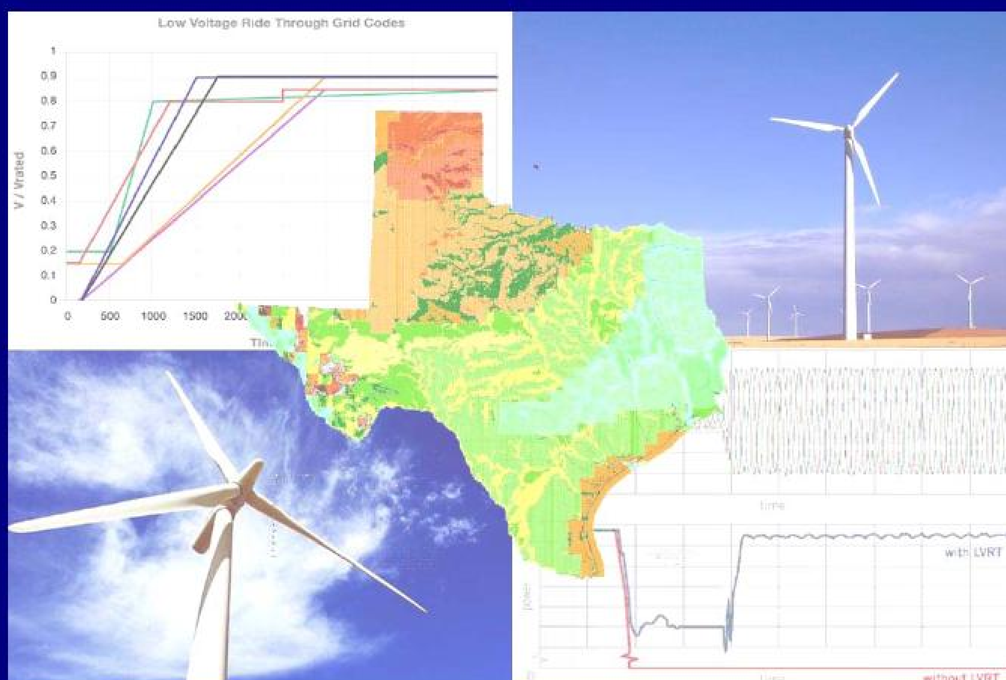
ERCOT VOLTAGE RIDE THROUGH STUDY

Phase III Report

June 15th 2010



Submitted by:

PB Power

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1 Executive Summary

The objective of Phase III of the ERCOT VRT Study was to utilize the updated WGR models developed as part of the Phase II effort to assess the reliability risks associated with WGRs that may not comply with the ERCOT VRT requirements (as defined in ERCOT Operating Guide Section 3.1.4.6.1) on the ERCOT system as a whole. No critical reliability risks attributable to the lack of WGR VRT capability were identified by the Phase III analysis and the results of this study do not indicate a need to modify the ERCOT voltage ride-through requirements provided by Operating Guide 3.1.4.6.1.

Updated WGR models were developed in Phase II to adequately and accurately represent the detailed WGR facility from a steady state and dynamic response standpoint. Documentation detailing the data collection and modeling process have been submitted to ERCOT as part of the Phase II deliverables. A total of 7 scenarios have been assessed as part of the Phase III effort for the 65 normal clearing and 31 breaker failure events identified and documented in the Phase I report. The 7 scenarios assessed as part of this study are as follows:

- High Wind High Load (HWHL) Case
- High Wind Low Load (HWLL) Case
- Change Case 1 – High Wind Low Load conditions with conventional generation units in West Texas off-line
- Change Case 2 – High Wind High Load Case with dynamic load models for West Texas
- Change Case 3 – Change Case 1 with dynamic load models for West Texas
- Change Case 4 – Sensitivity analysis to assess impact of pre-fault WGR terminal voltages and voltage control scheme on WGR trips
- Change Case 5 – Investigation into events posing potential reliability risks for HWHL/HWLL cases and Change Cases 1 through 4

The WGR dispatch and the dynamic load models characterizing each of the scenarios identified above were provided to PB by ERCOT. The normal clearing events were initially executed with a 1-2 cycle margin to assess the worst case scenario. In cases where a large amount of WGR trips were observed, the event was re-evaluated utilizing the expected normal fault clearing time as indicated by the associated Transmission Service Provider (TSP). The reliability metrics outlined in Phase I were utilized to assess the risks associated with the lack of WGR VRT capability for each of the 7 scenarios. A summary of the reliability metrics is provided below:

- WGR trips exceeding ERCOT's current Responsive Reserve Requirement of 2300 MW in terms of WGR dispatch associated with the scenario
- WGR trips exceeding ERCOT's current Responsive Reserve Requirement of 2300 MW in terms of WGR capacity associated with the scenario
- Acceptable system frequency response and post-event frequency deviations
- Acceptable voltage recovery and post-event voltage levels

No reliability risks associated with the lack of WGR VRT capability were identified with respect to the HWHL and/or HWLL cases for any of the normal clearing and/or breaker failure events simulated.

No reliability risks associated with the lack of WGR VRT capability were witnessed with respect to Change Cases 1 and 2 for any of the normal clearing and/or breaker failure events simulated. CTG5 was initially observed to result in WGR trips indicative of potential reliability risks for Change Case 1 when simulated with 6 cycle fault duration. The utilization of normal expected TSP fault clearing time for CTG5 does not indicate any reliability risks associated with the lack of WGR VRT capability for Change Case 1.

CTG5 was identified to pose a risk of voltage instability and a potential subsequent voltage collapse for Change Case 3. The observation is based on and dependent on the conditions modeled in Change Case 3 especially the load models utilized for dynamic representation of the motor load in West Texas. Assuming that the dynamic load models accurately and adequately represent actual system conditions in West Texas, the West-North transfer modeled in Change Case 3 is found to result in short-term voltage instability which is observed to lead to voltage collapse in the absence of reduced West-North transfer by virtue of WGR trips. The lack of WGR VRT capability is not the primary cause associated with the risk of voltage instability observed in Change Case 3 for CTG5. No other normal clearing and/or breaker failure event simulated was witnessed to pose reliability risks due to the lack of WGR VRT capability.

The impact of lower pre-fault WGR terminal voltage on the over-all WGR trips is investigated as part of Change Case 4. Special focus is placed upon the pre-fault voltages of WGRs with no VRT capability. The pre-fault WGR terminal voltage is lowered while still maintaining the transmission bus voltage within acceptable limits. Lower pre-fault WGR terminal voltages are observed to impact trips for WGRs on the margin in terms of the voltage dip magnitude vis-à-vis their under-voltage relay settings. The impact of lower pre-fault WGR terminal voltage is observed to be more pronounced on Change Cases 1 and 3 in the absence of conventional voltage support due to synchronous generation units being off-line. The incremental WGR trips by virtue of lower pre-fault terminal voltages do not pose reliability risks based on the metrics outlined above.

PB has maintained continuous and regular dialog associated with various aspects of the study with ERCOT for the entire duration of the ERCOT VRT study by means of bi-weekly conference calls. Furthermore, PB has provided ERCOT with presentation associated with each bi-weekly meeting during the study.

Disclaimer:

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3 Introduction

3.1 Objectives & Deliverables

The objectives and deliverables associated with Phase III of the Electrical Reliability Council of Texas (ERCOT) Voltage Ride-Through Capability (VRT) Study, as identified in the original Scope of Work and agreed upon by ERCOT and PB Power (PB) are as follows:

- The development of acceptable initial conditions for performing dynamic simulations for the ERCOT system based on the validated models obtained through the Phase II effort.
- The performance of dynamic simulations using the validated and updated models to assess possible system reliability risks associated with any wind power plants that do not comply with ERCOT's VRT requirements.
- The performance of similar dynamic simulations for 6 additional change cases as identified by ERCOT in consultation with PB and based on the results obtained from the High Wind High Load (HWHL) and High Wind Low Load (HWLL) cases. The additional change cases could comprise of a combination of increased stress cases and/or the implementation of appropriate mitigation measures based on the results of the HWHL/HWLL cases.
- Identification of potential reliability risks for the ERCOT system as a whole by virtue of the lack of Wind Generation Resource (WGR) VRT capability across the HWHL/HWLL and/or the additional change cases based on the reliability metrics outlined in Phase I.
- Comprehensive Phase III report identifying and documenting the results, observations and conclusions associated with the dynamic simulations. Recommendations comprising appropriate mitigation options in case of reliability risks identified for any change case and/or dynamic event.

This section of the report provides a brief overview of the modeling efforts and aspects accomplished as part of Phase II. A sub-section has been dedicated to outlining the deliverables provided to ERCOT as part of the Phase II effort. References have been provided to detailed documents and/or White Papers developed and delivered to ERCOT as part of the Phase II deliverables.

Finally, the section provides an overview of the structure of the Phase III report. The discussions presented in each of the ensuing chapters have been briefly discussed.

