Dynamic Stability Assessment of High Penetration of Renewable Generation in the ERCOT Grid

Version 1.0

Document Revisions

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Executive Summary

The instantaneous penetration of renewable generation, in terms of percentage of system load that was served by renewable generation, exceeded 50% (not including self-serve load) in the ERCOT grid in 2017. According to the Generation Interconnection Status report in December 2017, approximately 35 GW of renewable generation was under study for future interconnection in the ERCOT grid. Of that total, more than 10 GW of renewable generation capacity had a signed interconnection agreement but did not satisfy all of the requirements to be included in the transmission planning models. Higher penetrations of renewable generation can be expected in the ERCOT grid in the future and can bring greater challenges to maintain system and network stability. As an example, the Panhandle Export Limit, which limits wind generation in the Panhandle due to stability constraints, had the second highest congestion rent on the ERCOT system in 2017 and is expected to become the constraint with the highest congestion over the next several years.

To identify and increase the understanding of system issues under high penetration of renewable generation, ERCOT conducted a dynamic stability assessment for such high penetration conditions and evaluated potential solutions. The results of this study as presented in this report are intended to inform ERCOT staff and stakeholders of the challenges associated with a high penetration of renewable generation in areas far from load centers and potential mitigation options. The study was not designed to recommend a specific set of system upgrades, and ERCOT did not evaluate the economic merit of, or attempt to optimize, any system improvements. Instead, the results of this analysis are intended to be indicative of likely future challenges to be faced in the ERCOT grid and recommendations are provided to further evaluate and address those challenges.

The ERCOT 2016 Long Term Stability Assessment[1] (LTSA) for Year 2031 Current Trends scenario was used as a reference to develop the dynamic stability study scenario for a high penetration of renewable generation with a total of 40 GW renewable generation capacity. A total of 28 GW of renewable generation, including both wind and solar generation, was dispatched to serve about 66% of the total system load (including self-serve load). The total system inertia based on committed synchronous generators for the study case was 117 GW-sec.

Although the case was built based on the LTSA 2031 model, the conditions represented could manifest sooner depending on ERCOT generation fleet changes. Additionally, the focus of this analysis was not to determine at what penetration level of renewable generation would the various observed phenomena occur; rather, the focus was on what phenomena would occur at a higher penetration of renewable generation. Hence, no conclusions should be made with respect to a maximum penetration level for renewable generation.

Since the majority of renewable generation projects are concentrated in the North, West, and Far West Weather Zones, a high penetration of renewable generation naturally leads

[1] http://www.ercot.com/content/wcm/lists/89476/2016_Long_Term_System_Assessment_for_the_ERCOT_Region.pdf

to high power exports from those areas. The study case was developed to represent a scenario with maximum power transfer from North and West Texas to load centers along the I-35 corridor and the Houston area. The study case conditions, as shown in the Figure E.1, highlighted the reliability challenges associated with potential future operating scenarios characterized by low inertia, low system strength, high penetration of renewable generation in remote areas, and long distance high power transfers.

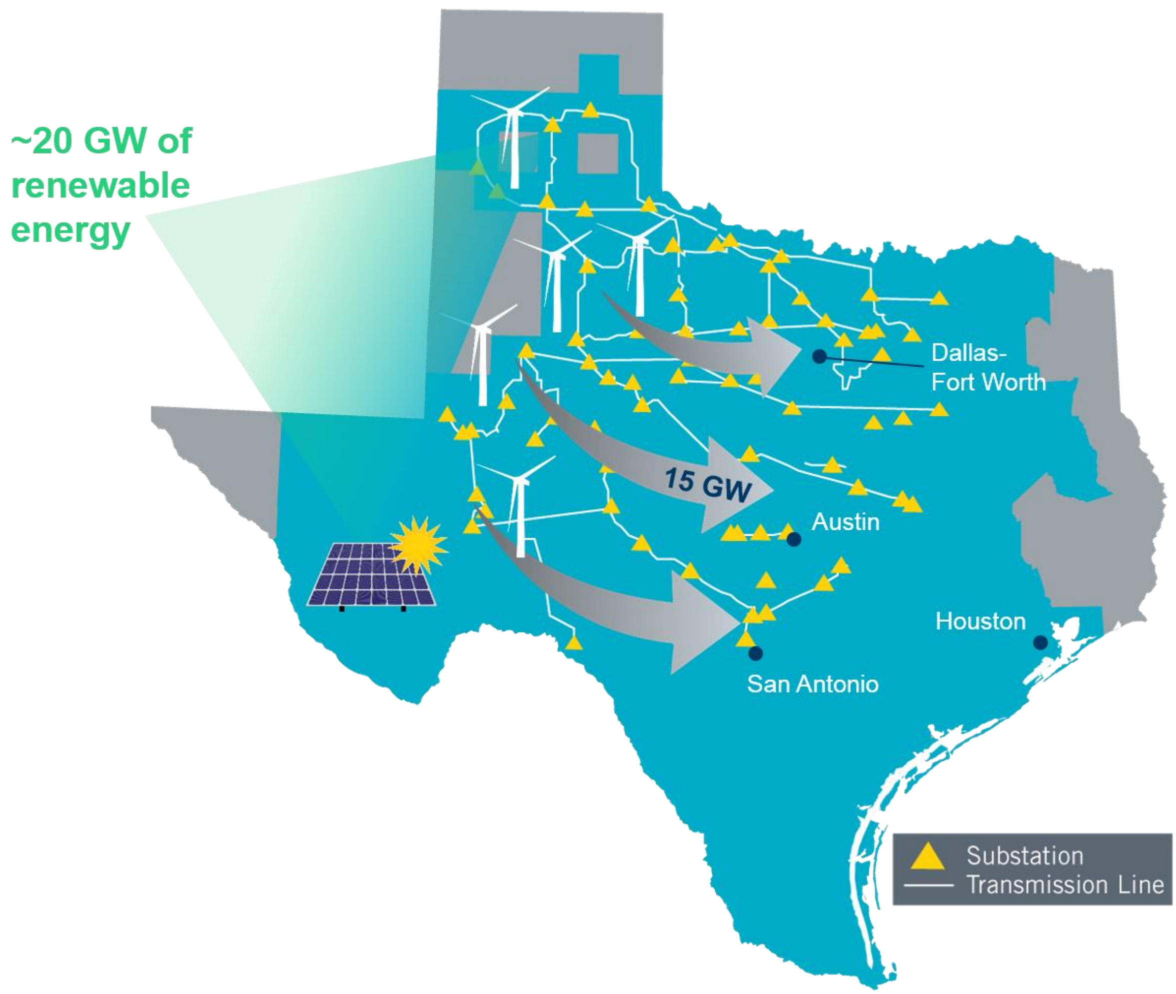

Figure E.1: Renewable generation dispatch overview in the study case

Key Study Observations

- Significant active and reactive losses were found under high West Texas export conditions.
- Additional transfer paths between West Texas and Central Texas were beneficial.
- An acceptable modeled steady-state condition may not guarantee a stable response under low system strength conditions.

- Inverter-based generation controllers require sufficient system strength for reliable operation.
- Synchronous condensers are subject to synchronous machine stability limitations.
- Typical phasor-based dynamic stability models and tools may not be adequate for future high renewable penetration scenarios.
- Large generation trips may cause voltage deviations before large frequency deviations are observed.
- Higher voltage transmission circuits were beneficial from a stability perspective.

Recommendations

- The Long Term System Assessment process should consider the impact of stability constraints.
- ERCOT, transmission service providers, and generation owners should regularly review controller settings in low system strength areas.
- Industry should investigate robust inverter control capability.
- Planners should consider synchronous machine stability when recommending synchronous condensers.
- ERCOT should explore requirements for system damping support from renewable generation resources and transmission dynamic reactive devices.
- ERCOT should consider dynamic model performance validation for all dynamic components.
- ERCOT should develop a standardized wide-area PSCAD model process and the ability to perform regular wide-area PSCAD studies.
- Dynamic load models should be regularly reviewed and validated.
- ERCOT and stakeholders should evaluate the full range of benefits of higher voltage level transmission circuits.

Contents

Chapter 1. Study Scenario

1.1 Background

ERCOT continues to see an increase in renewable generation. In 2017, installed wind generation capacity surpassed 20 GW while installed solar capacity exceeded 1 GW. The highest penetration of wind generation was recorded on October 27, 2017 to serve 54% of ERCOT system load (not including self-serve load) of 28,416 MW. In 2017 ERCOT received the highest number of requests in a year to study new generation interconnections. According to the Generation Interconnection Status report in December 2017, approximately 35 GW of renewable generation was under study for future interconnection in the ERCOT grid. Of that total, more than 10 GW of renewable generation capacity had a signed interconnection agreement but did not satisfy all of the requirements to be included in the transmission planning models. Higher penetrations of renewable generation can be expected in the ERCOT grid in the future and can bring greater challenges to maintain system and network stability. As an example, the Panhandle Export Limit, which limits wind generation in the Panhandle due to stability constraints, had the second highest congestion rent on the ERCOT system in 2017 and is expected to become the constraint with the highest congestion over the next several years.

The changing resource mix in the ERCOT region has presented new challenges for grid operators although it has not negatively impacted system reliability. To identify and increase the understanding of system issues under high penetration of renewable generation, ERCOT conducted a dynamic stability assessment for such high penetration conditions and evaluated potential solutions. The results of this study as presented in this report are intended to inform ERCOT staff and stakeholders of the challenges associated with a high penetration of renewable generation in areas far from load centers and potential mitigation options. The study was not designed to recommend a specific set of system upgrades, and ERCOT did not evaluate the economic merit of, or attempt to optimize, any system improvements. Instead, the results of this analysis are intended to be indicative of likely future challenges to be faced in the ERCOT grid and recommendations are provided to further evaluate and address those challenges. Additionally, the focus of this analysis was not to determine at what penetration level of renewable generation would the various observed phenomena occur; rather, the focus was on what phenomena would occur at a higher penetration of renewable generation. Hence, no conclusions should be made with respect to a maximum penetration level for renewable generation.

1.2 Study Scenario Development

The ERCOT 2016 Long Term System Assessment (LTSA) Year 2031 Current Trends was used as a reference to develop the study scenario for a high penetration of renewable generation with total of 40 GW renewable generation capacity. Although the case was built based on the LTSA 2031 model, the conditions represented could manifest sooner depending on ERCOT generation fleet changes.

The transmission topology was consistent with the 2031 Current Trends case. The system load (including self-serve load) was 42.2 GW and the total system inertia based on committed synchronous generators was 117 GW-sec. A total of 28 GW of renewable generation, including 17 GW of wind generation and 11 GW of solar generation, was dispatched to serve about 66% of total system load (including self-serve load). The West Texas Export, expressed as the power flow on 345 kV transmission circuits between West Texas and the rest of the ERCOT grid, was approximately 15.5 GW and the North-to-Houston power flow was approximately 5.3 GW. An overview of zone-to-zone active power flow is shown in Figure 1.1.

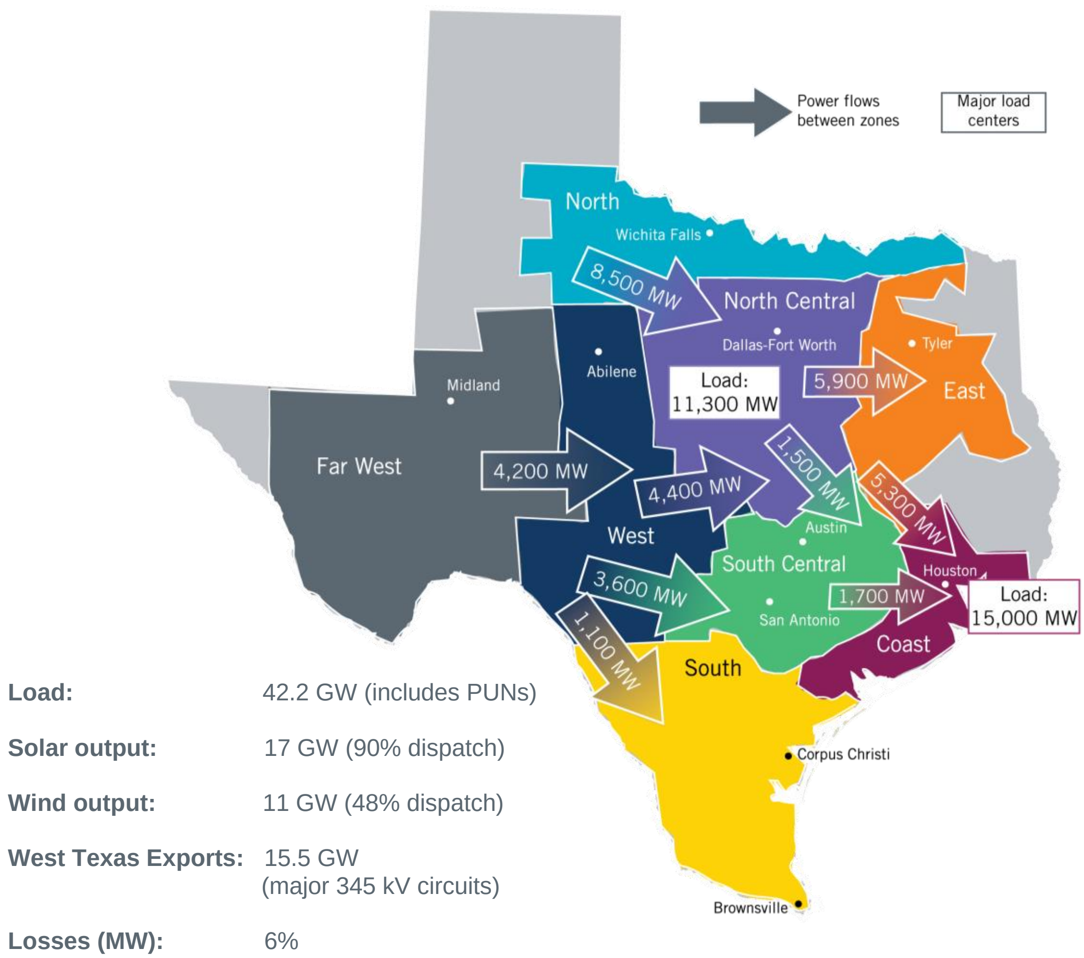

Figure 1.1: Overview of active power flows

1.3 System Strength Assessment

When a portion of the grid has low short circuit currents relative to the power flow it is said to be an area of low system strength. The existing renewable generation resources are also referred to as inverter-based generation since they are mainly connected to the grid through converters, which require sufficient system strength for reliable operation. Areas with high penetrations of inverter-based renewable (solar and wind) generation with limited or no synchronous generators are expected to have low system strength and are prone to system and network instability.

A system strength assessment was performed for the high renewable penetration system condition in the developed case as described in Section 1.2 to identify the low system strength areas. The assessment first provided the short circuit current at each transmission bus and then identified clusters of buses with renewable generation resources connected. A low system strength cluster was identified wherever a large amount of renewable generation capacity was connected to buses with low short circuit current. The circled areas in Figure 1.2 show these low system strength clusters.

The Panhandle, as expected, was one of the low system strength clusters. A significant amount of wind generation resources have been connected to the South Texas system creating potential low system strength conditions if synchronous generators are not on-line in the region. In addition, according to the 2016 LTSA, a significant amount of solar generation was projected to be added in West and Far West. As a result, the West and Far West Texas regions were also identified as a low system strength cluster.

