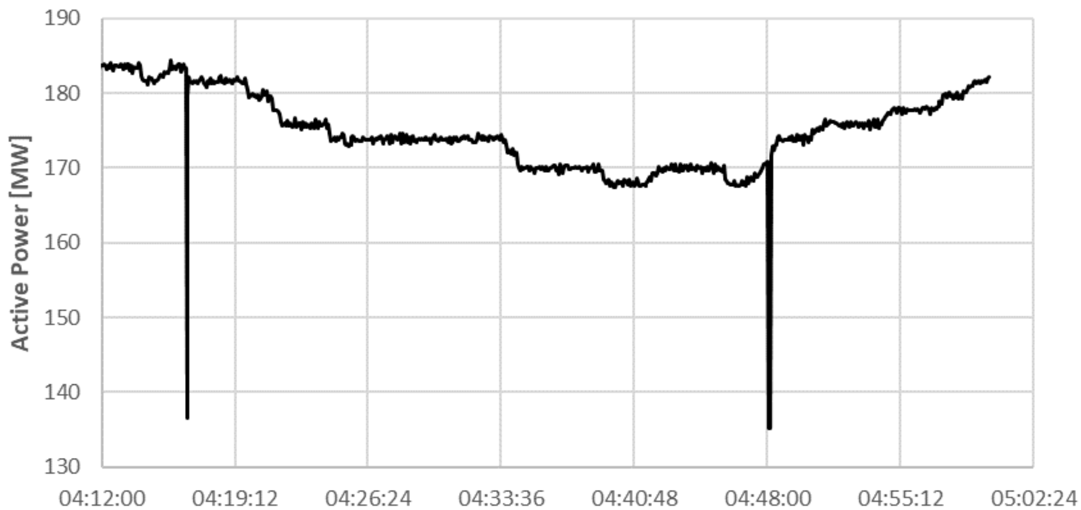


Figure A.11: Plant Active Power Output

Plant J

During the first fault, one wind plant was tripped consequentially due to the fault on the generator tie-line. These actions involved normal protective relaying and disconnection of the wind plant for this specific fault. The plant was producing 273 MW at the time of the fault.

Appendix B: Similar Wind Plant Performance Issue

NERC recently analyzed another wind facility that exhibited abnormal response to a normally cleared BPS fault nearby. This event occurred in a different Interconnection yet had similarities and worthwhile findings to include in this report as they highlight that these issues can and are occurring across North America. Reliability Coordinators and BAs are encouraged to develop or enhance automated monitoring tools able to identify anomalous behavior of generating resources such that corrective actions can be developed in a timely manner.

The facility described here is a BES generating resource in the Western Interconnection that was commissioned in 2020 (i.e., a relatively new facility). The BPS experienced a single-line-to-ground fault that was normally cleared in February 2022. **Figure B.1** shows the overall response of the facility captured with two-second SCADA data provided by the local TOP. As **Figure B.1** shows, the plant exhibited a significant reduction in active power at the time of the fault. After fault clearing, the plant then exhibited a very slow ramp of active power to a new output level over a seven-minute period. This type of response is indicative of plant-level controller interactions impeding the individual turbines from providing essential reliability services during the event. NERC discussed this response with the equipment manufacturer who recognized that this type of response is unexpected and should be corrected.

Figure B.2 shows high resolution oscillography data at the POI and shows the response of the plant around the time of the fault. When the fault occurred, wind turbine current increased (providing fault current), active power dropped slightly, and reactive power increased; this is the expected response of a wind turbine to a BPS fault. However, towards the time of fault clearing, active power rapidly dropped to 0 MW and remained at that level for a prolonged period of time after voltage has returned to nominal. The wind plant controls dictated the response of the plant, and these controls were not performing in an expected or reliable manner. This type of information is also not captured in the lower-resolution SCADA data shown in **Figure B.1** and would be otherwise unknown if this data were not available.

NERC recommended the TOP work with the facility owner to seek corrective actions in collaboration with the equipment manufacturer.