3.2 Phase II – Modeling Overview

While all the detailed models and associated documentation for Phase II of the ERCOT VRT study has been provided to ERCOT, it is important to outline the aspects taken into account while developing the updated WGR models utilized in Phase III. The following aspects span the data collection and/or modeling efforts performed by PB as part of Phase II of the ERCOT VRT Study:

- Development of individual VRT Data Request Forms (DRF) for each WGR in order to perform the data collection in an organized fashion and standard format. The VRT DRF was developed taking into account comments provided by ERCOT, PB and the WGRs (at the ERCOT Wind Workshop dated June 26, 2009).
- Collaboration with each WGR during the data collection process thereby assisting the WGR representatives with technical implications of various data requests and associated formats
- Validation of the data filled out in each WGR VRT DRF vis-à-vis the technical specification sheets, facility one-line diagrams, collection system layouts and machine manufacturer data to ensure accurate modeling of each WGR campus from a steady state and dynamic standpoint
- Utilization of individual WGR VRT DRFs in conjunction with custom PB software modules to develop detailed models for each WGR campus. These models include accurate representation of the following aspects associated with a detailed model for a WGR campus:
    - Accurate modeling of reactive capability of various wind turbine types
    - Accurate modeling of reactive operation/control scheme for various wind turbine types
        - Ability to distinguish between reactive capability and control amongst various types of wind turbines
            - Type of Control
            - Range of Control
            - Point of Control
    - Station Transformer Load Tap Changer (LTC) Settings
        - Tap Settings & Step Size
        - Location of the tap changer
        - Side controlled by LTC – Numerous WGR facilities locate the LTC on the high side controlling the medium voltage side to provide the

facility the ability to limit over-voltages on the turbine side especially in the presence of sub-station capacitor banks

- o Medium Voltage Capacitor Banks & Reactor Banks
    - Size
    - Type – Fixed/Discrete/Continuous
    - Control Mechanism – Manual/Automated Switching
    - Control Point & Settings – Avoid conflicts with LTC and/or turbine control
- o Accurate Detailed Collection System
    - Detailed modeling of each cable segment comprising the entire collection system was performed for each WGR campus
    - The cable type, voltage level and cable segment lengths were taken into account to determine individual cable segment impedances for each WGR campus
- o Built-in look-up table for impedances (per unit length) for all major U/G cables and/or O/H lines utilized for collection system
- o O/H line segment connecting WGR to POI was modeled with accurate parameters
- o Short Circuit Standpoint
    - X_{source} database for various turbines
    - Drastically different from the traditional Xd' & Xd'' for conventional machines
    - Grounding scheme
        - Pad-Mount transformer
        - Station Transformers

- Development of novel voltage-profile based approach to develop collector system aggregated models to be included in the comprehensive ERCOT dynamic data set. The overview of the approach is as shown below:
    - o Identify the active and reactive power losses at Point of Interconnection (POI) for detailed model utilizing a standard power flow tool
    - o Perform 3-Phase fault analysis at the POI for detailed model to identify
        - 3-Phase SCC level
        - Voltage profile at all turbine terminals within the WGR facility

- Utilize voltage profile obtained above in conjunction with voltage relay settings associated with the machine type being assessed to identify the number of collector equivalents needed to accurately represent the facility or section of the facility from a voltage response standpoint
- In case of a WGR campus comprising of more than one wind turbine type, the approach needs to be applied to each turbine type group thereby assuming a minimum number of collector system aggregated models equal to the number of wind turbine types within the campus
- Utilize MVA_{sc} approach for each identified group to develop the collector system equivalent. Details about this approach and associated calculations have been provided as Appendix to the White Paper titled *"Recommended Practices for Developing Collector System Equivalent Models for Wind Generation Resources"* authored by PB and submitted to ERCOT as part of the Phase II deliverables.
- Utilize the number of machines and pad-mounts in each group to develop the machine and pad-mount transformer equivalent for each group
- Validate the resulting collector system aggregated model from steady state standpoint:
  - Comparing the active and reactive power losses at POI between the detailed and aggregated model
  - Comparing the active and reactive power exchange with system at POI between the detailed and aggregated model
- Validate the resulting collector system aggregated model from short circuit standpoint:
  - Comparing the SCC levels for 3-Phase fault at POI between the detailed and aggregated model
  - 3-Phase faults have been focused upon since the ERCOT VRT requirements outlined in Operating Guide Section 3.1.4.6.1 are based on a 3-Phase fault at the Point of Interconnection (POI)
- Validate the resulting collector system aggregated model from a dynamic response standpoint:
  - Append the detailed collector system model to the ERCOT case on an individual basis
  - Identify 6 turbines across the WGR facility
    - 2 Up String close to sub-station
    - 2 Mid string midway to sub-station
    - 2 Down string far away from sub-station
- Perform dynamic simulations for 3-Phase fault at POI and observe the response of the detailed collector system model vis-à-vis the aggregated collector model for the following quantities:
  - P_{elec} for selected wind turbines and WGR equivalent model

   - Q_{elec} for selected wind turbines and WGR equivalent model
   - E_{term} for selected wind turbines and WGR equivalent model
   - POI Voltage and Frequency deviation for detailed collector and aggregated model

- Elaborate details, test and validation results associated with the proposed approach can be found in the White Paper titled *"Recommended Practices for Developing Collector System Equivalent Models for Wind Generation Resources"* authored by PB and submitted to ERCOT as part of the Phase II deliverables.
- Utilization of resulting collector system aggregated models to accurately and adequately reflect the detailed collector system models in the ERCOT Dynamic Data Set from a VRT standpoint.
- Development of Python-script based modules for the addition of user-defined WGR models to the ERCOT dynamic data set for developing and testing the wind flat start for the updated HWHL and HWLL cases
- Updated voltage relay settings associated with the turbine model for each WGR to reflect the updated VRT capability information obtained via the Phase II data collection process.
- Individual testing and validation of PSS/E Version 31 wind turbine models utilizing the sample PTI "savnw" case and the ERCOT HWHL/HWLL cases while observing the dynamic response associated with the following parameters of the turbine model following a system disturbance:
   - Active Power Response
   - Reactive Power Response
   - Terminal Voltage Response
   - Voltage & Frequency Response at POI
- PB worked with Siemens PTI and machine manufacturers (through WGRs) to identify and correct turbine model issues observed in PSS/E Version 31 in order to ensure a "well-behaved" ERCOT dynamic data set following the addition of all WGR models
- Unlike Phase I, no WGR models were left Gnetted out in the updated HWHL/HWLL cases developed in Phase III with the exception of a single WGR campus utilizing the Kennetech wind turbine model. The Kennetech wind turbine has been discontinued and at the time of this study, no updated models existed for this wind turbine that could be utilized with PSS/E Version 31. Additionally, it was judged that the site could be Gnetted without significantly impacting the study results.

- Development and validation of acceptable flat starts for the resulting updated HWHL and HWLL cases following the addition of all WGR models.

3.3 Phase II – Deliverables & Accomplishments

A summary of the deliverables from the Phase II effort as accomplished by PB and submitted to ERCOT has been provided below.

1. Updated ERCOT High Wind High Load (HWHL) & High Wind Low Load (HWLL) dynamic data sets

    a. ERCOT HWHL & HWLL Dynamic Data sets in PSS/E Version 31 with acceptable wind flat start including voltage relay settings for updated VRT capability for each WGR campus
    b. PSS/E Version 31 wind machine models as obtained via WGRs including detailed documentation, technical specifications and manuals
    c. Detailed & Aggregated collection system models for all ERCOT WGRs
        i. Provided in “raw” format to ensure compatibility with PowerWorld Simulator, PSS/E and ASPEN
    d. Python source codes for adding WGR models to the dynamic data sets to produce acceptable wind flat start
    e. PSS/E Version 31 Flat Start Procedural Guide
        i. Outline the utilization of modules developed by PB to develop wind flat starts in the future
        ii. Acceptable wind flat start and/or individual turbine model behavior testing and validation practices

2. Detailed & Aggregated Collector System Models for all ERCOT WGRs

    a. Detailed collector system models with all ERCOT WGRs in “pwb” and/or “raw” format
    b. White Paper on *Recommended Practices for developing collection system aggregated models for WGRs* outlining the process and guidelines in detail
    c. PowerPoint presentation for each individual WGR campus outlining the development of collection system aggregated model including model validation:
        i. Steady State Standpoint
        ii. Short Circuit Standpoint
        iii. Dynamic Response Standpoint

d. Comprehensive training session to demonstrate the collection system aggregation process to ERCOT via a web conference dated 04/05/2010
e. Documentation to serve as guideline for utilizing the VRT Data Request Forms to develop detailed collection system models for individual WGR campuses

3. Comprehensive ERCOT WGR Database

    a. Comprehensive ERCOT WGR Database in Microsoft Excel containing the following information for each WGR campus:
        i. Number & Type of wind machines
        ii. Reactive Capability, Operational & Control Scheme of wind machines at WGR campus
        iii. Sub-station Capacitor/Reactor Bank configuration and control scheme
        iv. VRT Capability Information
        v. PSS/E Model & Python Source code utilized for machines at WGR campus
        vi. Model Development & Validation details

4. Phase II WGR Data

    a. Completed VRT Data Request Forms for WGRs that provided the complete forms
    b. Collection system and/or facility one-line layouts for individual WGR campuses as submitted by WGRs
    c. Wind Machine models and associated documentation as submitted by WGRs
    d. WGR Campus Reactive Capability test data, if any as submitted by WGRs
    e. VRT Capability information and/or test data as submitted by WGRs

The resulting updated HWHL and HWLL datasets as obtained from the Phase II efforts were utilized for dynamic simulations for 65 normal clearing and 31 breaker failure events for the Phase III assessment.

3.4 Organization of Report

Following this introductory chapter, the discussion presented in Chapter 4 focuses on describing the HWHL/HWLL and the change cases developed for the Phase III assessment. The discussion includes the wind dispatch and load assumptions characterizing each of the change cases including any generation and/or transmission changes that may have been incorporated to realize the change case.

Chapter 5 presents documentation associated with the assessment of normal clearing and breaker failure events for the updated HWHL and HWLL cases. Detailed results identifying the number of WGR trips associated with each event and plots for the severe events are presented in this section. This section also presents a discussion associated with the assessment of the results for the HWHL and HWLL cases vis-à-vis the reliability metrics outlined in Phase I report.

Chapters 6 through 10 present documentation associated with the assessment of normal clearing and breaker failure events for Change Cases 1 through 5 respectively. Detailed results identifying the number of WGR trips associated with event and plots for the severe events are presented in each of these sections. Each of these sections also presents a discussion associated with the assessment of the results for the associated Change Case vis-à-vis the reliability metrics outlined in Phase I report and the observations made thereof.

Chapter 11 presents the final conclusions associated with Phase III of the ERCOT VRT study including recommendations based on mitigation measures analyzed as part of the change cases for potential reliability risks, if any. Chapter 11 also summarizes the events and change cases that seem to pose potential reliability risks and the range of technically feasible and optimal solutions assessed as mitigation measures for the identified risks.

4 Case Definitions

The discussion presented in this section provides details associated with the composition of the final updated HWHL/HWLL and the subsequent change cases utilized for dynamic simulations in Phase III. The discussion includes all modeling and/or study assumptions associated with each of the cases addressed in this section.

4.1 WGR Dataset Overview

The previous section provided an overview of the modeling efforts associated with Phase II, the resulting models from which have been utilized to develop an accurate and detailed dynamic data set for Phase III simulations. The final WGR dataset was obtained after accurate modeling and validation efforts were performed in Phase II and for which updated models have been included in the Phase III dynamic data set.