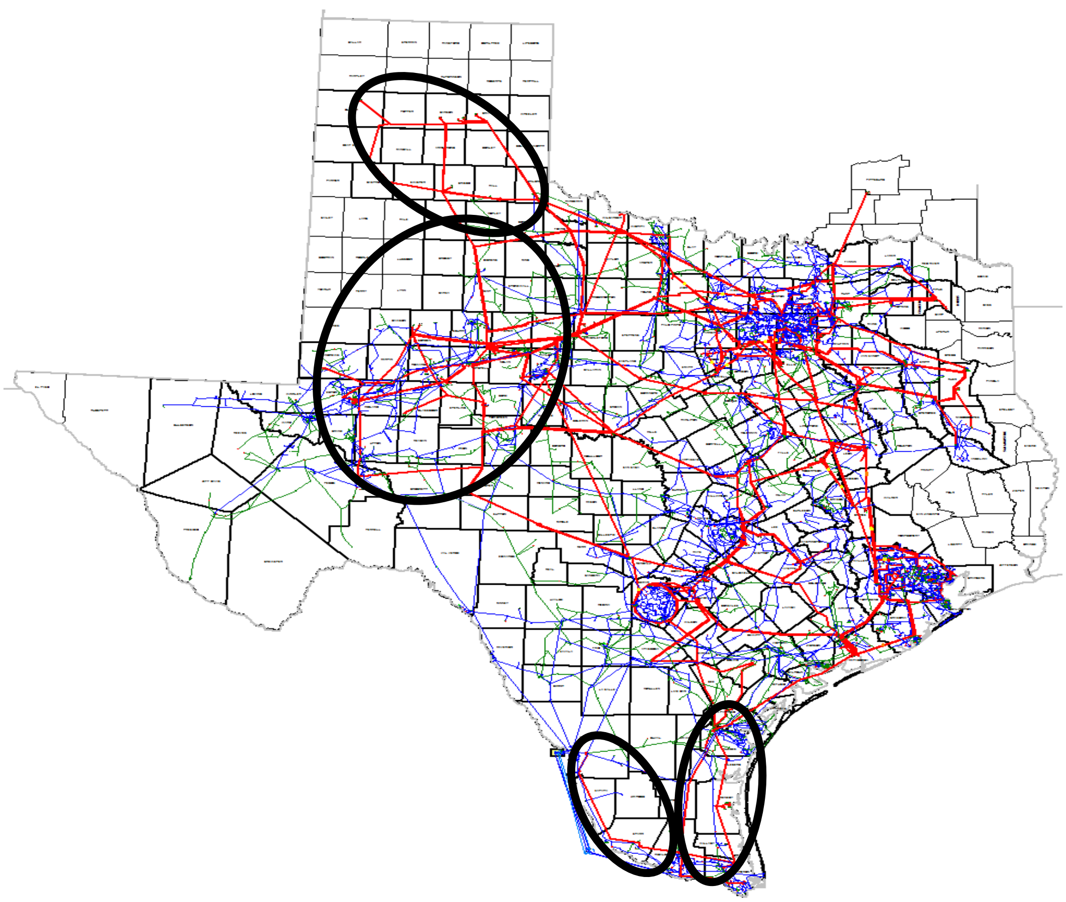

Figure 1.2: Areas with low system strength in the study case

Chapter 2. Key Observations and Recommendations

ERCOT completed a dynamic stability assessment of a high penetration of renewable generation scenario in the ERCOT grid. This assessment identified system challenges associated with a high penetration of renewable generation in areas far from load centers from a stability perspective and evaluated the reliability impact of potential solutions. Detailed dynamic analysis results are included in Appendix A.

Observation 1: Significant Active and Reactive Power Losses Were Found Under High West Texas Export Conditions

The study base case developed for this stability assessment included 40 GW renewable generation capacity and a total of 28 GW of renewable generation was dispatched to serve about 66% of total system load (including self-serve load). The majority of the projected new renewable generation for the studied 2031 conditions was added in West and Far West zones since these zones have the highest projected annual capacity factors for both solar and wind generation. Hence, the study conditions showed a larger reliance on West Texas generation to meet total system load than what has been observed historically in ERCOT.

Much of the power from these renewable resources was transferred from West Texas to the load centers located approximately 300~450 miles in the eastern part of the state over the existing 345 kV transmission network. As a result, significant active and reactive losses were observed due to long distance and large power transfer from West Texas to the load centers.

Current system cases developed by the Steady State Working Group indicate that ERCOT transmission losses are generally close to 2% of system load. As shown in Figure 1.1, the total system active power losses were more than 6% of system load in the case developed for this study. The reactive power losses on the West Texas Export corridors were about 4,000 MVAR when transferring 15.5 GW power. As a result, additional static and dynamic reactive devices were required to maintain an acceptable voltage response in normal operation and under contingency.

New transmission circuits spanning from West Texas to the load centers could substantially reduce both active and reactive power losses. This is because any new transmission lines running parallel to the existing lines would reduce the current flowing on them and losses are a function of the square of the current flow. For example, if the current flowing on a particular transmission line were reduced by half, the losses would be reduced to just one fourth of the original amount. Reducing the reactive losses would have the benefits of improving voltage stability and requiring less static and dynamic reactive devices to maintain an acceptable voltage response.

Observation 2: Additional Transfer Paths between West Texas and Central Texas Were Beneficial

To reduce the electrical transfer distance and system losses as stated in Observation 1, additional transfer paths out of West Texas were necessary for both normal and outage conditions. As shown in Figure 1.1, there was 3,600 MW power transfer from West Texas to South Central Texas through limited transmission paths. The large amounts of additional solar generation added in Far West Texas led to high power transfer on the McCamey-Big Hill-Kendall transmission path, resulting in unacceptable voltage profiles under normal conditions as well as instability under outage conditions.

An additional transfer path parallel to the McCamey-Big Hill-Kendall transmission path, as shown in Figure 2.1, was the most beneficial transmission upgrade from a reliability perspective to support high transfers from projected renewable resource locations to major ERCOT load centers. It should be noted that this result is based solely on analysis of the case developed for this study. Additional analyses will be required as system conditions change to develop specific actionable system upgrade alternatives.

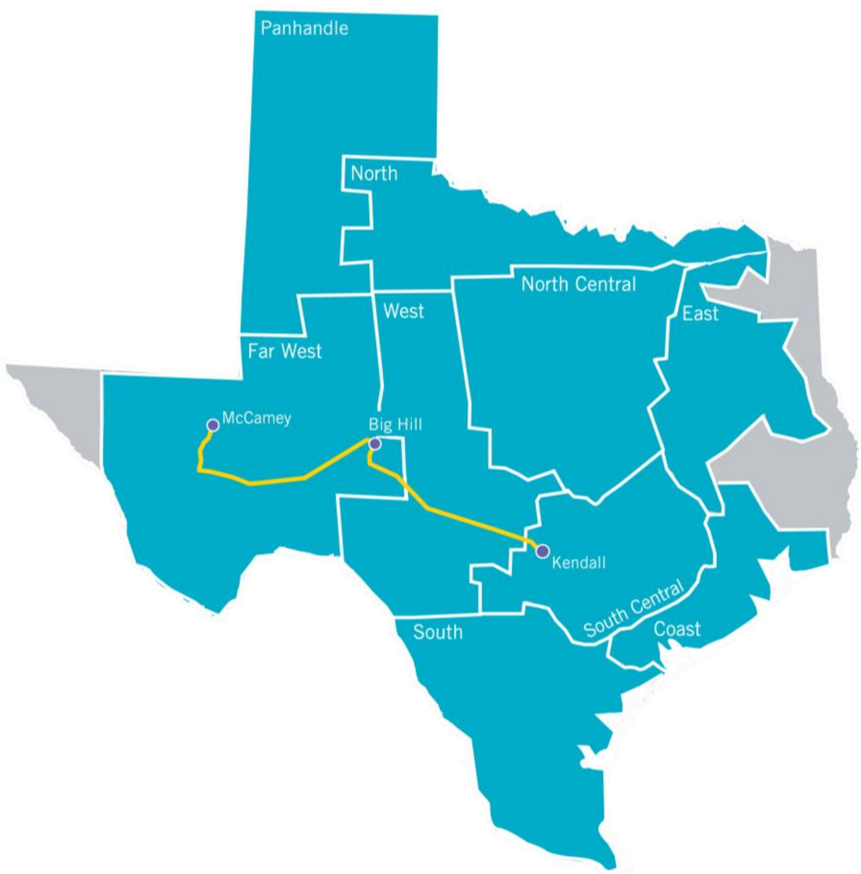

Figure 2.1: McCamey-Big Hill-Kendall Path

Observation 3: An Acceptable Steady State Condition May Not Guarantee a Stable Response under Low System Strength Conditions

An acceptable dynamic flat start condition was initially created as shown in Figure 2.2 to represent the stable initial steady state condition for the study base case.

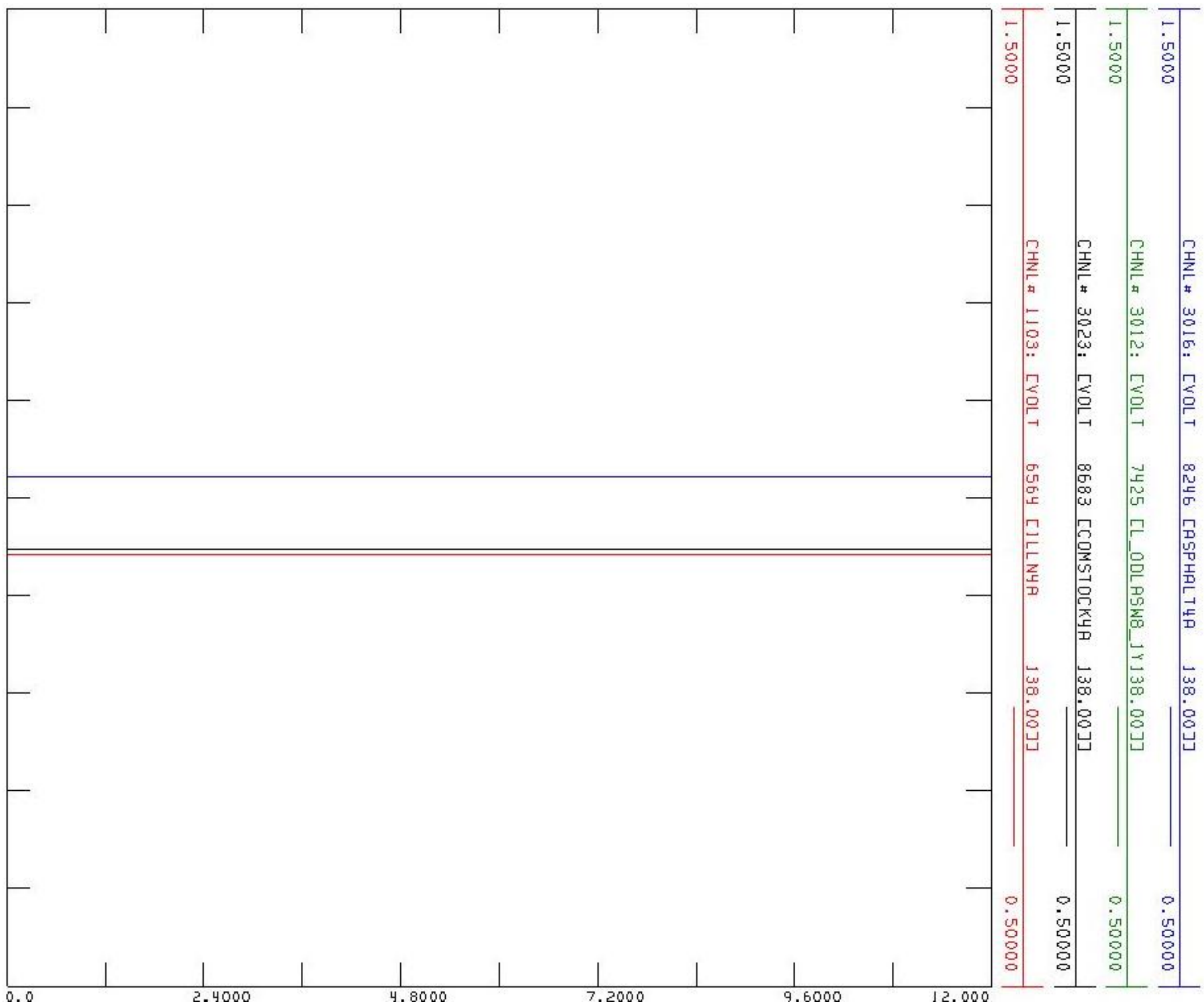

Figure 2.2 Flat system response under no disturbance

For a normal system condition, it is expected that the system will remain stable and return to a steady-state condition after a small perturbation. However, under low system strength conditions it is possible for unstable controller operation to be observed even following a small disturbance like capacitor switching or generation variation. Figure 2.3 shows the study case system response to a small perturbation. Instability was observed immediately following the small perturbation.

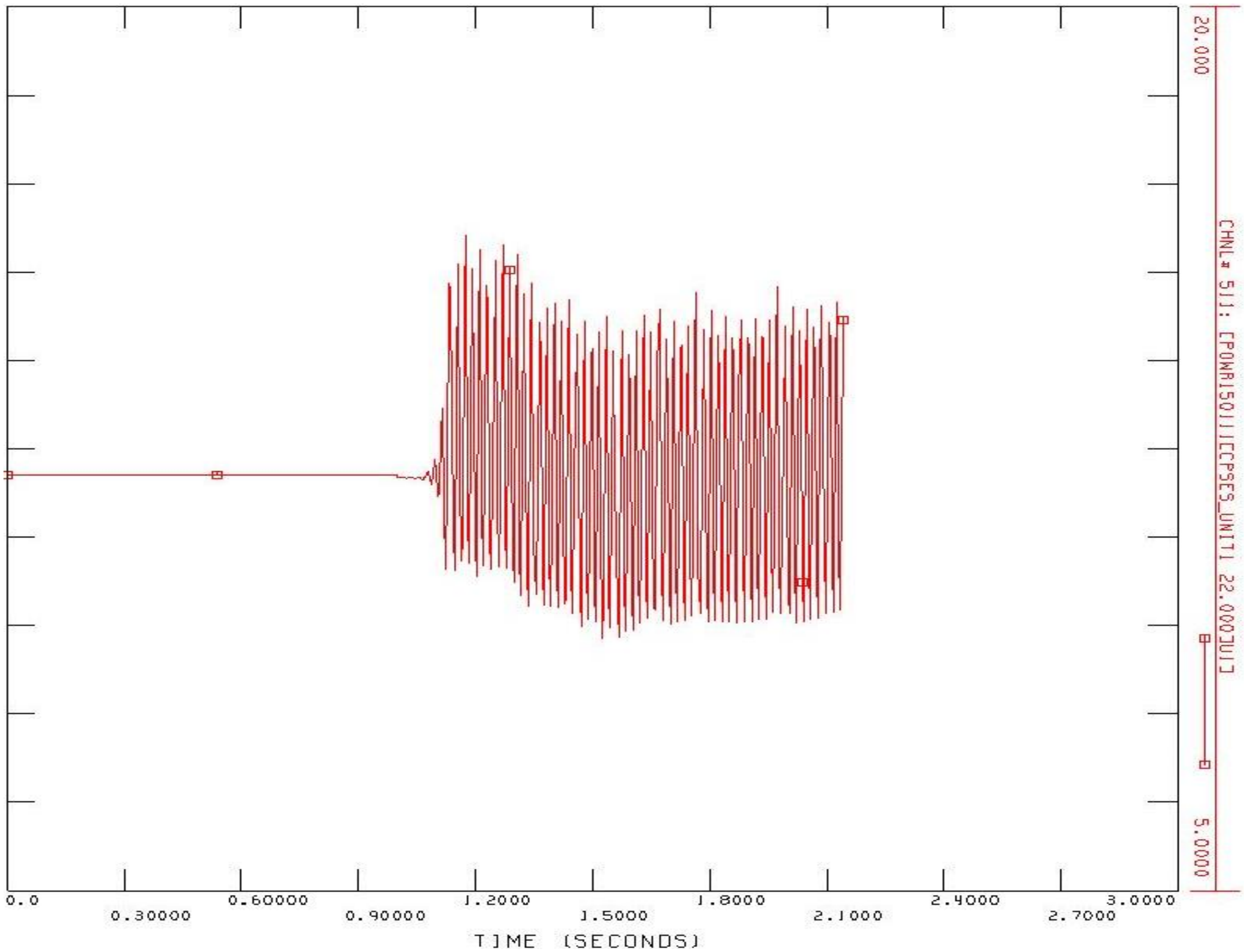

Figure 2.3: Unstable oscillatory response to small disturbance test

Synchronous condensers were added in areas of the grid where system strength was low. Figure 2.4 shows an acceptable system response for the small disturbance test with synchronous condensers added to the study case to improve system strength.