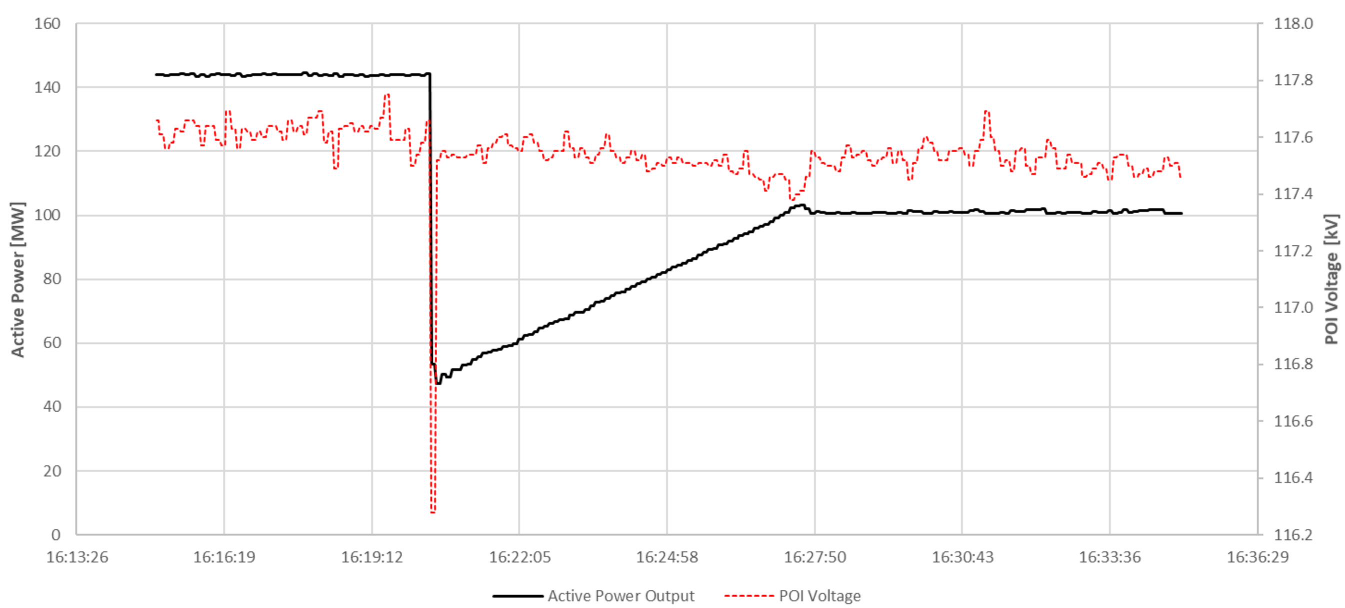


Figure B.1: Overall Wind Plant Response to BPS Fault

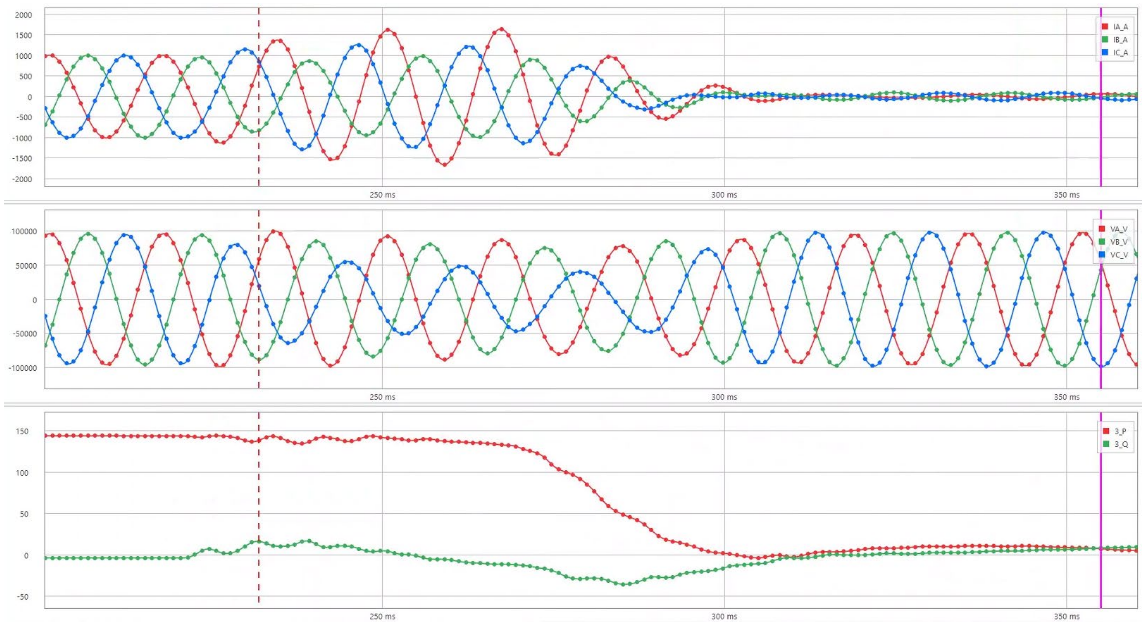


Figure B.2: High Speed Oscillography Data at POI Showing Plant Response to Fault

Modeled Response Comparison

NERC recreated a reflective simulation of this event in a positive sequence dynamic simulation platform and applied a three-phase fault for three cycles at a BPS bus in the vicinity of the wind plant. The goal was not to recreate the event exactly (as this was an unbalanced fault) but rather to observe similarities or differences between the modeled and actual response of the plant. In the simulation, voltage drops to about 0.4 pu during the fault and then recovers after fault clearing. The plant power output drops to zero at the onset of the fault and recovers to about 75 MW by the time the fault has cleared. After clearing the fault, active power recovered back to predisturbance levels within 0.1 seconds. **Figure B.3** shows the simulation results; this simulation illustrates that the post-fault response of the wind plant during actual operation is not the intended or expected response per what was modeled in the interconnection study process nor what was reported for the facility's model verification testing.