The following aspects associated with each WGR campus have been taken into account for Phase III modeling purposes from a reactive & VRT capability standpoint:

- Size & Number of Blocks/Steps associated with any external sub-station and/or collector system-based capacitor/reactor banks for each WGR campus
- Control scheme associated with any external sub-station and/or collector system-based capacitor/reactor banks for each WGR campus
- Reactive capability and control scheme associated with the turbines comprising each WGR campus including
  - Range of Control
  - Type of Control
  - Point of Control
- The turbine reactive capability was ensured to be consistent across the steady state and dynamic data set for all WGR campuses modeled.
- Detailed and aggregated collection system models associated with all WGR campuses modeled in the study
- VRT capability/option associated with turbines comprising each WGR campus

Various aspects identified above have been utilized to develop detailed and aggregated models for each WGR that accurately reflect the behavior of the facility from a steady state and dynamic response standpoint.

The ensuing sub-section provides a brief description of the dynamic load models utilized for the development of some of the change cases for Phase III dynamic simulation.

4.2 Dynamic Load Model Overview

Dynamic load models were included in specific study scenarios to assess the impact of the resulting voltage response on WGR trips by virtue of lack of WGR VRT capability in West Texas.

The load models in West Texas were focused upon since a majority of the wind farms are located in West Texas. The dynamic representation of the load in West Texas was deemed important by PB from a VRT standpoint since the active and reactive power consumption of the motor loads is highly voltage dependent which in turn impacts the voltage recovery following a dynamic event. PB deemed it important to account for the dynamics of the voltage recovery following accurate representation of the motor load dynamics in West Texas to observe the impact of the resulting voltage response on the WGR trips by virtue of the lack of WGR VRT capability.

This section provides an overview of the assumptions associated with the load model and composition utilized for Phase III dynamic simulations.

ERCOT provided PB with dynamic load model representations for three (3) footprints associated with three (3) major Transmission Service Providers (TSPs) in West Texas, namely:

- ONCOR
- American Electric Power (AEP)
- Lower Colorado River Authority (LCRA)

It should be noted that for dynamic load modeling purposes, several smaller TSPs serving load in and around West Texas were included in the ONCOR footprint. These include Rayburn Country Electric Cooperative, Brazos Electric Power Cooperative, Texas-New Mexico Power, City of Denton, City of Garland and Greenville Electric.

For the purposes of preventing numerous induction motor models at each bus corresponding to different static load ID's at each bus, all the load at each bus was aggregated together prior to performing the load splitting. Following the load aggregation at each bus into a single load, the load at each bus (if greater than 5 MW) was split into the following load categories based on the specified percentages for the bus or the area associated with the bus:

- Large Induction Motor
- Small Induction Motor
- Air Conditioning Load (AC Motor)
- Constant Impedance ZIP load

The ONCOR load models were indicative of the utilization of PSS/E WECC Induction motor model “CIMWOW” for modeling the small and large induction motor loads and the utilization of the ABB “C5LSOW” user-defined load model for the AC motor loads. The AEP load models were indicative of the utilization of the ABB “C5LSOW” user-defined load model for the small, large and AC motor loads. The representation for AEP and ONCOR loads also included assumptions that modeled load at the distribution level bus instead of the transmission level bus.

The LCRA load models were also indicative of the utilization of the ABB “C5LSOW” user-defined load model for the small, large and AC motor loads. However, ERCOT provided individual bus-based dynamic data entry associated with each bus for LCRA without the provision of any generic area and/or bus-based parameters. Furthermore, PB was provided with individual dynamic data files outlining the dynamic load models for LCRA footprint in West Texas for the high and light load conditions.

PB performed flat start tests with the dynamic data set including the dynamic load models to ensure acceptable initialization of the resulting dynamic data set including user-defined wind turbine models. The ensuing sub-section provides an overview on the HWHL/HWLL and change case compositions utilized for dynamic simulation in Phase III.

4.3 Case Definitions

4.3.1 HWHL & HWLL Cases

The Phase I report outlined the composition of the original HWHL and HWLL cases developed to serve as “base cases” for the ERCOT VRT study. No changes were made to composition of the HWHL and HWLL cases as defined in the Phase I report.

The salient features characterizing the HWHL case comprised of:

- Approximately 58,000 MW of ERCOT System load
- Approximately 4,800 MW of Wind output for West Texas
- The generation dispatch obtained in the HWHL case corresponded to an N-1 Security Constrained dispatch

The salient features characterizing the HWLL case comprised of:

- Approximately 36,000 MW of ERCOT System load
- Approximately 4,300 MW of Wind output for West Texas
- The generation dispatch obtained in the HWHL case corresponded to an N-1 Security Constrained dispatch

The primary change in the HWHL and HWLL cases going from the Phase I model to the Phase III model was the updated WGR models in terms of all the aspects described in the previous chapter. All WGRs were modeled with associated wind turbine models with the sole exception of the wind farm utilizing Kennetech turbines as identified in the previous chapter. Slight changes to the individual WGR dispatch levels were made in order to ensure proper behavior of the resulting dynamic data set. Exhibits 1 and 2 depict the individual WGR dispatch levels associated with the updated HWHL and HWLL cases respectively as utilized for Phase III.

A new model for the Siemens SMK 2.3 wind turbine allowed the use of a 1ms simulation time step and facilitated inclusion of all wind turbine models and certain equipment models (such as the Parkdale Static VAR Compensators (SVC)) in the Phase III simulation. Certain generation units in Houston were Gnetted in the HWLL dataset in order to obtain a better behaved data set for dynamic simulations following the inclusion of user-defined WGR models.

Since the generation units are in Houston, the Gnet should have no significant impact on the results of the VRT study for WGRs concentrated in West Texas.

4.3.2 Change Case 1

Change Case 1 was developed from the HWLL case by turning off the conventional units in and around West Texas. The salient features characterizing the Change Case 1 comprised of:

- Approximately 36,000 MW of ERCOT System load
- Approximately 5,100 MW of Wind output for West Texas
- No Conventional generation in West Texas

Since Change Case 1 was developed from the HWLL case, the dynamic data set changes applied to HWLL case are also applicable to Change Case 1 including the Gnet for units in Houston region. Apart from that, the DSTATCOM models associated with AEP devices at the following locations were updated in Change Case 1:

- Friend Ranch DRCS
- Beeville
- Hamilton
- Zapata
- Falfurri DRCS

Exhibit 3 depicts the individual WGR dispatch levels associated with Change Case 1 as utilized for Phase III. Certain user-defined WGR model voltage control settings were altered from controlling the transmission bus voltage to the terminal voltage to obtain better behavior of the dynamic data set in the absence of conventional generation in West Texas.

WGR Facility	HWHL Dispatch (MW)	Pmax (MW)
WGR#1	136.50	195.98
WGR#2	171.00	180.90
WGR#3	12.80	16.08
WGR#4-a	52.26	67.34
WGR#4-b	40.56	52.26
WGR#5	146.30	210.05
WGR#6	63.53	90.75
WGR#7	56.00	80.40
WGR#8-a	43.05	61.50
WGR#8-b	40.95	58.50
WGR#9	14.40	144.00
WGR#10	91.35	130.50
WGR#11	84.00	120.00
WGR#12	26.25	37.50
WGR#13	69.60	87.00
WGR#14	104.49	129.00
WGR#15	82.52	105.80
WGR#16	66.01	80.50
WGR#17	174.30	249.00
WGR#18	88.55	126.50
WGR#19	72.00	120.00
WGR#20-a	15.38	61.50
WGR#20-b	27.00	108.00
WGR#21	42.00	60.00
WGR#22	42.23	124.20
WGR#23	14.84	98.90
WGR#24	65.55	142.50
WGR#25	50.65	120.60
WGR#26	37.49	220.50
WGR#27	69.78	170.20
WGR#28	144.07	165.60
WGR#29	20.33	59.80
WGR#30-a	51.30	90.00
WGR#30-b	29.93	52.50
WGR#31	65.84	115.50

Exhibit 1: HWHL Case WGR Dispatch – Phase III

WGR Facility	HWHL Dispatch (MW)	Pmax (MW)
WGR#32	23.09	40.50
WGR#33	89.78	157.50
WGR#34	50.40	84.00
WGR#35	45.90	76.50
WGR#36	85.33	121.90
WGR#37	254.88	283.20
WGR#38-a	42.00	60.00
WGR#38-b	1.26	1.80
WGR#39	48.72	69.60
WGR#40	84.00	120.00
WGR#41	42.00	84.00
WGR#42	41.16	58.80
WGR#43	185.00	200.00
WGR#44	162.80	176.00
WGR#45	22.20	24.00
WGR#46	58.80	84.00
WGR#47	57.75	82.50
WGR#48	57.51	213.00
WGR#49	69.92	184.00
WGR#50	191.52	201.60
WGR#51	89.40	223.50
WGR#52	40.25	115.00
WGR#53	78.75	112.50
WGR#54	28.21	40.30
WGR#55	55.51	79.30
WGR#56	55.51	79.30
WGR#57	55.51	79.30
WGR#58	54.05	77.22
WGR#59	49.50	82.50
WGR#60	104.65	149.50
WGR#61	150.15	214.50
WGR#62	130.20	186.00
WGR#63	78.75	112.50
WGR#64	79.80	114.00
WGR#65	52.97	160.50
WGR#66	105.00	150.00
WGR#67-a	12.06	13.86
WGR#67-b	21.25	24.42
WGR#68	44.10	63.00
WGR#69	111.30	159.00
	5323.71	**8492.45**

Exhibit 1: HWHL Case WGR Dispatch – Phase III (Contd)

WGR Facility	HWLL Dispatch (MW)	Pmax (MW)
WGR#1	156.00	195.98
WGR#2	126.00	180.90
WGR#3	14.10	16.08
WGR#4-a	59.00	67.34
WGR#4-b	45.80	52.26
WGR#5	125.40	210.05
WGR#6	29.00	90.75
WGR#7	43.20	80.40
WGR#8-a	24.60	61.50
WGR#8-b	23.40	58.50
WGR#9	64.80	144.00
WGR#10	70.50	130.50
WGR#11	69.60	120.00
WGR#12	33.00	37.50
WGR#13	76.60	87.00
WGR#14	113.50	129.00
WGR#15	93.10	105.80
WGR#16	70.80	80.50
WGR#17	117.00	249.00
WGR#18	77.20	126.50
WGR#19	42.00	120.00
WGR#20-a	36.90	61.50
WGR#20-b	64.80	108.00
WGR#21	36.60	60.00
WGR#22	49.70	124.20
WGR#23	61.30	98.90
WGR#24	82.70	142.50
WGR#25	72.30	120.60
WGR#26	130.10	220.50
WGR#27	81.70	170.20
WGR#28	147.40	165.60
WGR#29	26.90	59.80
WGR#30-a	36.00	90.00
WGR#30-b	21.00	52.50
WGR#31	46.20	115.50
WGR#32	16.20	40.50