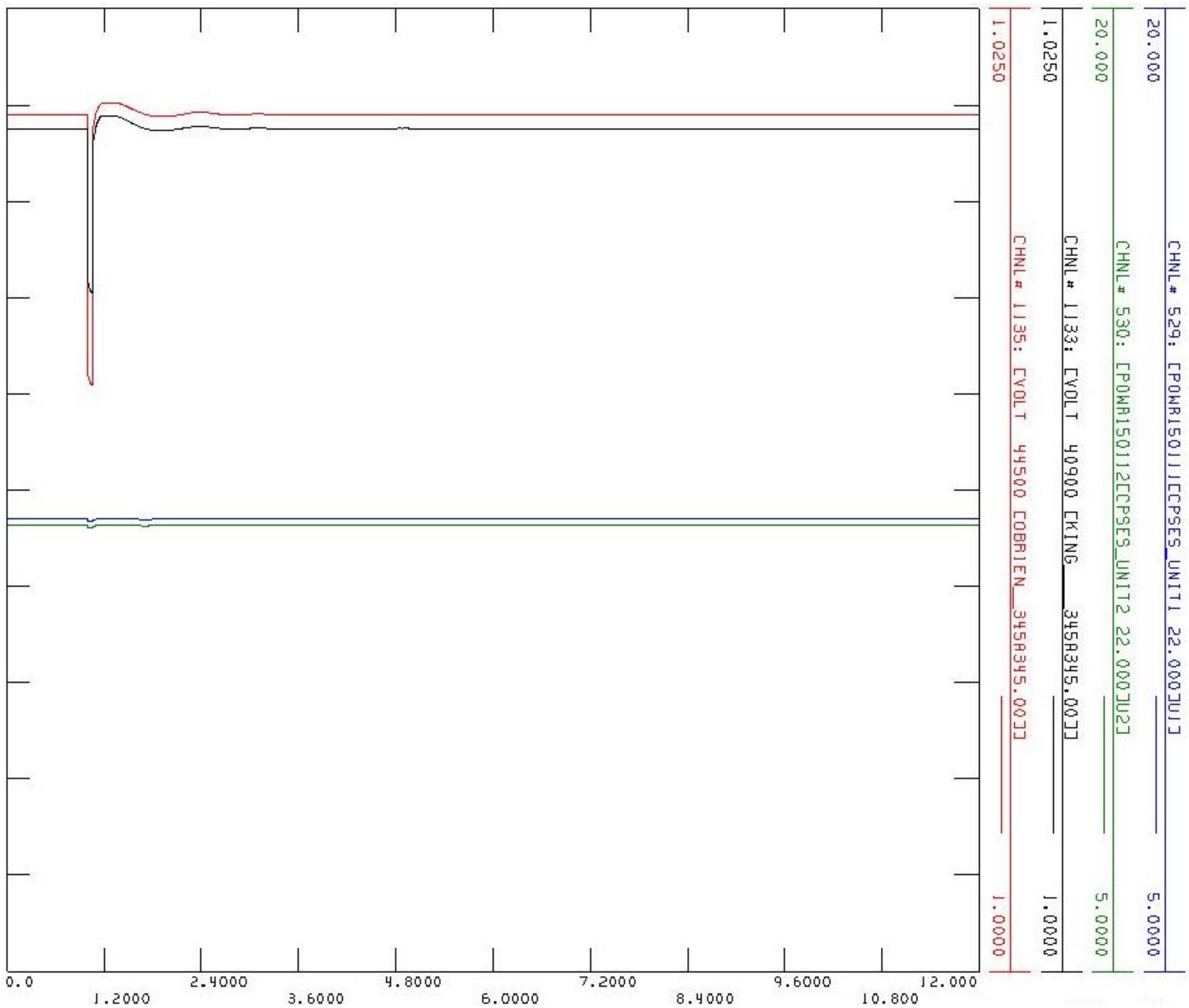

Figure 2.4: Small disturbance test with synchronous condensers added to study case

Recommendation 1: The LTSA Process Should Consider the Impact of Stability Constraints

In the ERCOT 2016 Long Term System Assessment (LTSA) process, the reliability analysis focused on summer peak powerflow analysis to identify the transmission upgrade needs from a steady-state perspective. As identified in this stability assessment, stability challenges are likely to be the most limiting constraints for high renewable penetration conditions and could significantly affect the need for improvements on the system. Specifically, any analysis of transmission system needs for areas with high penetrations of renewable generation that only considers thermal line constraints may substantially underestimate the actual system needs that would be identified in a stability analysis.

Based on Observations 1, 2, and 3, it is recommend that the LTSA process (and any other study of transmission system needs under a high penetration of renewable generation) consider stability constraints to reflect likely system limitations under high penetration of renewable generation conditions. Additionally, it is suggested that AC powerflow analysis be used to properly capture voltage support challenges.

Since stability studies are time consuming and may not fit into the current LTSA process timelines, ERCOT and stakeholders may need to investigate new methodologies for incorporating stability constraint proxies into the analysis.

Observation 4: Inverter-Based Generation Controllers Require Sufficient System Strength for Reliable Operation

Oscillatory and unstable responses under low system strength conditions have been recorded in real time operations. An example is shown in Figure 2.5 for an ERCOT wind plant connected to a weak grid under outage conditions.

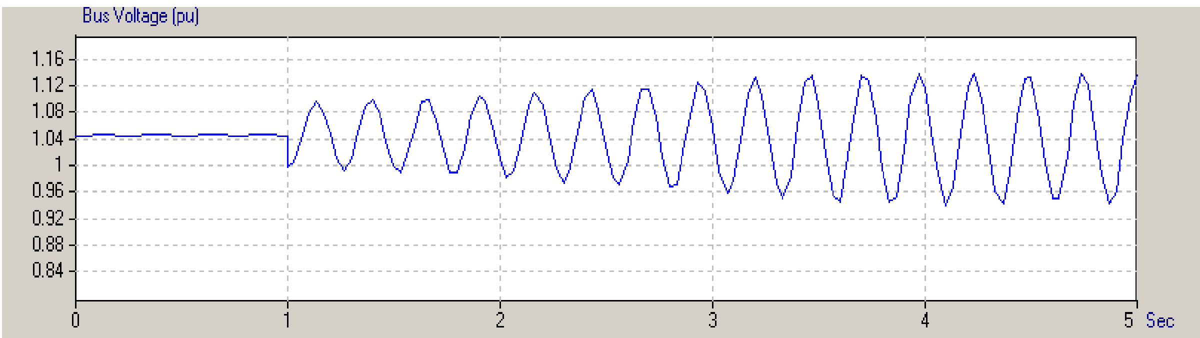

Figure 2.5: Recorded unstable response for a wind plant connected to a weak transmission grid

Extrapolating this concept, under a condition of a system-wide high penetration of renewable generation, the overall system performance will be dominated by inverter-based generation controllers operating in a low system strength environment. However, all of the existing inverter-based generation controllers in ERCOT require sufficient system strength for reliable operation. Hence, the addition of more renewable generation has the compound effect of requiring more system strength while at the same time causing the grid to weaken.

As described previously, the study case exhibited several areas that had low system strength, and synchronous condensers were added to obtain an acceptable response. ERCOT found that tuning and coordinating controller settings was beneficial to the stability of the system under these conditions and may lessen the need for system improvements.

Specifically, it was found that controller tuning and coordination could help dampen oscillations. As an example, Figure 2.6 shows the response to a disturbance of two controller settings of a generic solar plant dynamic model used to represent added solar generation in this study. The only difference between these two simulations is a change in the voltage control gain settings. The higher gain setting (red line) could lead to poor or undamped oscillation while the lower gain setting (black line) indicates an acceptable response. The need for precise controller settings and coordination will be more important and beneficial under low system strength conditions to ensure reliable operation.

However, it may not be possible to rely solely on controller tuning and coordination to resolve low system strength induced stability issues. Even though controller tuning and coordination can improve stability, today's inverter controllers still require a minimum system strength threshold. This means that there is a limit to the benefits of controller tuning and coordination. In addition, controller settings are under the purview of the generator owner, not ERCOT. In areas with multiple generation plants there will be many different resource owners with varying levels of technical sophistication. Optimizing, coordinating and validating controller settings in these situations will be difficult.

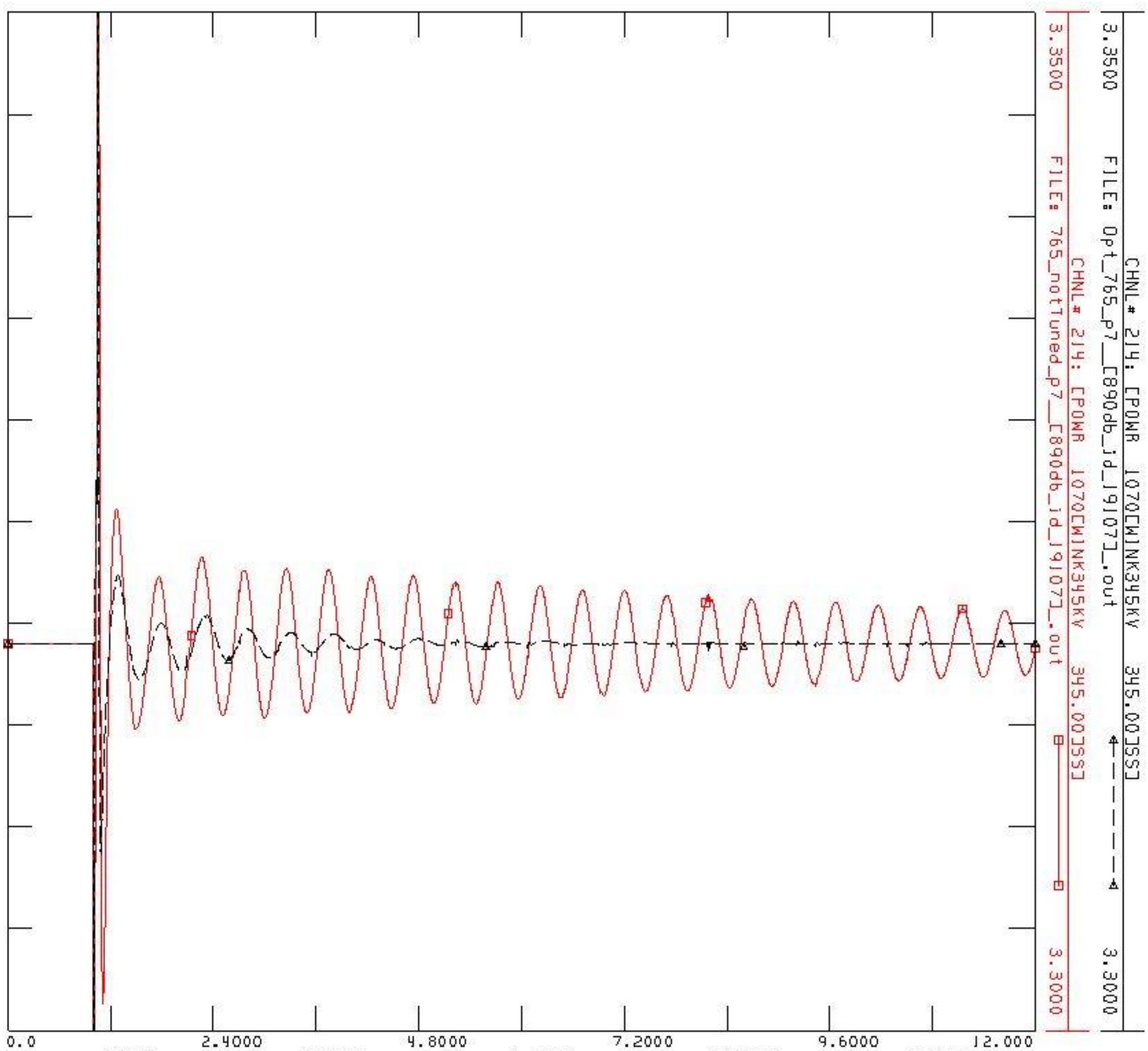

Figure 2.6: Active power flow response with higher voltage control gain (red color) and low control gain (black color)

Recommendation 2: ERCOT, Transmission Service Providers, and Generation Owners Should Regularly Review Controller Settings in Low System Strength Areas

As described in Observation 4, system stability can be improved by tuning and coordinating the controller settings of inverters located in areas of low system strength. However, as the system changes over time these settings will need to be reviewed and adjusted because generation controller settings that work acceptably in one system strength condition may not be suitable for a different system strength condition. In this case, either the controller settings could be adjusted or operational limitations will need to be modified. Additionally, as system stability becomes more reliant on controller settings, which are under the purview of generator owners, it will become more important to ensure that actual and modeled settings stay aligned (see also Recommendation 6). Therefore, the controller settings and coordination of inverter-based generators should be regularly reviewed by ERCOT, Transmission Service Providers, and the generation owners. System operational results as recorded in PMU (Phasor Measurement Unit) or DDR (Digital Fault Data Recorder) data should be reviewed for occasional oscillatory response as this can indicate areas of concern.

Recommendation 3: Industry Should Investigate Robust Inverter Control Capability

Existing inverter-based renewable generation technology in ERCOT requires sufficient system strength for reliable operation. Essentially, the inverter controls require a strong grid signal under disturbance conditions, such as a fault, in order to properly regulate generation active and reactive output. The system strength conditions in West Texas observed in this analysis were well below levels currently seen on the system today. Reliable operations at very high penetration levels of inverter-based generation will likely require a fundamental change in operating practices or inverter control strategies/technologies that allow operation at lower system strength. These may include (but are not limited to):

- Implementation of system strength support requirements for generation resources; and/or
- Development and commercialization of adaptive and/or innovative controls for inverters, like grid-forming or virtual synchronous machine concepts, to allow reliable operation under a wider range of system strength conditions.