[22] As expected, the plant controller interactions are also not represented in the dynamic models. Therefore, this plant is operating in an unreliable manner with plant performance that does not match the reliability studies conducted prior to allowing the plant to connect to the grid. Corrective actions should be taken immediately at this facility to address these issues.

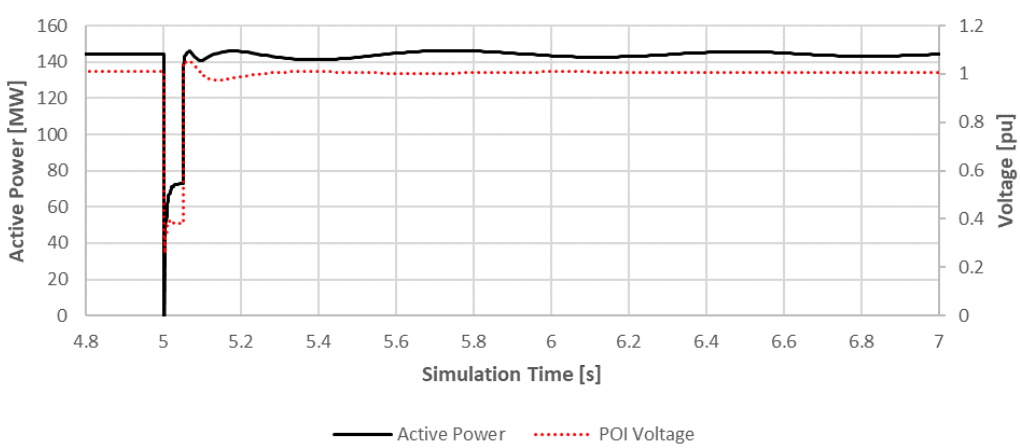


Figure B.3: High Speed Oscillography Data at POI Showing Plant Response to Fault

[22] Per the currently effective NERC MOD-026 and MOD-027.

Appendix C: List of Contributors

This disturbance report was published with the contributions of the following individuals. NERC gratefully acknowledges Texas RE, ERCOT, and the affected TOs, TOPs, GOs, and GOPs. Coordination between all affected entities was crucial for the successful analysis of this disturbance and the publishing of this report. NERC would also like to acknowledge the continued engagement and support of the inverter manufacturers to ensure that the mitigating measures being developed are pragmatic. Lastly, members of the NERC IRPS continue to support NERC in its mission to ensure reliable operation of the BPS, particularly as the BPS is faced with rapidly changing technology and evolving grid performance characteristics.

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