Exhibit 2: HWLL Case WGR Dispatch – Phase III

WGR Facility	HWLL Dispatch (MW)	Pmax (MW)
WGR#33	63.00	157.50
WGR#34	36.10	84.00
WGR#35	32.90	76.50
WGR#36	43.90	121.90
WGR#37	226.60	283.20
WGR#38-a	19.20	60.00
WGR#38-b	0.60	1.80
WGR#39	37.60	69.60
WGR#40	70.80	120.00
WGR#41	33.60	84.00
WGR#42	23.50	58.80
WGR#43	186.00	200.00
WGR#44	163.70	176.00
WGR#45	22.30	24.00
WGR#46	33.60	84.00
WGR#47	34.70	82.50
WGR#48	74.60	213.00
WGR#49	62.60	184.00
WGR#50	133.10	201.60
WGR#51	78.20	223.50
WGR#52	65.60	115.00
WGR#53	40.50	112.50
WGR#54	16.10	40.30
WGR#55	31.70	79.30
WGR#56	33.30	79.30
WGR#57	33.30	79.30
WGR#58	32.40	77.22
WGR#59	34.70	82.50
WGR#60	82.20	149.50
WGR#61	118.00	214.50
WGR#62	102.30	186.00
WGR#63	61.90	112.50
WGR#64	68.40	114.00
WGR#65	65.80	160.50
WGR#66	61.50	150.00
WGR#67-a	5.70	13.86
WGR#67-b	10.00	24.42
WGR#68	36.50	63.00
WGR#69	91.60	159.00
	4752.50	**8492.45**

Exhibit 2: HWLL Case WGR Dispatch – Phase III (Contd)

WGR Facility	Change Case 1 Dispatch (MW)	Pmax (MW)
WGR#1	156.00	195.98
WGR#2	171.00	180.90
WGR#3	14.10	16.08
WGR#4-a	59.00	67.34
WGR#4-b	45.80	52.26
WGR#5	125.40	210.05
WGR#6	29.00	90.75
WGR#7	69.60	80.40
WGR#8-a	24.60	61.50
WGR#8-b	23.40	58.50
WGR#9	64.80	144.00
WGR#10	110.90	130.50
WGR#11	102.00	120.00
WGR#12	33.00	37.50
WGR#13	76.60	87.00
WGR#14	113.50	129.00
WGR#15	93.10	105.80
WGR#16	70.80	80.50
WGR#17	117.00	249.00
WGR#18	77.20	126.50
WGR#19	48.00	120.00
WGR#20-a	36.90	61.50
WGR#20-b	64.80	108.00
WGR#21	36.60	60.00
WGR#22	105.60	124.20
WGR#23	61.30	98.90
WGR#24	82.70	142.50
WGR#25	102.50	120.60
WGR#26	189.60	220.50
WGR#27	144.70	170.20
WGR#28	60.00	165.60
WGR#29	26.90	59.80
WGR#30-a	76.50	90.00
WGR#30-b	44.60	52.50
WGR#31	98.20	115.50
WGR#32	32.40	40.50

Exhibit 3: Change Case 1 WGR Dispatch – Phase III

WGR Facility	Change Case 1 Dispatch (MW)	Pmax (MW)
WGR#33	126.00	157.50
WGR#34	44.50	84.00
WGR#35	40.50	76.50
WGR#36	103.60	121.90
WGR#37	226.60	283.20
WGR#38-a	19.20	60.00
WGR#38-b	0.60	1.80
WGR#39	60.60	69.60
WGR#40	99.60	120.00
WGR#41	71.40	84.00
WGR#42	23.50	58.80
WGR#43	80.00	200.00
WGR#44	70.00	176.00
WGR#45	10.00	24.00
WGR#46	64.70	84.00
WGR#47	45.40	82.50
WGR#48	74.60	213.00
WGR#49	62.60	184.00
WGR#50	133.10	201.60
WGR#51	78.20	223.50
WGR#52	65.60	115.00
WGR#53	81.00	112.50
WGR#54	22.60	40.30
WGR#55	44.40	79.30
WGR#56	42.80	79.30
WGR#57	42.80	79.30
WGR#58	42.50	77.22
WGR#59	34.70	82.50
WGR#60	121.10	149.50
WGR#61	173.70	214.50
WGR#62	150.70	186.00
WGR#63	85.50	112.50
WGR#64	68.40	114.00
WGR#65	65.80	160.50
WGR#66	61.50	150.00
WGR#67-a	5.70	13.86
WGR#67-b	10.00	24.42
WGR#68	36.50	63.00
WGR#69	91.60	159.00
	5469.70	**8492.45**

Exhibit 3: Change Case 1 WGR Dispatch – Phase III (Contd)

The resulting dynamic data set was tested for acceptable “wind flat start” to ensure acceptable dynamic initialization of the data set prior to running any normal clearing and/or breaker failure simulations. Details associated with the wind flat start methodology and the power system parameters monitored are discussed in detail in the *Wind Flat Start Procedural Guide* documented by PB and provided to ERCOT as part of the Phase II deliverables.

4.3.3 Change Case 2

Change Case 2 was developed from the HWHL case by incrementally adding the dynamic load model representation for all loads in West Texas. As mentioned in the previous sub-section, the dynamic load model representation spanned 3 major TSP footprints in West Texas namely ONCOR, LCRA and AEP. All details associated with the dynamic load model representation and associated assumptions have been discussed in the previous sub-section. Since Change Case 2 was developed from the HWHL case, the concentration of different load categories was corresponding to the high load conditions and was provided by ERCOT to PB. As with Change Case 1, the resulting dynamic data set was assessed for acceptable dynamic initialization following the addition of user-defined wind turbine and dynamic load models. Acceptable flat start deviations were ensured prior to running any dynamic simulations associated with Change Case 2 dynamic data set.

4.3.4 Change Case 3

Change Case 3 was derived from Change Case 1 by incrementally adding the dynamic load models associated with West Texas. Dynamic load models associated with ONCOR, AEP and LCRA were added in the same fashion as that described in the previous sub-section. However, the penetration of various load model categories was altered to reflect light load conditions since Change Case 3 is a derivative of the HWLL case.

All dynamic simulations on Change Case 3 were performed following the assessment of acceptable flat start associated with the final dynamic data set.

4.3.5 Change Case 4

The HWLL/HWHL cases and Change Cases 1 through 3 were aimed at assessing the system-wide response to specific changes made to West Texas in order to reflect optimally stressed yet reasonable system conditions. While Change Case 1 deals with assessing the impact of lack of any conventional voltage support by virtue of no conventional generation in West Texas, Change Case 2 deals with the impact of the dynamic voltage response of the motor loads in West Texas. Change Case 3, in essence, represents the most stressed condition in terms of lack of any conventional voltage support and the implementation of the dynamic load models in West Texas.

Change Case 4 is designed to assess the impact of certain modeling aspects on the ERCOT system from a VRT standpoint. In specific, the following aspects are investigated as part of Change Case 4, in order to assist ERCOT in understanding the impact of WGR modeling variations on simulation results from a VRT standpoint:

- Impact of low collector-side pre-fault voltage on WGR VRT capability and/or WGR trips, especially for wind turbine models with no VRT capability
- Impact of remote transmission bus voltage control vis-à-vis terminal voltage control on turbine voltage response

The sensitivity analysis has been performed on select severe events across HWHL/HWLL cases and Change Cases 1 through 3.

4.3.6 Change Case 5

Change Case 5 was designed to perform detailed investigation into cases and events resulting in WGR trips indicative of potential reliability risks to the ERCOT system as a whole. The following events and case combinations were investigated for Change Case 5:

- CTG5, Change Case 3

Each of these events resulted in WGR trips and/or system phenomenon that were indicative of a potential reliability risk. In-depth investigation was performed to identify the primary cause for concern and the role of lack of WGR VRT capability was assessed for these events as part of Change Case 5.

4.3.7 Change Case 6

The HWHL/HWLL cases and the Change Cases 1 through 5 are reflective of the 2009/10 topology and/or dynamic dataset as developed in 2009. Change Case 6 comprises of including the WGR models developed by PB in Phase II to an updated 2010 ERCOT dynamic data set to develop a 2010 Wind Flat Start. The objective of developing a 2010 Dynamic data set is to assess some of the severe events identified across the HWHL/HWLL cases and Change Cases 1 through 5 on the 2010 ERCOT dynamic data set from a VRT standpoint.

With a 2010 ERCOT dynamic data set yet to be provided to PB at the time of documentation of this report, the modeling assumptions, flat start assessment and results associated with Change Case 6 are not included as part of this report. The same would be furnished as an addendum to this report since the same has no major bearing on the results of the ERCOT VRT study as defined in the original Scope of Work agreed upon by PB and ERCOT.

The ensuing chapter focuses on the results associated with normal clearing and breaker failure simulations for the HWHL and HWLL cases for Phase III of the ERCOT VRT study.

5 Simulation Results – HWHL & HWLL Cases

This chapter presents the results associated with normal clearing and breaker failure dynamic simulations for HWHL & HWLL cases. The discussion presented in this chapter provides all the assumptions characterizing the normal clearing and breaker failure dynamic simulations as performed for Phase III. A brief review of the reliability metrics outlined in Phase I is also presented. Finally the results for the HWHL and HWLL cases are discussed vis-à-vis the reliability metrics to identify reliability risks associated with the lack of WGR VRT capability, if any. Dynamic simulation plots for select events are also depicted in order to better explain the phenomenon.

5.1 Dynamic Simulation – Event Definitions & Assumptions

The events utilized for normal clearing and breaker failure dynamic simulations in Phase III are the same as those identified in Phase I. As mentioned in the Phase I report, the normal clearing and breaker failure events were defined utilizing a combination of steady state screening techniques that included:

- AC Contingency Analysis
- Fault Analysis
- PV Analysis

The events were chosen in a fashion so as to exert optimal stress on the pre-identified wind farm clusters from a voltage response standpoint in order to comprehensively assess the reliability risks due to lack of WGR VRT capabilities, if any. A total of 65 three-phase fault normal clearing and 31 S-L-G fault breaker failure events were identified for dynamic simulation. Details associated with the event screening approach and methodology can be found in the Phase I report submitted to ERCOT by PB.