Observation 5: Synchronous Condensers Are Subject To Synchronous Machine Stability Limitations

Two synchronous condensers were installed in April, 2018 to improve system strength and provide dynamic reactive support to the Panhandle region. This technology can be considered a default solution to low system strength induced issues since synchronous condensers provide short circuit current, which directly increases system strength, at a lower cost than new transmission lines. When low system strength areas were identified in the study case, as shown in Figure 1.2, additional synchronous condensers were considered to address system strength and dynamic stability issues under contingency.

However, after adding multiple synchronous condensers in the study case in West Texas, ERCOT observed several stability challenges typical of synchronous machines under large, long distance power transfers. These stability challenges included angular instability and oscillatory responses as shown in Figure 2.7 and Figure 2.8.

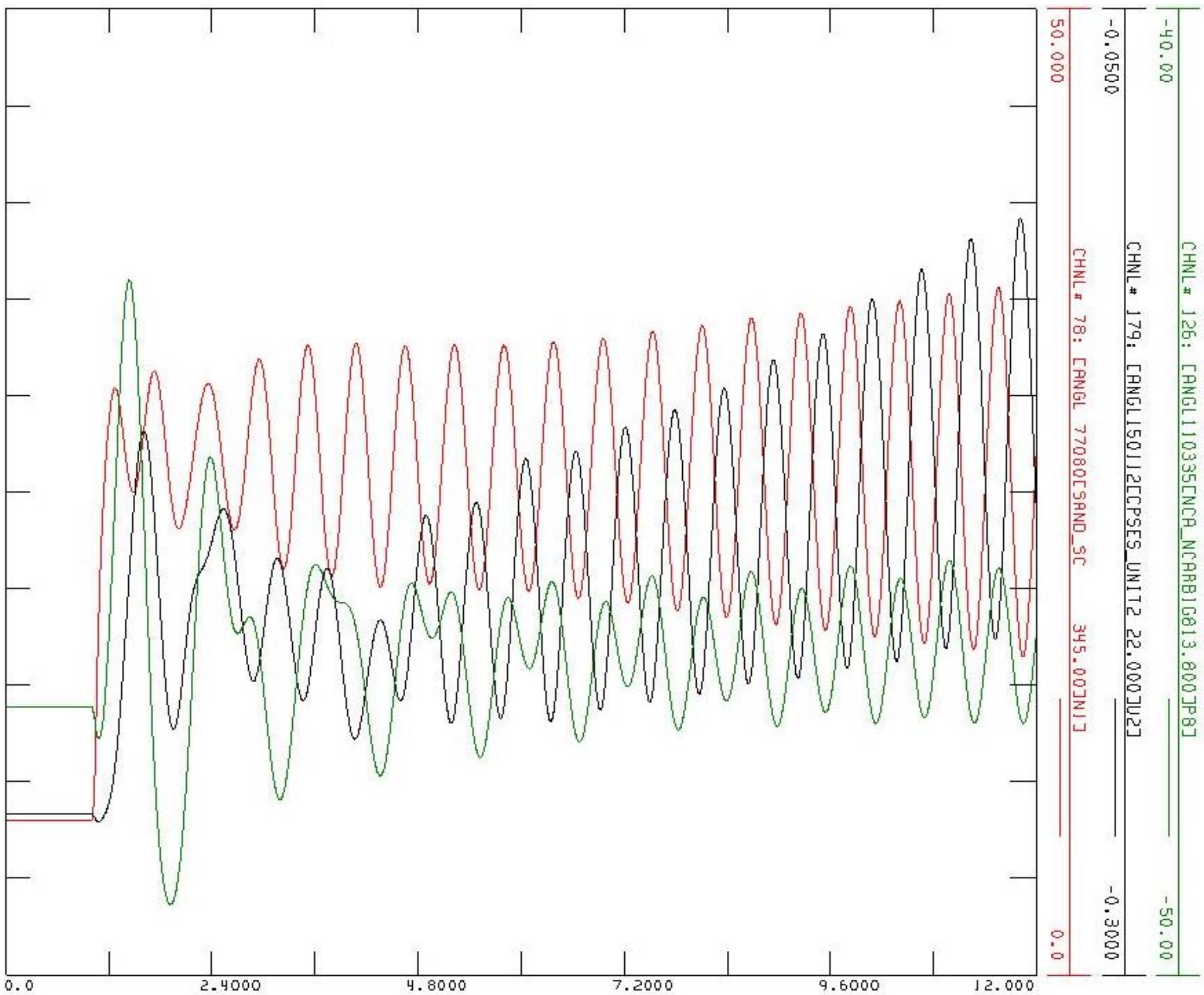

Figure 2.7: Undamped Power Oscillations

It was found that in order to prevent angular instability and inter/intra area oscillation, upgrades consisting of a combination of both transmission circuits and synchronous condensers were needed to fully address the dynamic stability issues related to low system strength and high power transfers.

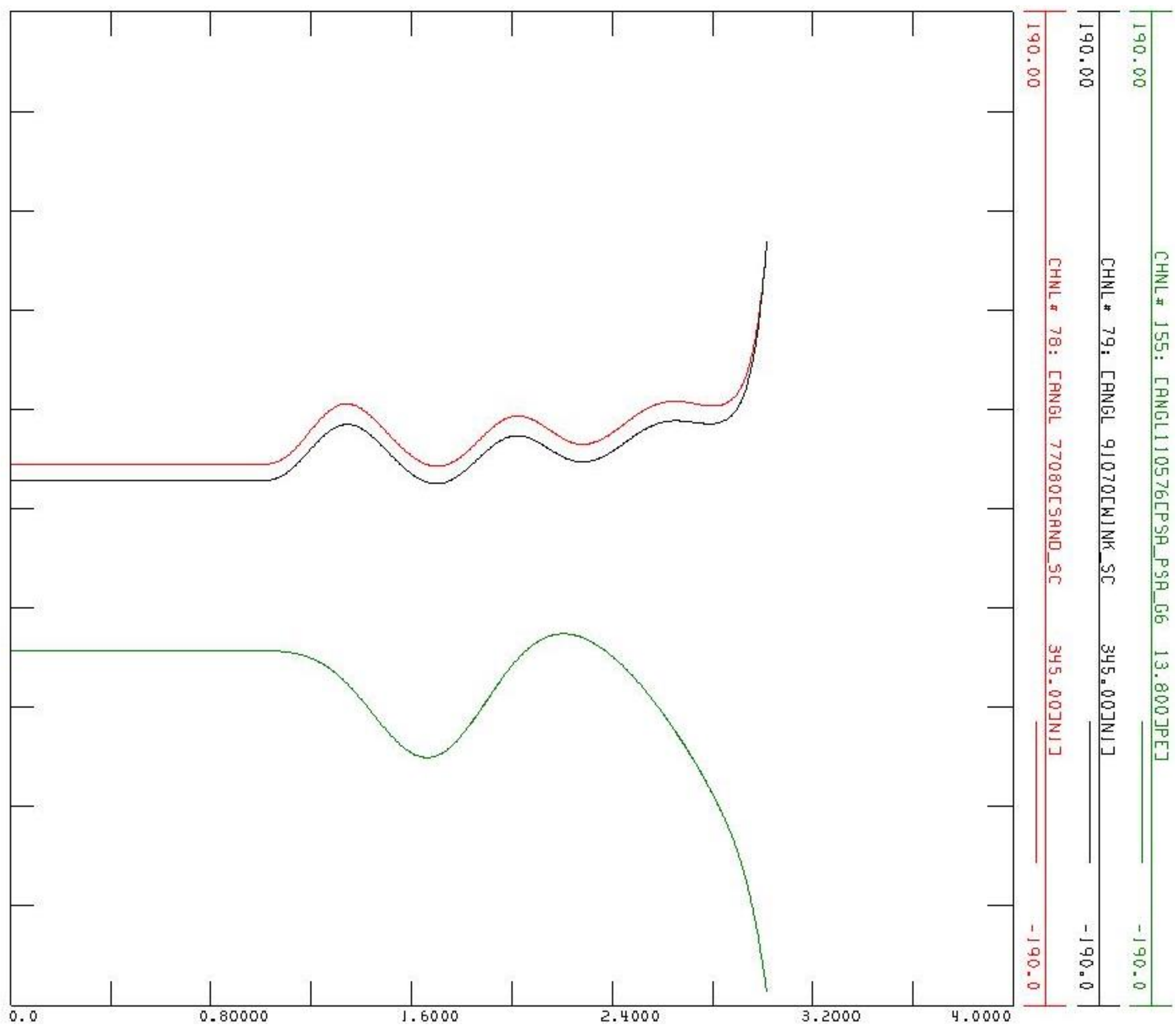

Figure 2.8: Angular instability of Synchronous Condenser under high power transfer

Recommendation 4: Planners Should Consider Synchronous Machine Stability When Recommending Synchronous Condensers

Low system strength is a key stability challenge to the continued integration of renewable generation in ERCOT. However, if planners only focus on adding synchronous condensers to improve the system strength it could lead to angular instability and/or oscillatory responses under high power transfer scenarios as described in Observation 5. Therefore, it is recommended that when considering the addition of synchronous condensers, planners should consider synchronous machine stability limitations, such as angular instability and oscillatory response. When taking these considerations into account a more optimal solution may be combinations of additional transmission circuits and synchronous condensers.

Recommendation 5: ERCOT Should Explore Requirements for System Damping Support from Renewable Generation Resources and Transmission Dynamic Reactive Devices

A power system stabilizer (PSS) is a supplementary control in the excitation system of a synchronous generator that provides damping and increases grid stability. Synchronous generators are required by the ERCOT Nodal Operating Guides to have power system stabilizers (PSS) that provide damping in the range of 0.2 to 2 Hz. Unlike synchronous generators which utilize an excitation system for voltage regulation, inverter-based generators and transmission system dynamic reactive devices, such as STATCOMS, and SVCs, regulate voltage support through inverter controllers. Consequently, these devices do not provide damping similar to resources with a PSS. While synchronous condensers can be implemented in areas with high renewable penetration to provide dynamic voltage support and short circuit contribution, these devices do not also provide damping support.

To provide effective and fast dynamic reactive support, an excitation system with high gain is typically implemented in synchronous condensers. However, these settings can reduce damping torque and cause small signal instability (oscillatory responses). In the study case unacceptable oscillatory responses were observed when multiple synchronous condensers (without damping support) were added to improve system strength and dynamic reactive power support.

ERCOT recommends that the application of PSSs on synchronous condensers be considered. In addition, inverter or dynamic reactive device controllers could theoretically incorporate a PSS-like function to provide damping. As such, the application of PSS-like control functions should also be considered for inverter-based generation and transmission dynamic reactive devices.

Observation 6: Typical Phasor-Based Dynamic Stability Models and Tools May Not Be Adequate for Future High Renewable Penetration Scenarios

Concerns around the adequacy of dynamic models and simulation tools under low system strength conditions were identified in the Panhandle System PSCAD study conducted in 2016[2]. The design of dynamic stability (phasor-based) models for inverter-based generators do not allow representation of power electronic controls in sufficient detail to reflect the behavior under low system strength conditions. Further, the phase lock loop (PLL) of inverter-based generators may not be represented at all. More detailed Electromagnetic Transient (EMT) simulation tools, such as PSCAD, can represent power system behavior, including the performance of inverter-based generation, in greater detail to assess the system response under low system strength conditions.

It should be noted that the stability assessment conducted for this study used typical (phasor-based) dynamic stability assessment tools. Careful review and adjustment of solution parameters in the study tool were necessary to overcome some non-

[2] http://www.ercot.com/content/news/presentations/2016/Panhandle%20System%20Strength%20Study%20Feb%2023%202016%20(Public).pdf

convergence and numerical instability issues under the observed low system strength conditions. Based on ERCOT's previous work, including the Panhandle System PSCAD study, the observed low system strength, non-convergence, and numerical instability issues in this analysis may point to the need to perform a detailed EMT analysis to confirm the dynamic stability study results under low system strength conditions.

Recommendation 6: ERCOT Should Consider Dynamic Model Performance Validation for All Dynamic Components

Both generation resources and transmission dynamic devices were found to significantly affect system response in the study case. In general, the dynamic behavior of equipment is more critical in sensitive grids with low system strength than in relatively strong ones as the dynamic control of real and reactive power output and consumption plays a larger role in maintaining stability under disturbance as system strength declines. Therefore, accurate, validated dynamic models for all these devices are vital for accurate system reliability assessment under low system strength conditions. Model validation requirements for generation resources are addressed in NERC reliability standards MOD-026 and MOD-027. ERCOT should consider requiring similar model validation requirements for all dynamic components connected to the ERCOT transmission grid.

Recommendation 7: ERCOT Should Develop a Standardized Wide-Area PSCAD Model Process and the Ability to Perform Regular Wide-Area PSCAD Studies

As discussed in Observation 6, detailed PSCAD studies are required to properly capture the system dynamics of conditions with high penetrations of renewable generation. While ERCOT has hired a consultant to perform ad hoc PSCAD analysis in the past, if the ERCOT system continues to add more inverter-based generation resources, PSCAD studies will need to be performed on a regular basis.

Detailed representations of generators and transmission dynamic devices in PSCAD format will be required to perform these types of studies. It should be noted that developing "generic" PSCAD representations of projected inverter-based resources would be a significant challenge and would likely limit the validity of study conclusions. Accurate, resource-specific PSCAD models are required to assess grid conditions in areas with low system strength. These resource-specific PSCAD models have not been required in the past, and ERCOT currently has only a limited number of models available. ERCOT should explore creating a standardized wide-area PSCAD model requirement and a process to validate and maintain these models. It is also recommended that ERCOT develop both staff resources and computing capability necessary to perform sophisticated and computation-intensive PSCAD studies.

Observation 7: Large Generation Trips May Cause Voltage Deviations Before Large Frequency Deviations Are Observed

In this stability assessment, two events were tested to evaluate the system frequency response immediately following the loss of a large power plant under low inertia conditions: a trip of power plant A with a total of 2,300 MW and a trip of power plant B with a total of 2,750 MW. The frequency responses for these two events are shown in Figures 2.9 and 2.10, respectively. Normally, a larger generation loss would be expected to result in a lower frequency nadir. However, ERCOT observed that the frequency nadir was lower for the trip of plant A, the smaller plant. Further investigation indicated the following factors contributed to the observed frequency response for the trip of plant B:

- The load in dynamics simulations is represented as a function of voltage, and as the voltage reduces, the system's load also reduces.
- The tripping of power plant B, located near a large metropolitan area resulted in the loss of voltage support for the area.
- The tripping of the power plant B also led to increased power import to serve the large load center. This in turn increased the reactive losses and depressed voltage further.
- Low system strength led to greater voltage deviations across a broader area.

The combination of high import power transfer and reduction of reactive support in a large metropolitan area could lead to voltage instability and slow voltage recovery. It should be noted that there was no Under Voltage Load Shedding (UVLS) scheme included in this assessment. A significant amount of load reduction was observed during the transient voltage recovery period that actually helped frequency recovery for the trip of power plant B. Therefore, a large generation loss may cause voltage deviations before large frequency deviations are observed under low system strength conditions. Planners may need to consider grid strength improvements not only in areas with high concentrations of inverter-based devices, but also in areas that have high demand but not sufficient synchronous generation support.