For reference purposes, Exhibits 4-a and 4-b depict the NERC Category for the normal clearing event definitions as determined and documented in the Phase I report.

An additional fault clearing margin was assumed for worst case situations for normal clearing events. The margin was assumed to result in all normal clearing faults being cleared at 6 cycles after the fault initiation. For investigation purposes, expected normal fault clearing times for each of the events defined in Exhibit 4 were also obtained from the concerned transmission companies.

Contingency Number	NERC Category
CTG1	D
CTG2	D
CTG3	D
CTG4	D
CTG5	D
CTG6	D
CTG7	D
CTG8	B
CTG9	D
CTG10	B
CTG11	B
CTG12	B
CTG13	B
CTG14	D
CTG15	D
CTG16	B
CTG17	B
CTG18	B
CTG19	B
CTG20	B
CTG21	D
CTG22	D
CTG23	D
CTG24	B
CTG25	B
CTG26	B
CTG27	B
CTG28	B
CTG29	B
CTG30	D
CTG31	D

Exhibit 4-a: Normal Clearing Event Definitions – Phase III Dynamic Simulations

Contingency Number	NERC Category
CTG32	D
CTG33	D
CTG34	B
CTG35	B
CTG36	B
CTG37	B
CTG38	B
CTG39	B
CTG40	B
CTG41	B
CTG42	D
CTG43	B
CTG44	B
CTG45	B
CTG46	B
CTG47	B
CTG48	B
CTG49	B
CTG50	B
CTG51	B
CTG52	B
CTG53	B
CTG54	B
CTG55	B
CTG56	B
CTG57	B
CTG58	D
CTG59	D
CTG60	B
CTG61	B
CTG62	B
CTG63	D
CTG64	B
CTG65	B

Exhibit 4-b: Normal Clearing Event Definitions – Phase III Dynamic Simulations

In the eventuality that a normal clearing event with fault cleared at 6 cycles did result in WGR trips and/or system behavior indicative of potential reliability risks, the event was simulated with the expected normal TSP fault clearing times as the primary mitigation measure. Exhibit 5 depicts the expected normal TSP fault clearing times associated with each of the 65 normal clearing events. Events for which the stations involved have more than one normal fault clearing time have also been identified in Exhibit 5.

Exhibits 6-a through 6-c depict the breaker failure event clearing times for the definitions as determined in Phase I. No such fault clearing margin was assumed for breaker failure events, with expected normal TSP primary and back-up breaker operation times being utilized for the dynamic simulations. The primary and breaker failure isolation times for each of the 31 breaker failure events have also been depicted in Exhibit 6.

5.2 Reliability Metrics

PB worked with ERCOT in identifying and defining the reliability metrics to be utilized to assess potential reliability risks associated with the lack of WGR VRT capability on the ERCOT system as a whole, if any. Elaborate discussion and rationale associated with the reliability metrics identified has been presented in the Phase I report. This sub-section provides an overview of the reliability metrics to assist putting the results for the HWHL/HWLL and the change cases in perspective. The reliability metrics outlined in Phase I for assessment of reliability risks associated with lack of WGR VRT capability are:

- Amount of wind generation (MW) tripped for each dynamic event based on the study case generation dispatch vis-à-vis ERCOT responsive reserve level (2300 MW)
- Amount of wind generation (MW) tripped for each dynamic event based on WGR capacity vis-à-vis ERCOT responsive reserve level (2300 MW)
- Acceptable system frequency response and post-event frequency deviations (no Under-Frequency Load Shedding (UFLS)) due to the amount of wind generation (MW) tripped
- Acceptable system voltage recovery and post-event voltage levels

Contingency Number	TSP Expected Normal Fault Clearing Time (Cycles)
CTG1	4
CTG2	4
CTG3	4
CTG4	4
CTG5	4
CTG6	4
CTG7	4
CTG8	4
CTG9	4
CTG10	5
CTG11	5
CTG12	5
CTG13	5
CTG14	4
CTG15	5/6
CTG16	6
CTG17	5
CTG18	6
CTG19	5
CTG20	5
CTG21	4
CTG22	4
CTG23	4
CTG24	5
CTG25	5
CTG26	5
CTG27	5
CTG28	5
CTG29	5
CTG30	4
CTG31	5/6
CTG32	5/6
CTG33	4

Exhibit 5: Expected Normal TSP Fault Clearing Times – Normal Clearing Events

Contingency Number	TSP Expected Normal Fault Clearing Time (Cycles)
CTG34	4
CTG35	4
CTG36	5
CTG37	5
CTG38	5
CTG39	5
CTG40	5
CTG41	5
CTG42	4
CTG43	5
CTG44	5
CTG45	5/6
CTG46	6
CTG47	5
CTG48	5
CTG49	5
CTG50	5
CTG51	5
CTG52	5
CTG53	6
CTG54	5
CTG55	5
CTG56	6
CTG57	6
CTG58	6
CTG59	5
CTG60	4
CTG61	4
CTG62	5
CTG63	4
CTG64	6
CTG65	6

Exhibit 5: Expected Normal TSP Fault Clearing Times – Normal Clearing Events (Contd)

Event	1st Event Time (Cycles)	BF Delay (Cycles)
BF#1	4	19
BF#2	4	19
BF#3	4	19
BF#4	4 4 5	19
BF#5	4	15
BF#6	4	15
BF#7	4	15
BF#8	5	21
BF#9	4	14
BF#10	4	14
BF#11	4	14
BF#12	4	14
BF#13	4	14
BF#14	4	15

Exhibit 6-a: Breaker Failure Event Definitions – Phase III Dynamic Simulations

Event	1st Event Time (Cycles)	BF Delay (Cycles)
BF#15	4	15
BF#16	4	15
BF#17	4	15
BF#18	4	15
BF#19	4	15
BF#20	4	15
BF#21	4	15
BF#22	5	15

Exhibit 6-b: Breaker Failure Event Definitions – Phase III Dynamic Simulations

Event	1st Event Time (Cycles)	BF Delay (Cycles)
BF#23	5	15
BF#24	5	15
BF#25	4	14
BF#26	4	14
BF#27	4	14
BF#28	4	14
BF#29	4	14
BF#30	4	14
BF#31	4	14

Exhibit 6-c: Breaker Failure Event Definitions – Phase III Dynamic Simulations

5.3 HWHL Case Results

This sub-section discusses the results associated with the High Wind High Load (HWHL) case for dynamic simulations associated with normal clearing and breaker failure events as described in the previous sub-section.

5.3.1 Normal Clearing Events

As mentioned in the previous sub-section, all normal clearing events are simulated with a fault clearing time of 6 cycles (assuming a margin of 1-2 cycles for 138/345 kV system faults). Exhibits 7-a and 7-b depict the results associated with the WGR trips for each of the 65 normal clearing events for the HWHL case.

Exhibits 7-a and 7-b depict the event, the HWHL dispatch level and capacity associated with the WGR trips for each of the 65 normal clearing events. As evident from Exhibits 7-a and 7-b, events associated with CTG9 and CTG30 result in maximum amount of WGR trips both in terms of the HWHL dispatch and the WGR capacity. CTG9 and CTG30 result in approximately 1140 MW of WGR trips as per the HWHL dispatch and 1706 MW in terms of the WGR capacity lost. The frequency deviation associated with both the events was identified to be 0.103 Hz.

To further investigate these events, both CTG9 and CTG30 were simulated with the inclusion of the Load Acting as Resource (LaaR) models to assess if the WGR trips and resulting frequency deviation initiates LaaR activation. No LaaR activation was witnessed which makes intuitive sense since the ERCOT LaaR models were indicative of the relay pick-up timer being activated only for under-frequency deviations 0.3 Hz and above. Most WGRs with no VRT capability trip during the voltage dips associated with CTG9 and CTG30.

In terms of reliability risks when assessed vis-à-vis the reliability metrics, the WGR trips for the most severe events for the HWHL case do not result in WGR trips exceeding the ERCOT RRS requirement (i.e. 2300 MW) either in terms of the case dispatch or the WGR capacity lost. As noted above, no LaaR activation is witnessed for the most severe events with the post-event frequency deviation being within acceptable levels.

No voltage recovery issues were observed and the post-event voltage levels in West Texas were deemed to be satisfactory. Exhibits 8-a through 8-d depict the plots associated with various power system quantities for dynamic simulation associated with CTG9 for the HWHL case. The higher post-event voltage level observed at 138kV buses in Exhibit 8-c is a manifestation of the turbine side and/or WGR related capacitor banks staying online even after the associated WGR has tripped. The over-voltage depicted in Exhibit 8-c would in most cases be restricted to simulation environment for the reasons mentioned above. No PSS/E crash issues were witnessed for any normal clearing event for the HWHL case.

Contingency Number	MW Tripped as per HWHL Dispatch	MW Capacity Lost
CTG1	63.74	258.00
CTG2	44.10	63.00
CTG3	398.13	800.10
CTG4	228.09	528.60
CTG5	171.00	180.90
CTG6	161.16	226.86
CTG7	182.40	251.28
CTG8	0.00	0.00
CTG9	1140.75	1706.20
CTG10	105.00	150.00
CTG11	0.00	0.00
CTG12	0.00	0.00
CTG13	65.55	142.50
CTG14	217.35	310.50
CTG15	0.00	0.00
CTG16	155.40	222.00
CTG17	610.31	991.42
CTG18	65.55	142.50
CTG19	0.00	0.00
CTG20	0.00	0.00
CTG21	0.00	0.00
CTG22	398.13	800.10
CTG23	0.00	0.00
CTG24	610.31	991.42
CTG25	65.55	142.50
CTG26	0.00	0.00
CTG27	198.60	295.50
CTG28	155.40	222.00
CTG29	0.00	0.00
CTG30	1140.75	1706.20
CTG31	0.00	0.00
CTG32	610.31	991.42

Exhibit 7-a: WGR Trips for Normal Clearing Events – HWHL Case

Contingency Number	MW Tripped as per HWHL Dispatch	MW Capacity Lost
CTG33	37.49	220.50
CTG34	70.35	100.50
CTG35	70.35	100.50
CTG36	155.40	222.00
CTG37	0.00	0.00
CTG38	0.00	0.00
CTG39	0.00	0.00
CTG40	65.55	142.50
CTG41	33.30	38.28
CTG42	79.80	114.00
CTG43	0.00	0.00
CTG44	499.29	832.82
CTG45	610.31	991.42
CTG46	610.31	991.42
CTG47	0.00	0.00
CTG48	155.40	222.00
CTG49	0.00	0.00
CTG50	0.00	0.00
CTG51	171.00	180.90
CTG52	171.00	180.90
CTG53	155.40	222.00
CTG54	610.31	991.42
CTG55	208.55	309.72
CTG56	362.60	552.72
CTG57	304.85	470.22
CTG58	610.31	991.42
CTG59	65.55	142.50
CTG60	114.39	378.60
CTG61	114.39	378.60
CTG62	0.00	0.00
CTG63	244.44	316.50
CTG64	44.10	63.00
CTG65	44.10	63.00

Exhibit 7-b: WGR Trips for Normal Clearing Events – HWHL Case

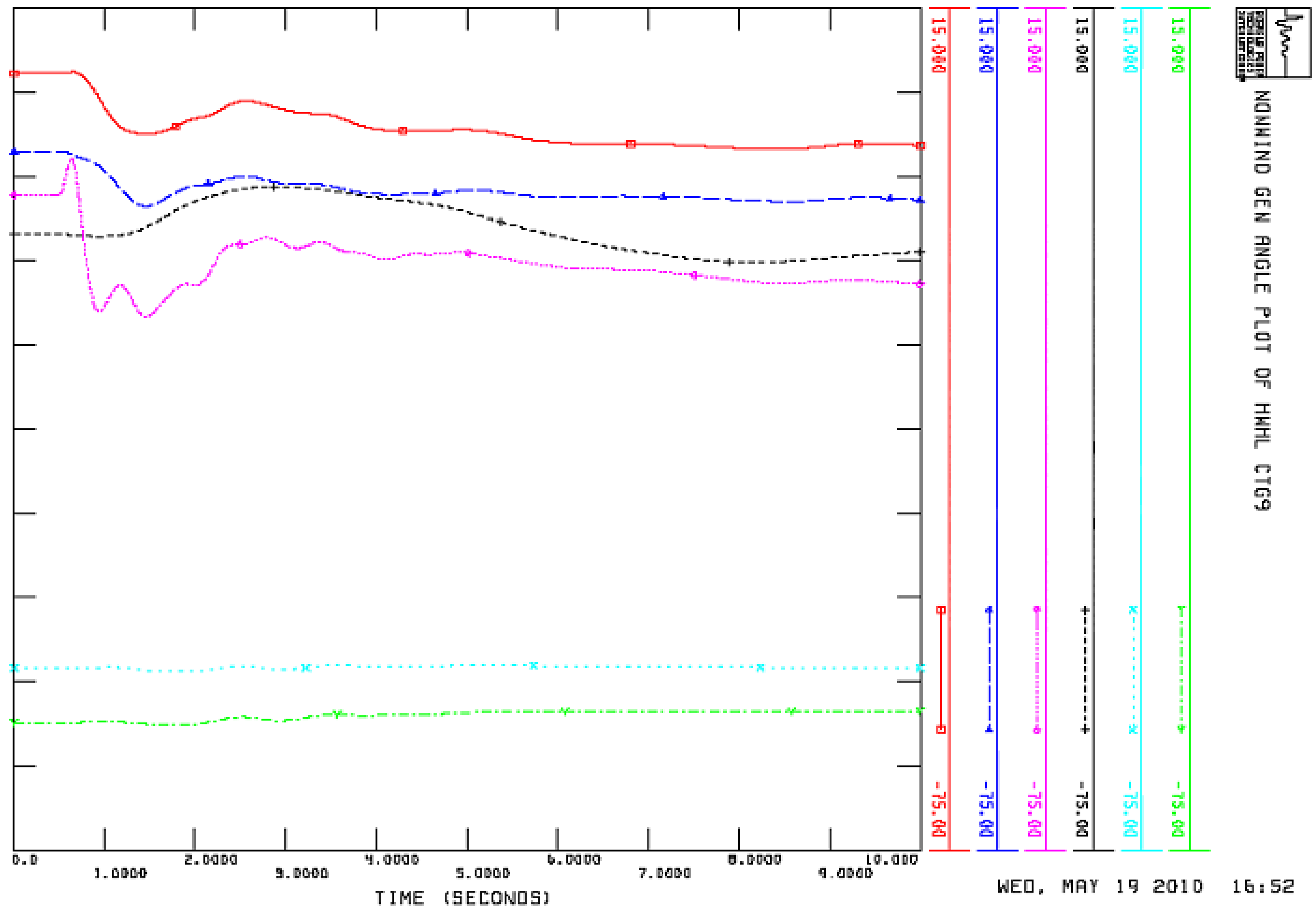

Exhibit 8-a: Rotor Angle Response for Conventional Generators for CTG9 – HWHL Case

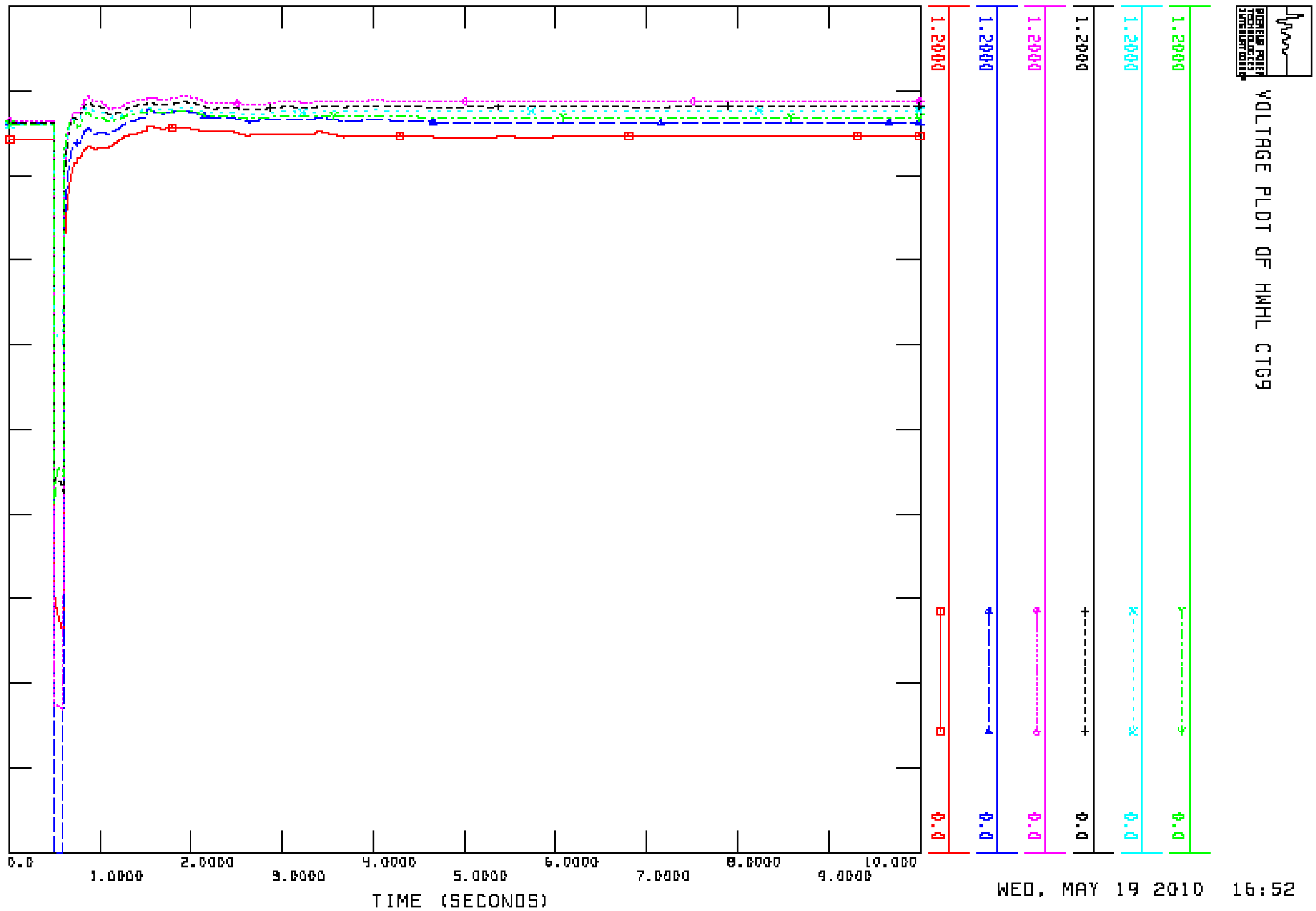

Exhibit 8-b: Voltage Response for 345 kV ERCOT West Stations for CTG9 – HWHL Case