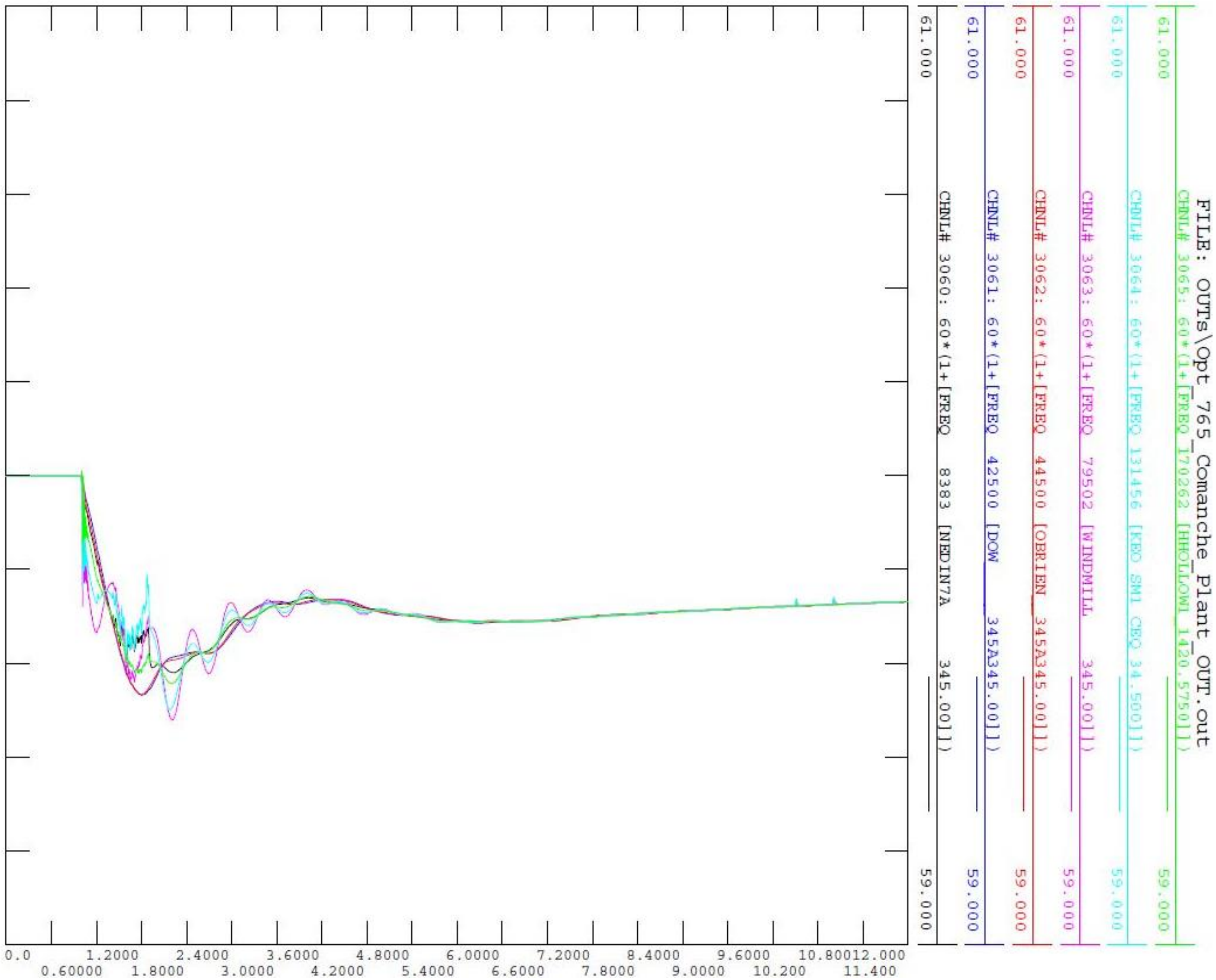

Figure 2.9: Frequency response for power plant A trip

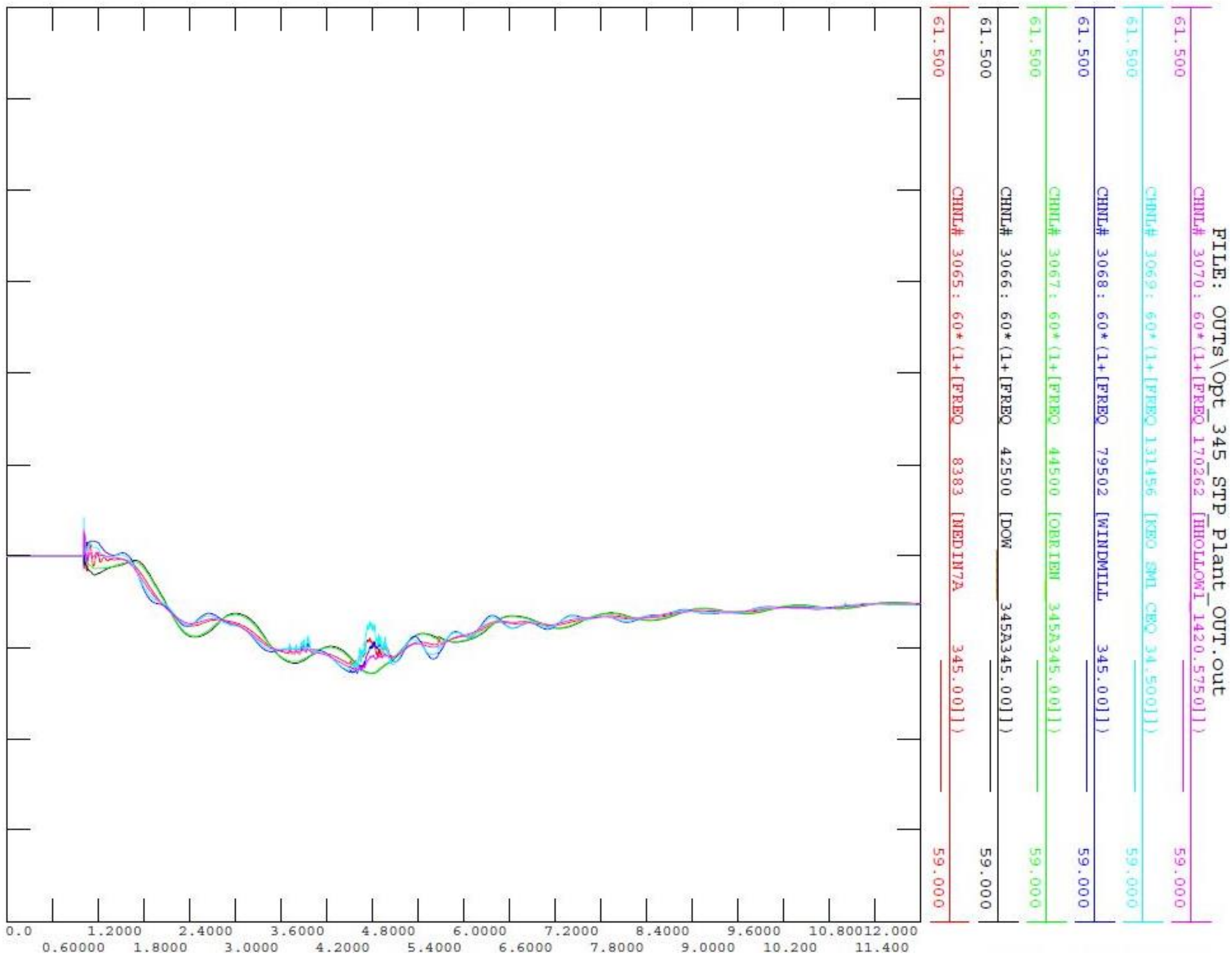

Figure 2.10: Frequency response for power plant B trip

Recommendation 8: Dynamic Load Models Should Be Regularly Reviewed and Validated

The transient or prolonged low voltage recovery noted in Observation 7 could have a significant impact on the load consumption in areas with low system strength depending on the assumed load models and dynamic response. It is likely that existing load models are tuned to represent load dynamic behavior based on today's relatively strong system dynamics, particularly in the large metropolitan areas where there are many synchronous generators. However, as more renewable generation is added to the system and more legacy synchronous generators near the load centers are retired, the behavior of the loads may change from a dynamics perspective. Accurate load model development, which is already an ongoing challenge, should be regularly reviewed, validated, and revised to properly reflect the response under voltage and frequency excursions as the system changes.

Observation 8: Higher Voltage Transmission Circuits Were Beneficial From a Stability Perspective

This assessment included an evaluation of 345 kV transmission options to obtain acceptable dynamic responses for the tested contingencies as this is the highest circuit voltage level currently in the ERCOT system. But in comparing a 765 kV transmission circuit as an alternative upgrade solution to a 345 kV double circuit, it was noted that while both options addressed the stability issues, the aggregate need for synchronous condensers could be reduced by using the higher voltage circuits.

These results could be project-specific. While a higher voltage circuit, such as 500 kV or 765 kV, has significantly less impedance compared to a 345 kV double circuit line, the impedance of the transformers that would be required to connect the higher voltage circuit could negate much of this impedance benefit. A network of higher voltage circuits is likely to show a much greater benefit than a single, standalone higher voltage circuit.

Recommendation 9: ERCOT and Stakeholders Should Evaluate the Full Range of Benefits of Higher Voltage Level Transmission Circuits

Although some benefits were observed with a 765 kV option, further study is needed to fully evaluate the benefits of incorporating a network of higher voltage level transmission circuits into the existing grid. ERCOT and stakeholders should develop processes to identify the full range of benefits of higher voltage transmission solutions for transferring large amounts of power over long distances.

Appendix A Dynamics Analysis

The subsequent sections summarize the results and identified challenges of the ERCOT study associated with high penetration of renewable generation and low system inertia conditions. The stability assessment was conducted using ERCOT's standard dynamic stability assessment tool, Siemens PTI PSSE (Version 33.10). It should be noted that the dynamic models developed for typical dynamic stability study purposes may not be suitable under low system strength conditions and could cause numerical instability. Careful review and adjustment of solution parameters in the study tool were necessary to overcome some non-convergence and numerical instability issues under these conditions. If an observed instability could not be addressed through the adjustment of solution parameters, system upgrades were considered as potential mitigation options. A detailed electromagnetic transient analysis may be necessary to confirm the dynamic stability study results under low system strength conditions.

A.1 Flat Start Case

Dynamic models from the most recent Dynamics Working Group (DWG) approved data sets (2016-2017 flat start cases) were used to represent machines and other transmission facilities with significant dynamic response capabilities where possible. New renewable generators that were not represented in DWG data sets were modeled using generic models with typical parameters. Proper model initialization and response for the dynamic study case was confirmed by satisfying two tests: No Disturbance Test and Small Disturbance Test.

A.1.1 No Disturbance Test

The dynamic study case was run for 10 seconds with no disturbance applied. An acceptable response is a "flat" and unchanging profile for monitored values (system voltages, power output, etc.) Figure A.1 shows acceptable responses under no-disturbance conditions.

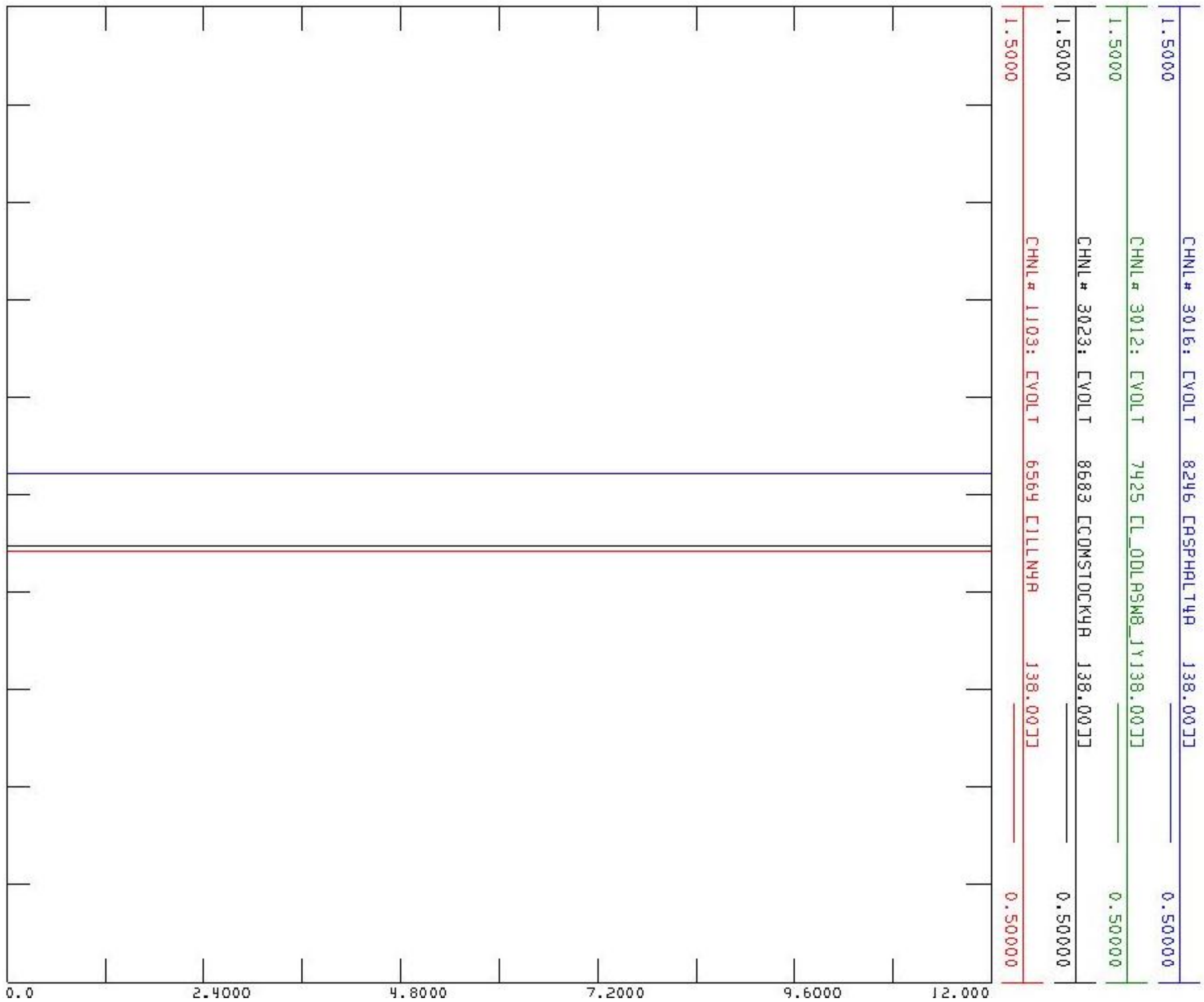

Figure A.1 Flat system response under no disturbance

A.1.2 Small Disturbance Test

The small disturbance test applied a perturbation to the system that did not trip any grid components. An acceptable model response would show the system remaining stable and returning to a steady-state condition after the perturbation.

Figure A.2 shows the system response for a small disturbance test. A shunt capacitor at a 345 kV substation was switched on for 4 cycles and then switched off. Instability was observed right after switching on the shunt capacitor and the simulation crashed shortly after the instability occurred.