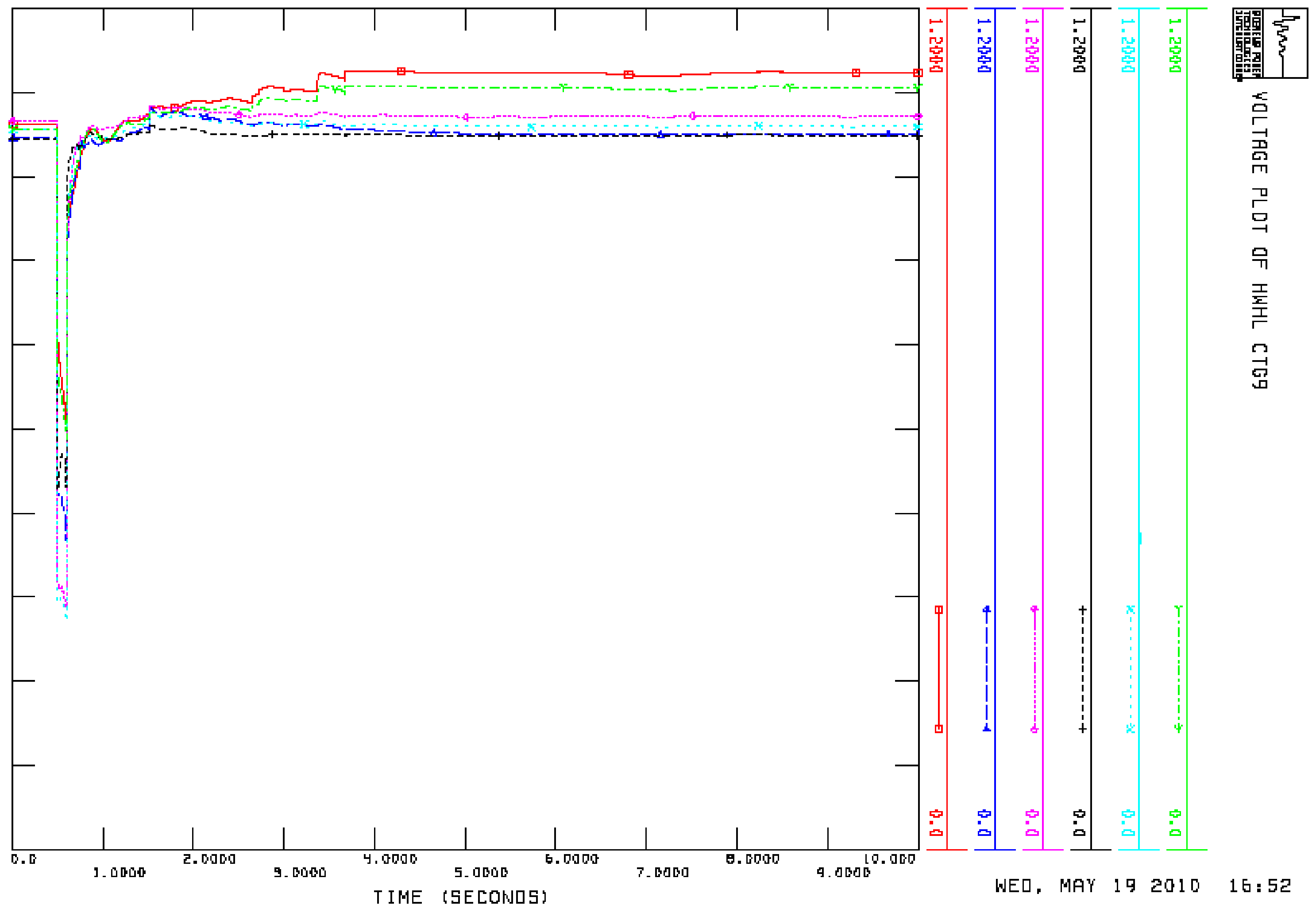

Exhibit 8-c: Voltage Response for 138 kV ERCOT West Stations for CTG9 – HWHL Case

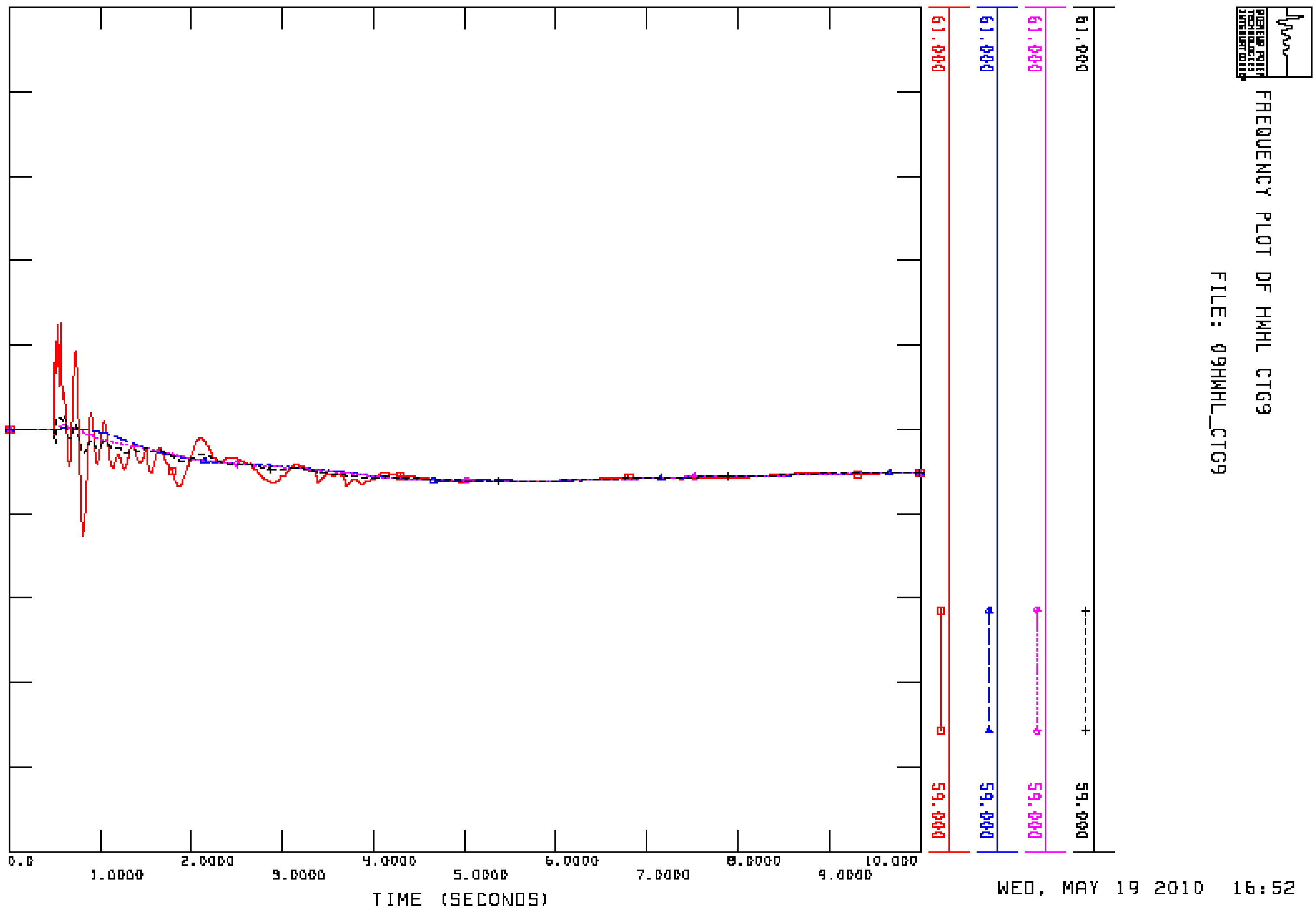

Exhibit 8-d: Frequency Response for all ERCOT Zones for CTG9 – HWHL Case

5.3.2 Breaker Failure Events

Exhibit 9 depicts the results associated with the WGR trips for each of the 31 breaker failure events for the HWHL case.

Exhibit 9 depicts the event, the HWHL dispatch level and capacity associated with the WGR trips for each of the 31 breaker failure events. As evident from Exhibit 9, none of the breaker failure events simulated seem to pose any reliability risks associated with the lack of WGR VRT capability. The most severe breaker failure event for the HWHL case is BF#8 resulting in WGR trips of approximately 514 MW as per the HWHL dispatch and 831 MW in terms of the WGR capacity lost. The frequency deviation associated with the event was identified to be 0.05 Hz. For further investigation, BF#8 was simulated with the inclusion of the LaaR models and no LaaR model activation was observed.

In terms of reliability risks when assessed vis-à-vis the reliability metrics, the WGR trips for the most severe breaker failure events for the HWHL case do not result in WGR trips exceeding the ERCOT RRS requirement (i.e. 2300 MW) either in terms of the case dispatch or the WGR capacity lost. As noted above, no LaaR activation is witnessed for the most severe events either and the post-event frequency deviation was observed to be within acceptable limits.

No voltage recovery issues were observed and the post-event voltage levels in West Texas were deemed to be satisfactory. Exhibits 10-a through 10-d depict the plots associated with various power system quantities for dynamic simulation associated with BF#8 for the HWHL case. The comment associated with over-voltage experienced at 138kV stations due to turbine side capacitor banks staying online despite the associated WGR tripping is valid for Exhibit 10-c.

No other breaker failure event out of the simulated events poses any reliability risks associated with the lack of WGR VRT capability for the HWHL case.

No PSS/E crash issues were witnessed for any breaker failure event simulated for the HWHL case.

Breaker Failure Event	MW Tripped as per HWHL	MW Capacity Lost
BF1	0.00	0.00
BF2	0.00	0.00
BF3	0.00	0.00
BF4	0.00	0.00
BF5	148.53	186.30
BF6	148.53	186.30
BF7	0.00	0.00
BF8	514.01	830.92
BF9	0.00	0.00
BF10	0.00	0.00
BF11	0.00	0.00
BF12	178.70	313.50
BF13	0.00	0.00
BF14	338.46	416.76
BF15	338.46	416.76
BF16	167.46	235.86
BF17	326.40	402.90
BF18	155.40	222.00
BF19	155.40	222.00
BF20	338.46	416.76
BF21	338.46	416.76
BF22	105.00	150.00
BF23	105.00	150.00
BF24	0.00	0.00
BF25	105.00	150.00
BF26	105.00	150.00
BF27	410.46	671.20
BF28	464.51	748.42
BF29	105.00	150.00
BF30	105.00	150.00
BF31	105.00	150.00