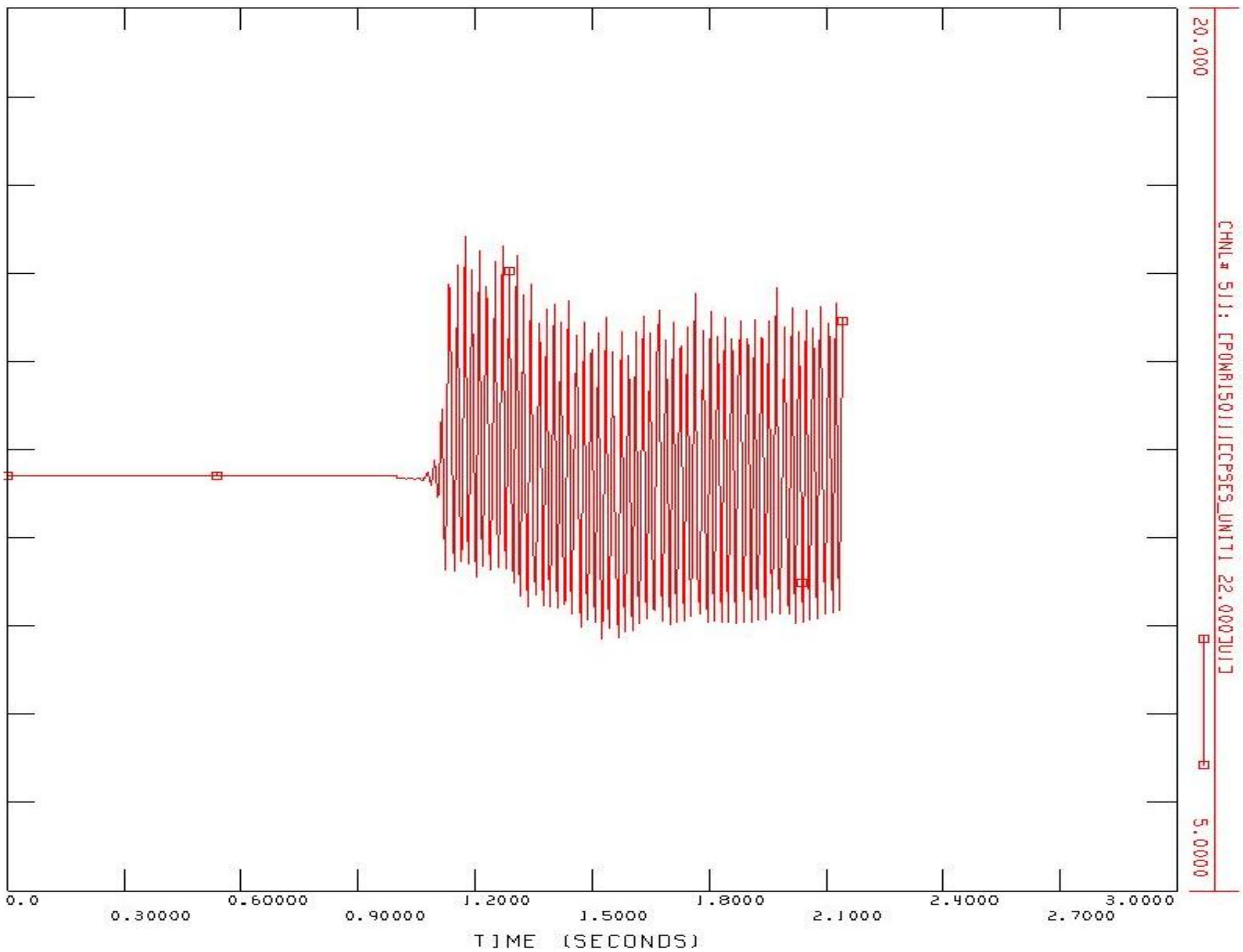

Figure A.2: Unstable oscillatory response to small disturbance test

To address the instability issues observed under small disturbance tests, synchronous condensers were added in areas of the system where system strength was low. Figure A.3 shows an acceptable system response for the small disturbance test with synchronous condensers added to the study case to improve system strength.

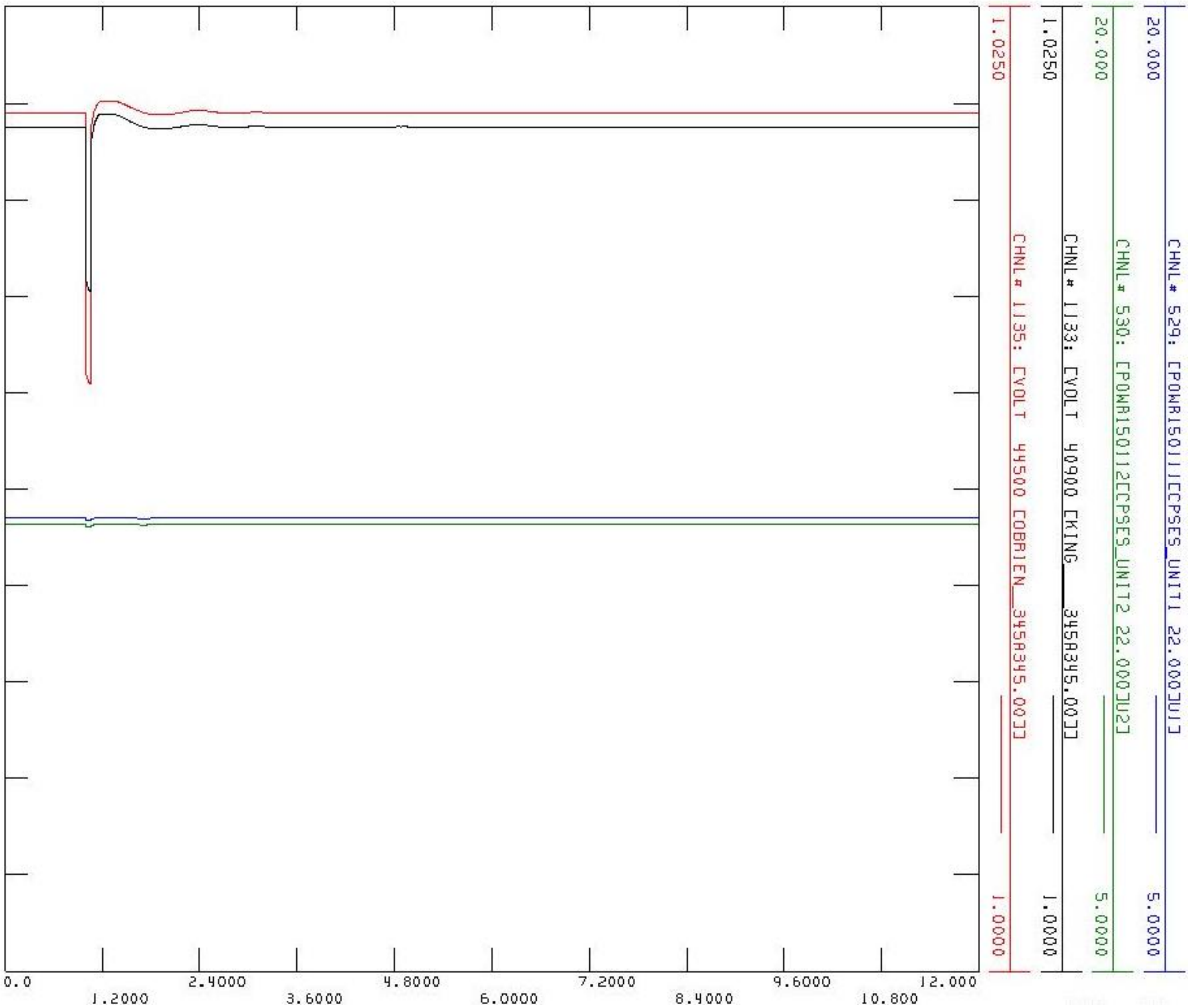

Figure A.3: Small disturbance test with synchronous condensers added to study case

A.2 Dynamic Contingency Analysis and Criteria

In the study case, most of the renewable generation resources were connected to the North, West, and Far West Weather Zones in ERCOT. Therefore, dynamic contingencies were primarily applied in these three zones where they were expected to have the greatest system impact due to the long-distance transmission lines, high power transfer, and low system strength identified in these zones. A total of 377 dynamic events, including 345-kV single-circuit and double-circuit events, were included in the dynamic stability analysis to evaluate the system dynamic response. Single-circuit contingencies were simulated in conjunction with a 3-phase (3ph) fault, while double-circuit contingencies were simulated in conjunction with a single line to ground (SLG) fault.

Performance was evaluated based on NERC and ERCOT Planning Criteria including:

- Post dynamic disturbance voltage recovery within the range from 0.9 pu to 1.1 pu within 5 seconds for NERC P1 single-circuit events and within 10 seconds for NERC P7 double-circuits event.
- Post dynamic disturbance frequency recovery within the range from 59.4 Hz to 60.4 Hz.
- Oscillations within the range of 0.2 Hz to 2 Hz decay with a minimum 3% damping ratio.

A.2.1 Large Disturbance Tests

Although several synchronous condensers were added to obtain acceptable dynamic flat start conditions under the no disturbance and small disturbance tests, unacceptable system responses were observed after applying dynamic events described in Section A.2. The observed instabilities were similar to the response shown in Figure A.2 (very high frequency oscillations). Therefore, additional synchronous condensers were added in the case to further enhance the system strength in an attempt to mitigate the observed instabilities observed under large disturbance conditions.

A.2.2 Oscillations

The addition of synchronous condensers significantly improved system strength, allowing stable operation of high penetrations of inverter-based resources. However, certain contingencies resulted in inter- and intra-area oscillation modes in which the synchronous condensers appeared to participate. Figure A.4 and Figure A.5 below show simulation results when a 345 kV single-circuit event resulted in oscillations. Undamped or poorly damped oscillations were typically observed when the dynamic events involved the loss of highly loaded 345 kV circuit(s).

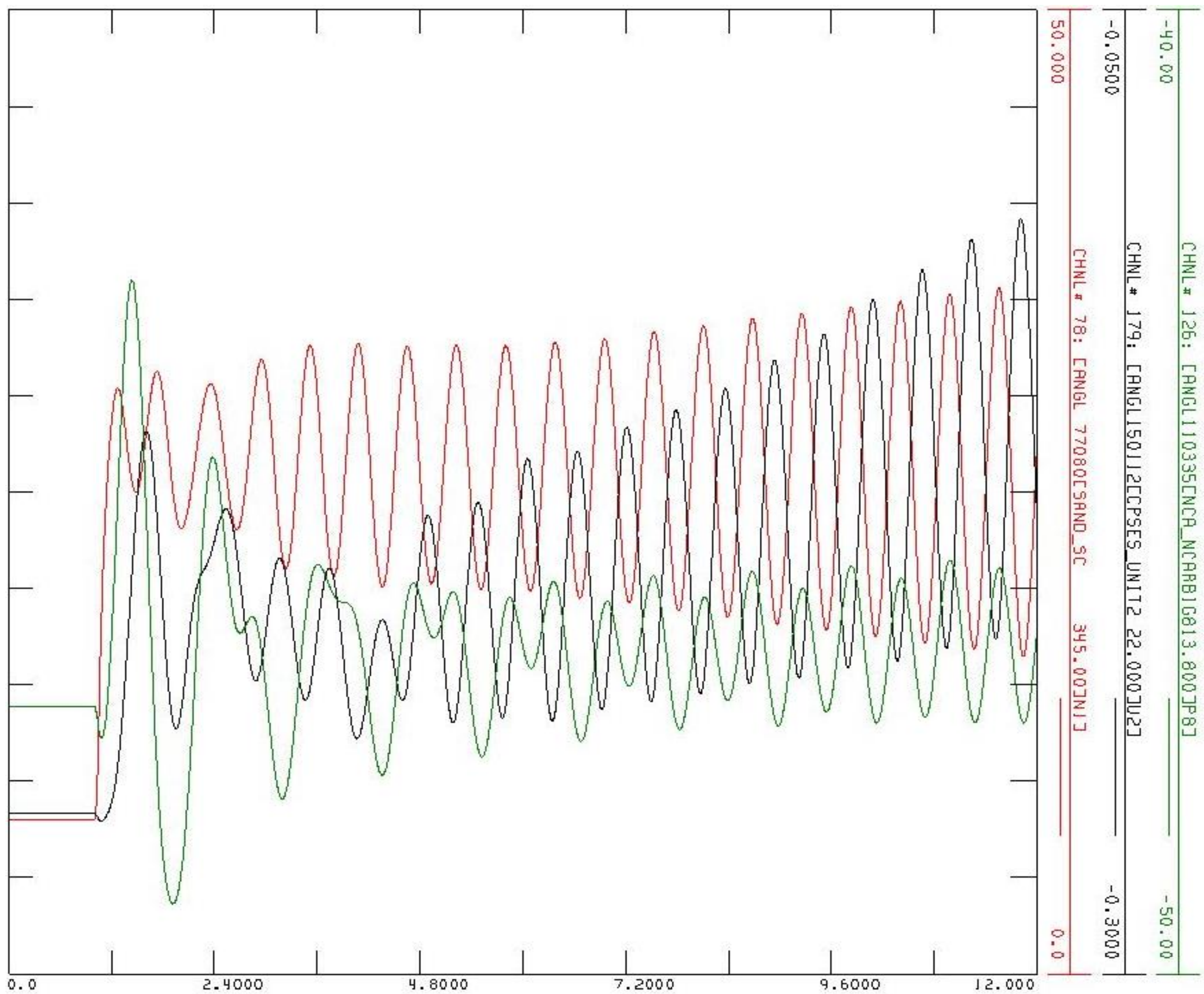

Figure A.4: Undamped Power Oscillations

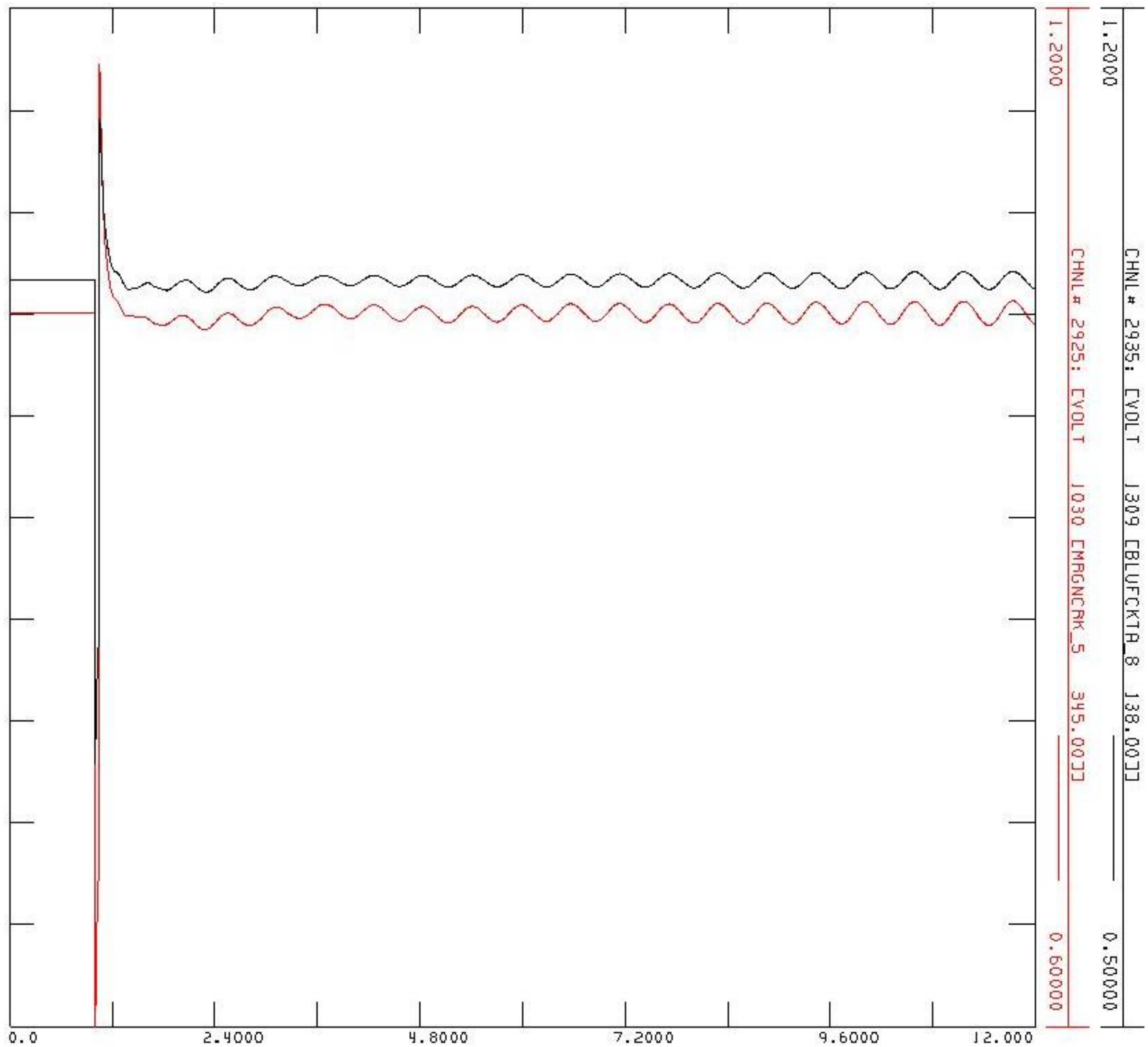

Figure A.5: Voltage Oscillations

A system is most susceptible to classical inter-area oscillations when one group of synchronous machines is connected to another group by a relatively high impedance path under heavy power transfer. The addition of synchronous condensers to improve system strength created those conditions in the study case. Thus, the following items were identified as probable contributors to the undesired oscillatory responses:

- The added synchronous condensers were located in West Texas (where a majority of the renewable generation was also located), electrically far from other synchronous machines connected to the ERCOT grid.
- The study scenario reflected high power transfers from renewable resources in West Texas to load centers primarily in the eastern portion of the ERCOT grid where synchronous generators were primarily located.

- The simulated dynamic events tripped major 345 kV circuit(s) and resulted in higher electrical distance (higher impedance) between the synchronous condensers and other synchronous machines connected to the ERCOT grid.
- The added synchronous condensers were not equipped with power system stabilizers that may help provide damping torque to mitigate oscillations.
- Other transmission dynamic devices, like SVCs, and renewable generation resources were not equipped with specifically tuned damping control features to mitigate oscillations.

The addition of transmission circuits was tested as one option to mitigate the undesired oscillations by reducing the electrical distance (impedance) between the synchronous condensers and other synchronous machines connected to the ERCOT grid. These new transmission circuits helped in stabilizing inter/intra area oscillations. Both 345 kV and 765 kV transmission options were tested and it was found that both options addressed the stability issues. The need for synchronous condensers was reduced by using higher voltage level transmission circuits. Figure A.6 shows the system response after addition of transmission circuits.

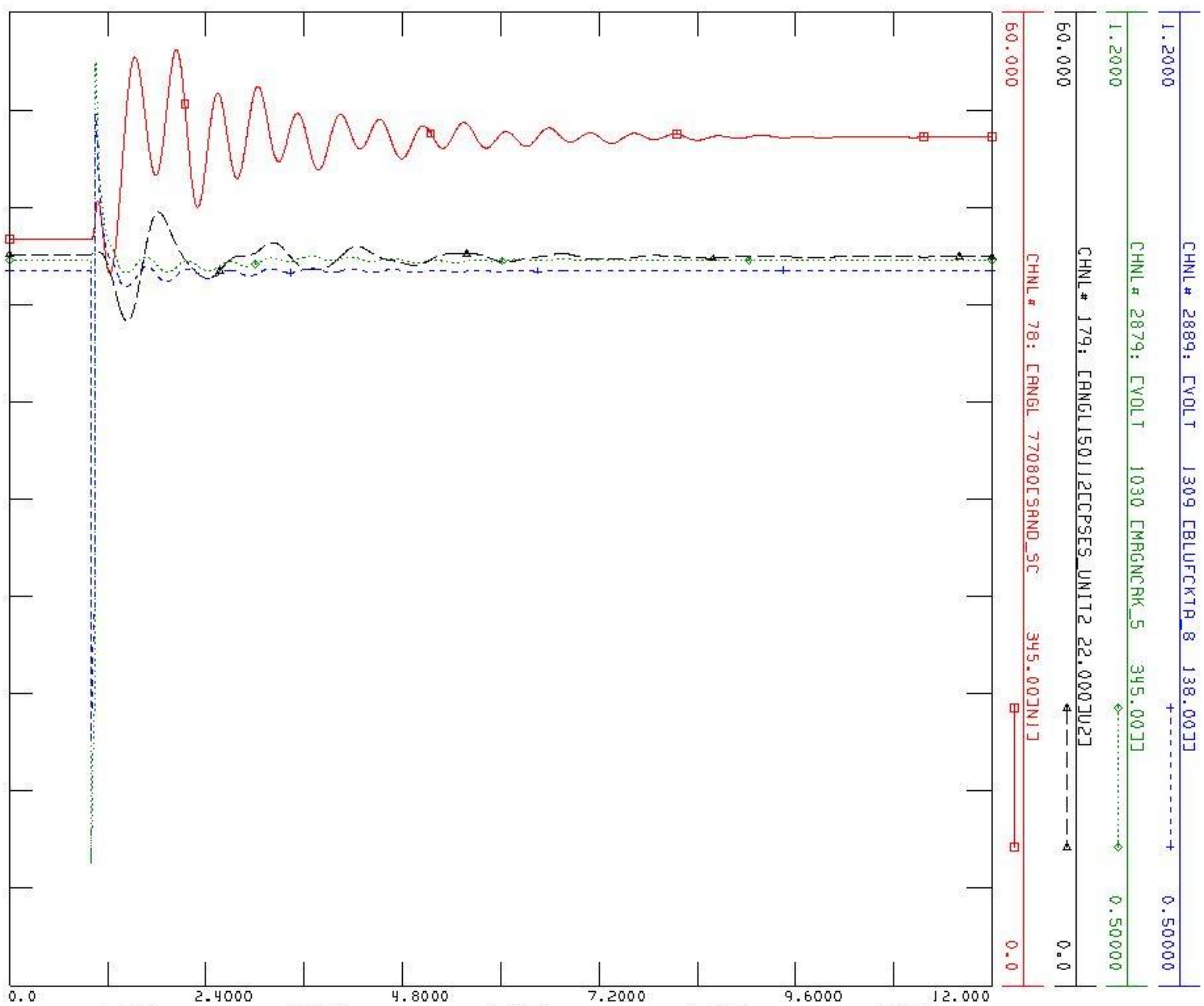

Figure A.6: Power and Voltage plots after adding transmission circuits

A.2.3 Angular Instability

The analysis revealed that the loss of certain high power flow transfer paths, which significantly increased overall system impedance, resulted in angular separation. Figure A.7 shows the dynamic responses for a particular contingency resulting in machine angular instability and separation. The synchronous machines in Figure A.7 are two synchronous condensers added in West Texas and one machine in the Houston area.

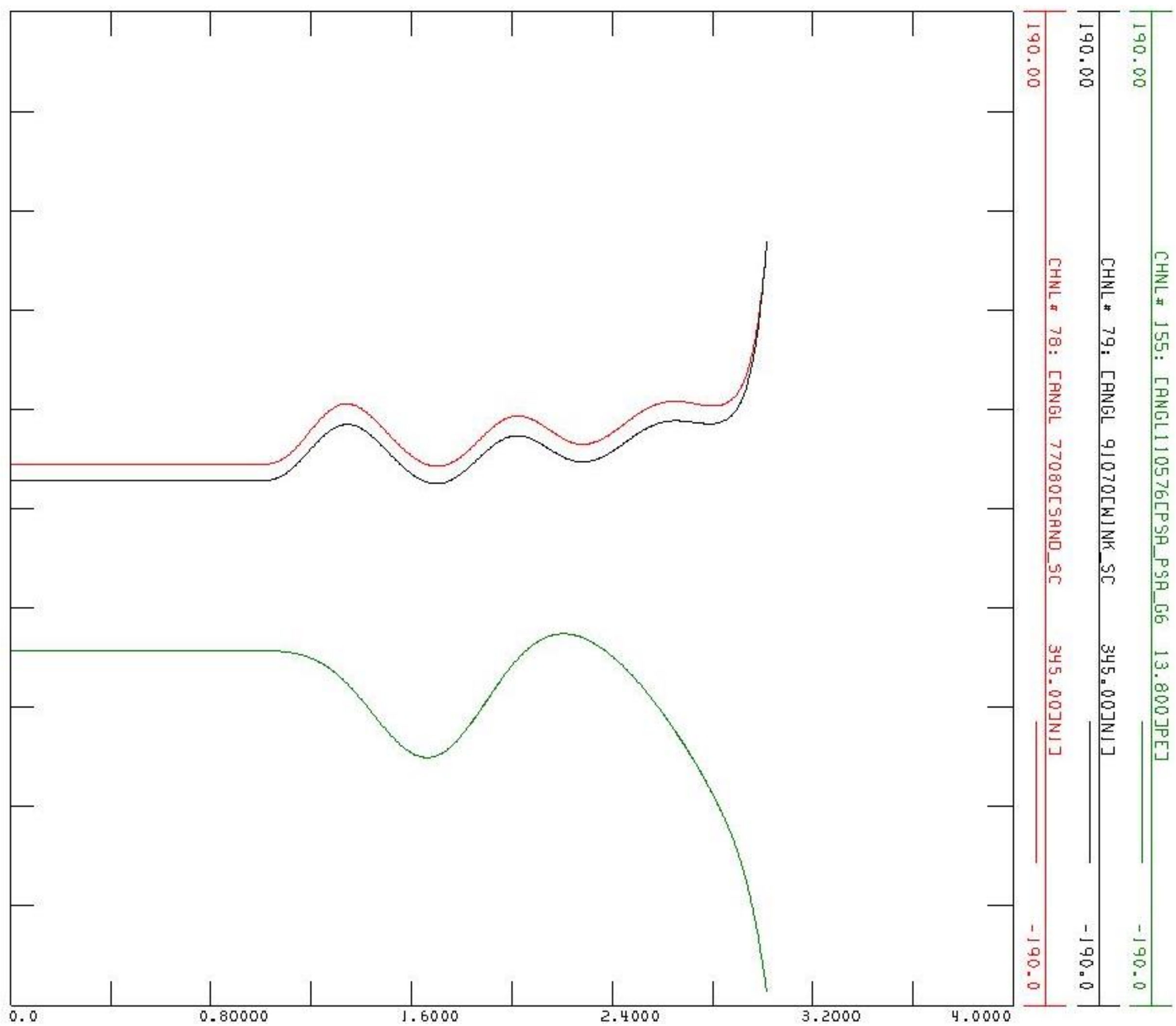

Figure A.7: Angular instability

The fundamental system conditions that contributed to the observed angular separation are essentially the same as the conditions that can contribute to oscillatory responses as described in Section A.2.2: one group of synchronous machines connected to another group of synchronous machines by a relatively high impedance path under heavy power transfer. The addition of transmission circuits was tested as one option to mitigate angular separation by reducing the electrical distance (impedance) between the sending and receiving end of power transfer. Figure A.8 shows the acceptable system response with the addition of transmission circuits for the same event depicted in Figure A.7.

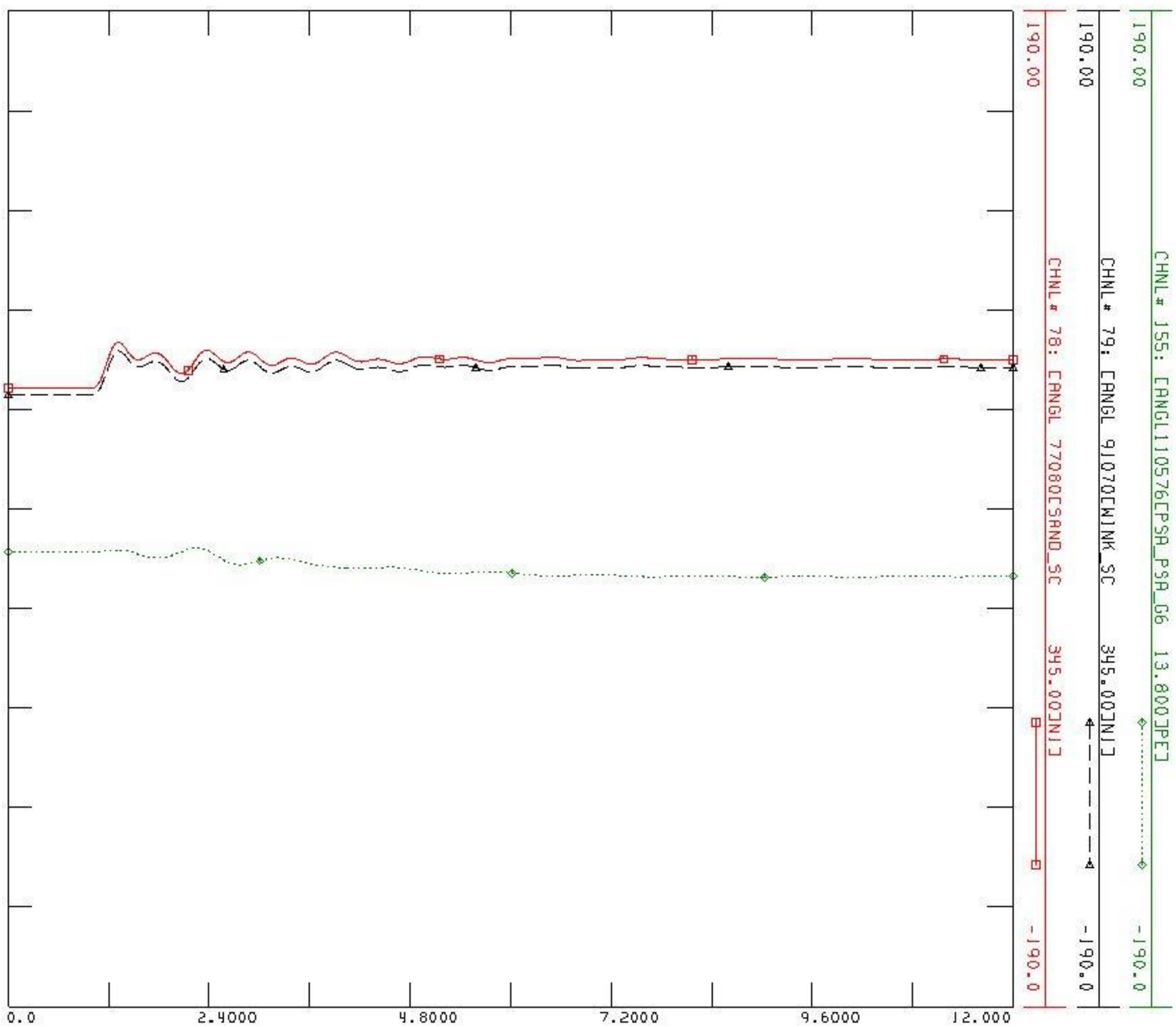

Figure A.8: System response with additional transmission circuits

A.2.3 Controller Settings for Generic Renewable Dynamic Models

One of the key assumptions in this study was the application of generic dynamic models with typical settings to represent future renewable generation resources. Recognizing that the generic models and the associated typical parameter values may not be adequate for low system strength conditions, additional simulations were run to test the impact of certain voltage controller gain settings. Figure A.9 shows the system response of two controller settings. The only difference between these two simulations was the settings of the controllers: setting the voltage control for higher gain (red color) could lead to poor or undamped oscillations while utilizing a lower gain settings (black color) resulted in an acceptable response.

These results indicate that slight controller adjustments or variations could result in significant improvement or deterioration of system response. Lower system strength conditions will result in reduced margin for reliable controller operation. In other words, precise controller settings and tight coordination will be required under low system strength conditions. It should be noted that these findings do not indicate particular settings to be adopted for future wind or solar controllers. Hopefully technological improvements in the future will provide better performance and will eventually allow inverter-based resources to be reliably connected under conditions of lower system strength.

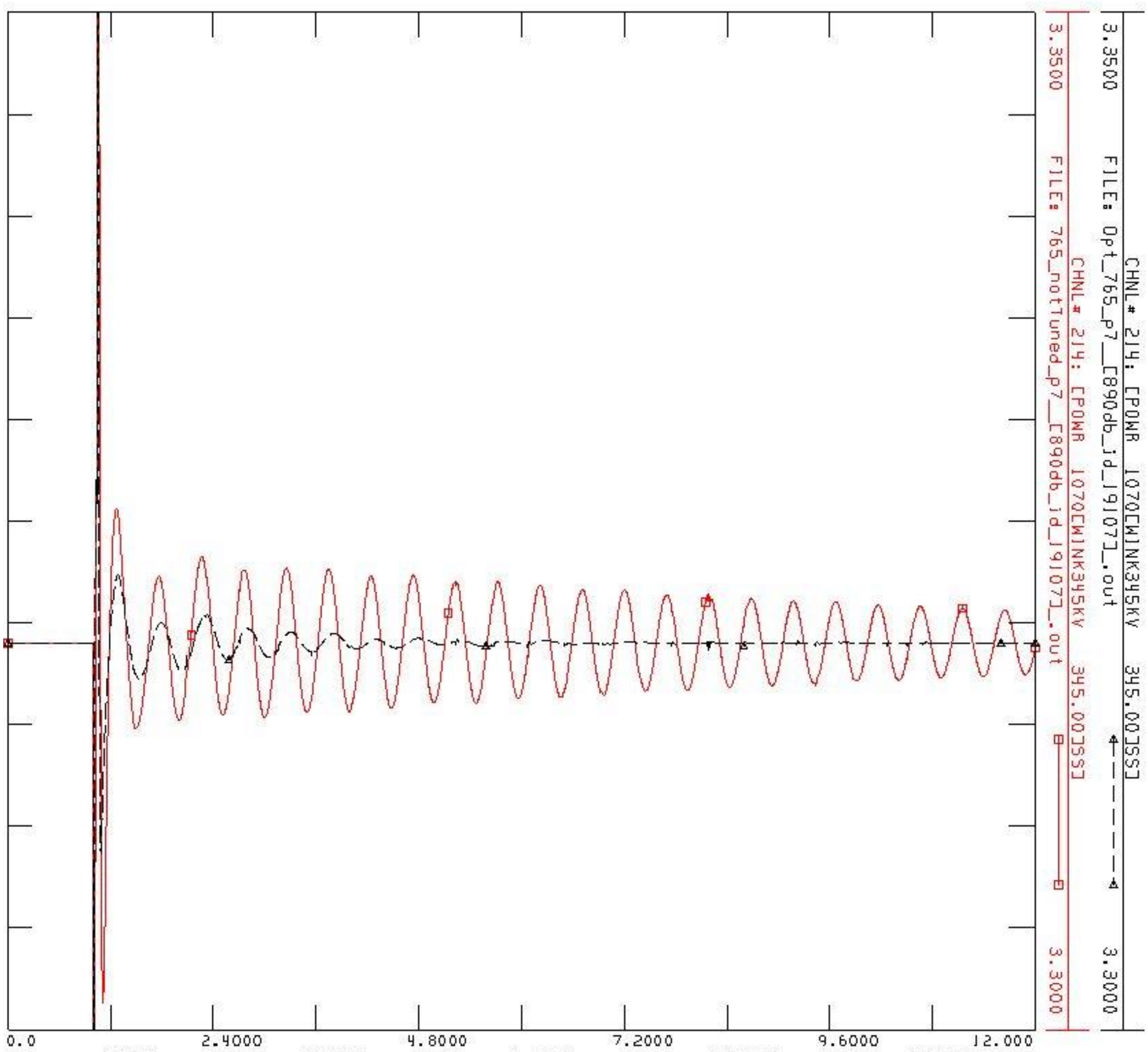

Figure A.9: Active power flow response with higher voltage control gain (red color) and low control gain (black color)

A.3 Frequency Stability Analysis

Two events were tested to evaluate the system frequency response when losing two large power plants under low inertia conditions. The study case reflected adequate Responsive Reserve capacity from Load Resources (LRs) that trip within 30 cycles once frequency decays to 59.7 Hz or lower and Generation Resources that provide primary governor response.

A.3.1 Power Plant A Trip in the North Central Region

A power plant with a total of 2,300 MW was tripped in the simulation and the frequency responses are shown in Figure A.10. The frequency decline triggered all the LRs, but the frequency nadir remained above the level that would trigger the first stage of Under Frequency Load Shed (UFLS) at 59.3 Hz. The largest Rate of Change of Frequency following generation loss was 0.66 Hz/second observed in the West Texas region where there were limited sources of synchronous inertia committed under the high renewable generation conditions. A similar system frequency response has been observed in real time operations where the largest frequency deviation typically occurs in West Texas. Higher renewable penetration together with less commitment of synchronous generators could exaggerate the frequency deviation.

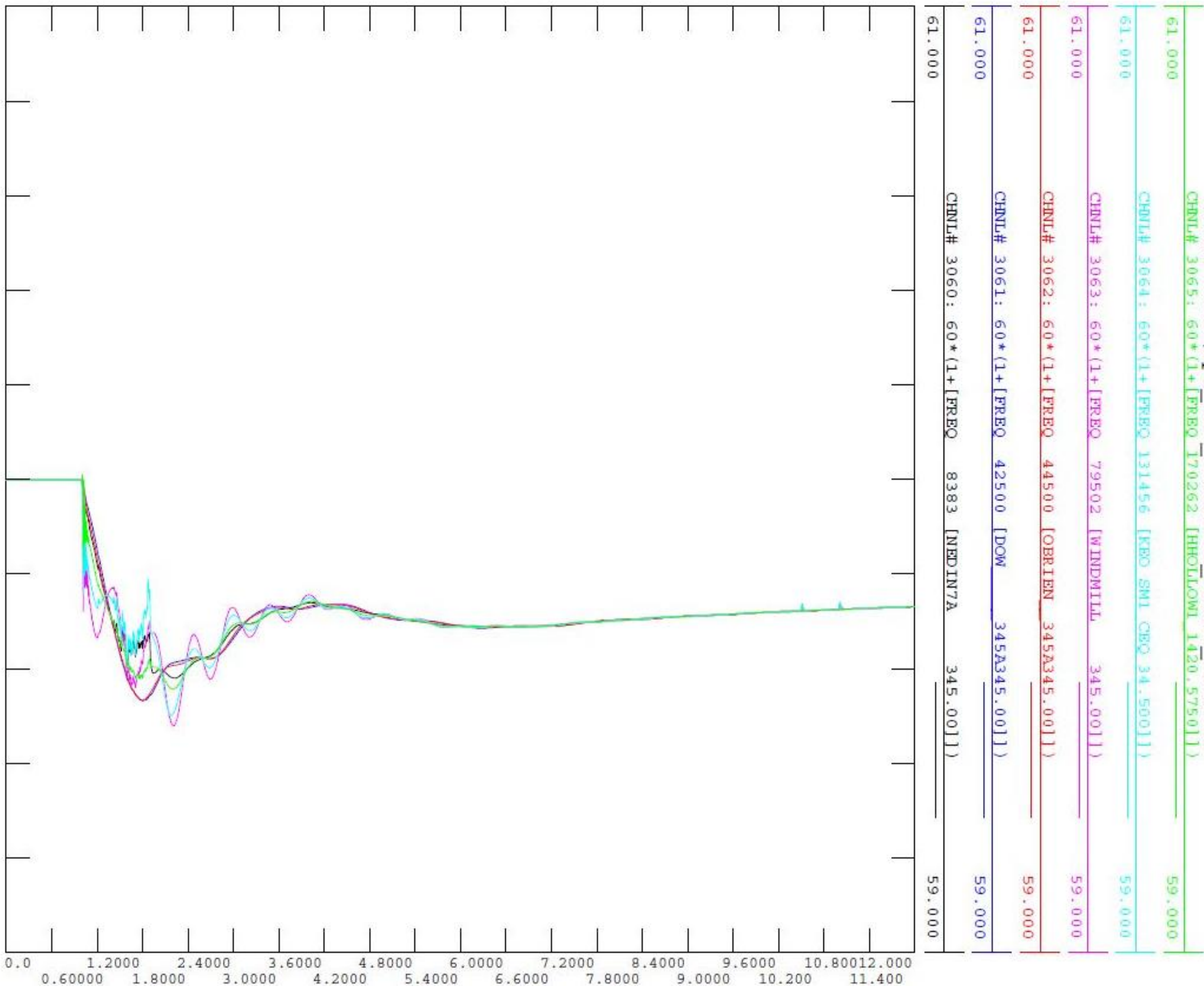

Figure A.10: Frequency response for power plant A trip

A.3.2 Power Plant B Trip in the Coastal Region

A power plant with a total of 2,750 MW was tripped in the simulation and the frequency responses are shown in Figure A.11. The frequency nadir remained above the level that would trigger the first stage of UFLS at 59.3 Hz. Although the generation loss was larger than the power plant A trip, the frequency responses were better compared to Figure A.10 and only partially triggered LRs.

As a result, a significant amount of load reduction was observed during the transient voltage recovery period that actually helped frequency recovery. It should be noted that such phenomena has not been observed in real time operation because the system strength in the area is generally strong and more generators in the region are typically committed compared to the study condition. In addition, there was no Under Voltage Load Shedding (UVLS) schema modeled in this assessment and such phenomena may not occur if load can be tripped by UVLS to help voltage stability. Additional system upgrades may be required to maintain adequate reliability for the modeled level of power import and generator de-commitments in the region. In addition, the load dynamic responses should be further reviewed to validate the load models used in the study.

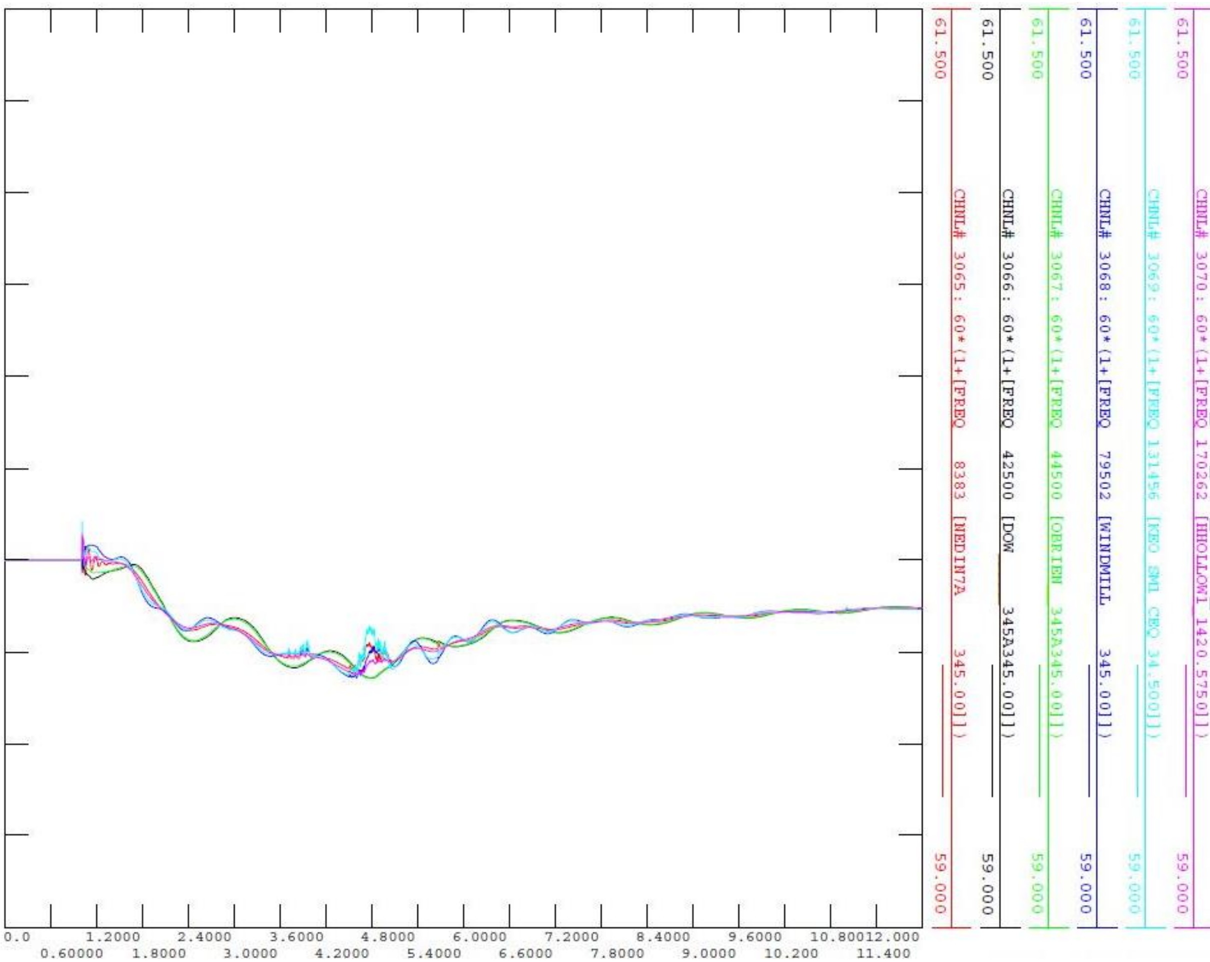

Figure A.11: Frequency response for power plant B trip