Exhibit 9: WGR Trips for Breaker Failure Events – HWHL Case

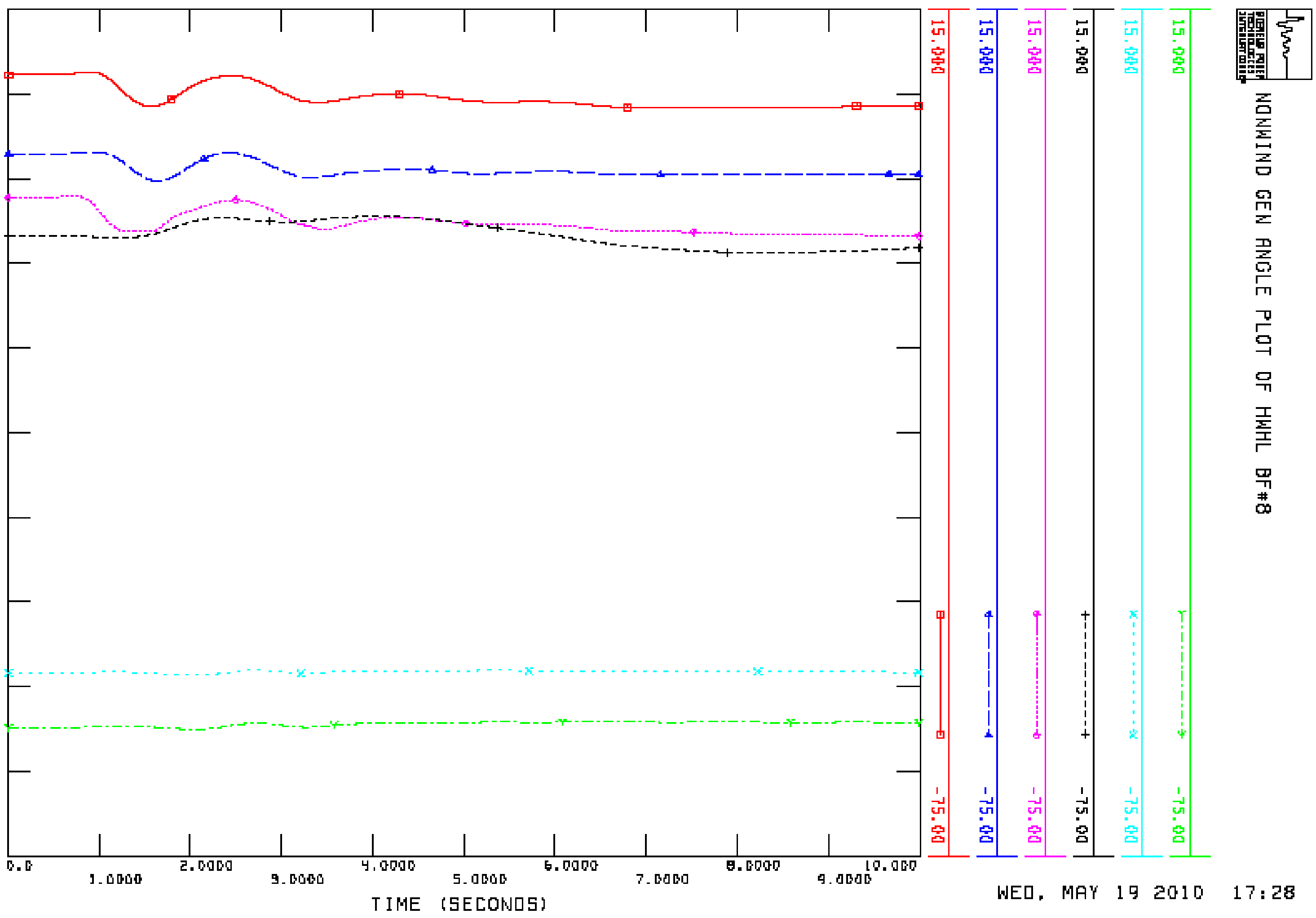

Exhibit 10-a: Rotor Angle Response for Conventional Generators for BF#8 – HWHL Case

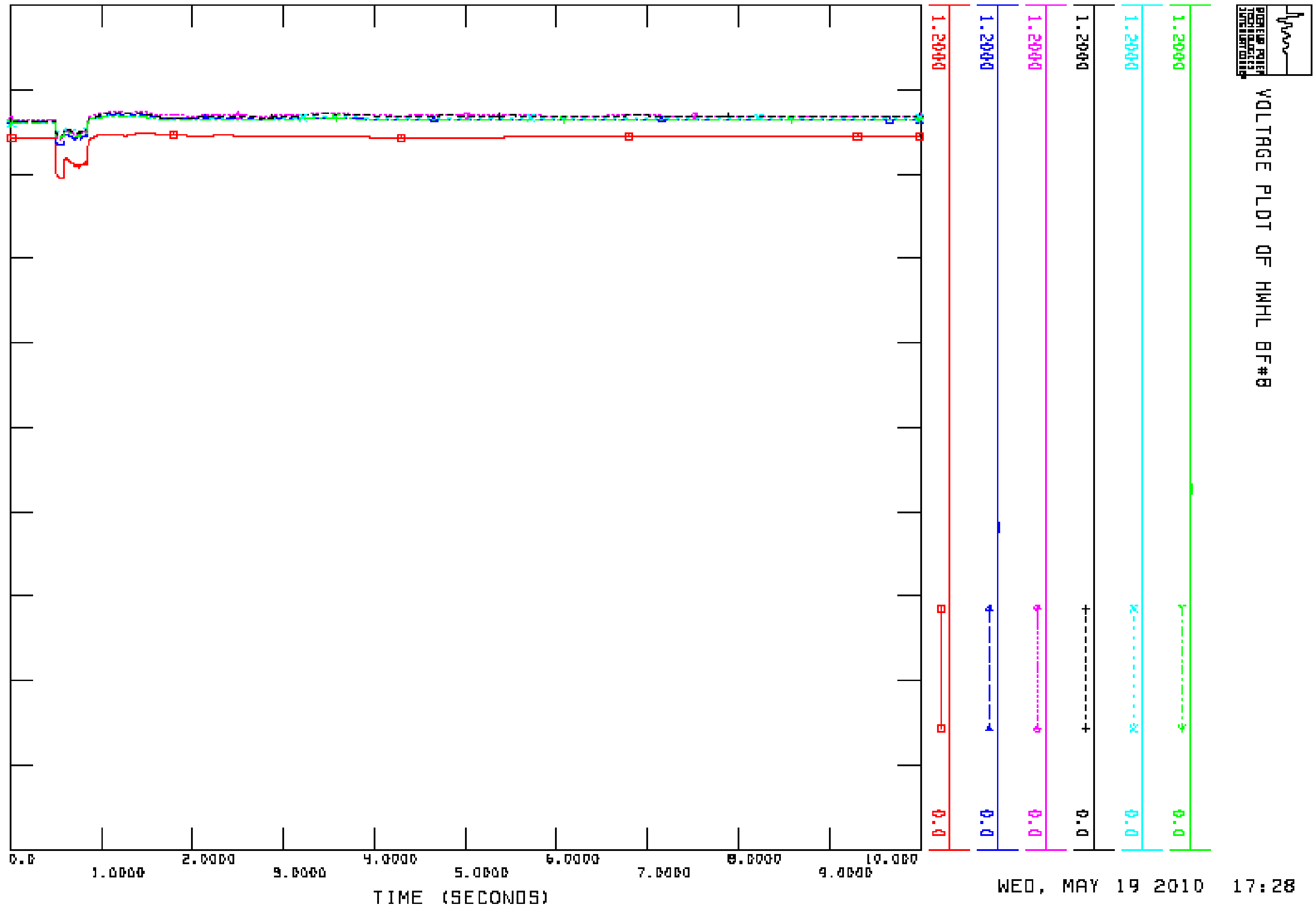

Exhibit 10-b: Voltage Response for 345 kV ERCOT West Stations for BF#8 – HWHL Case

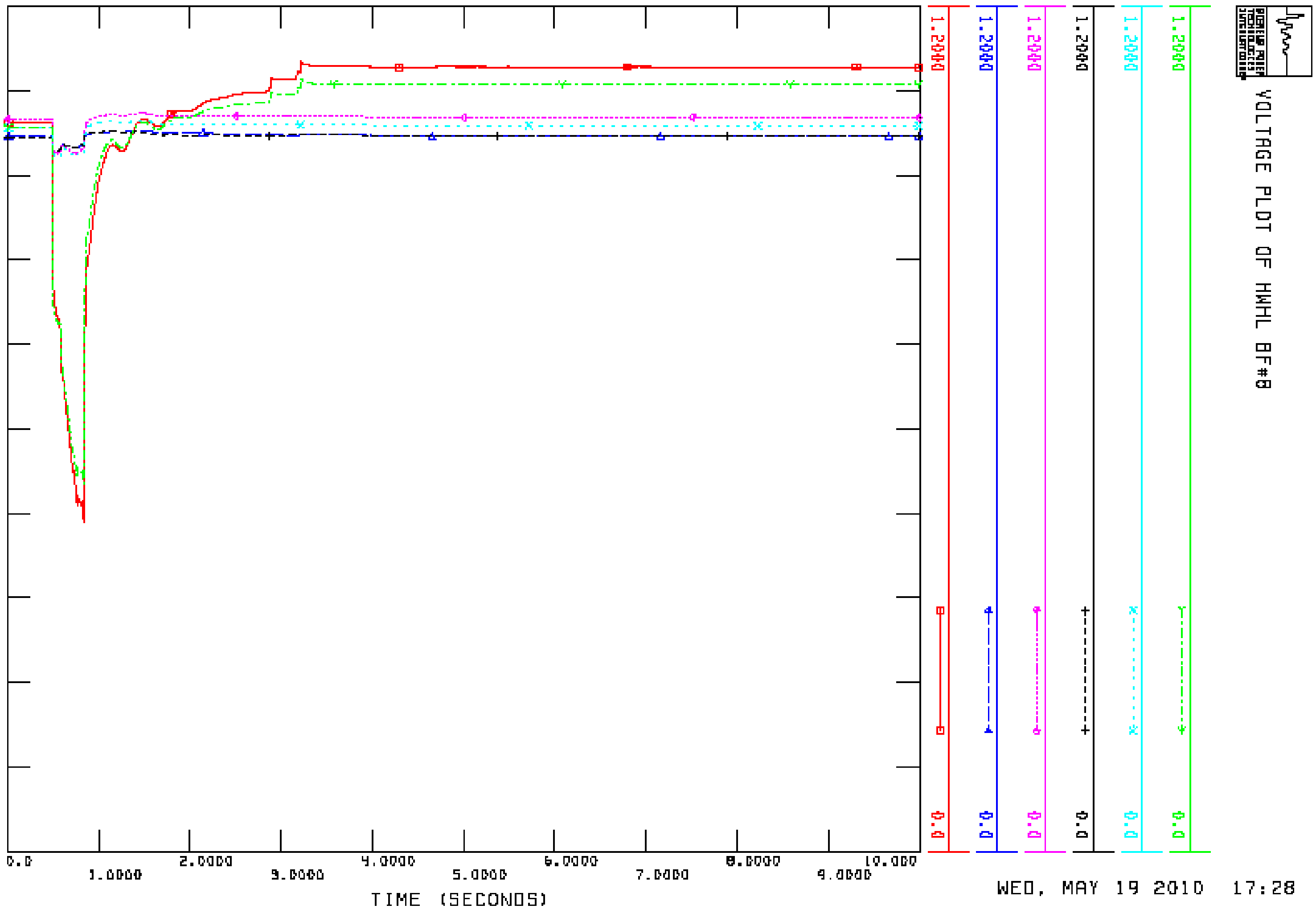

Exhibit 10-c: Voltage Response for 138 kV ERCOT West Stations for BF#8 – HWHL Case

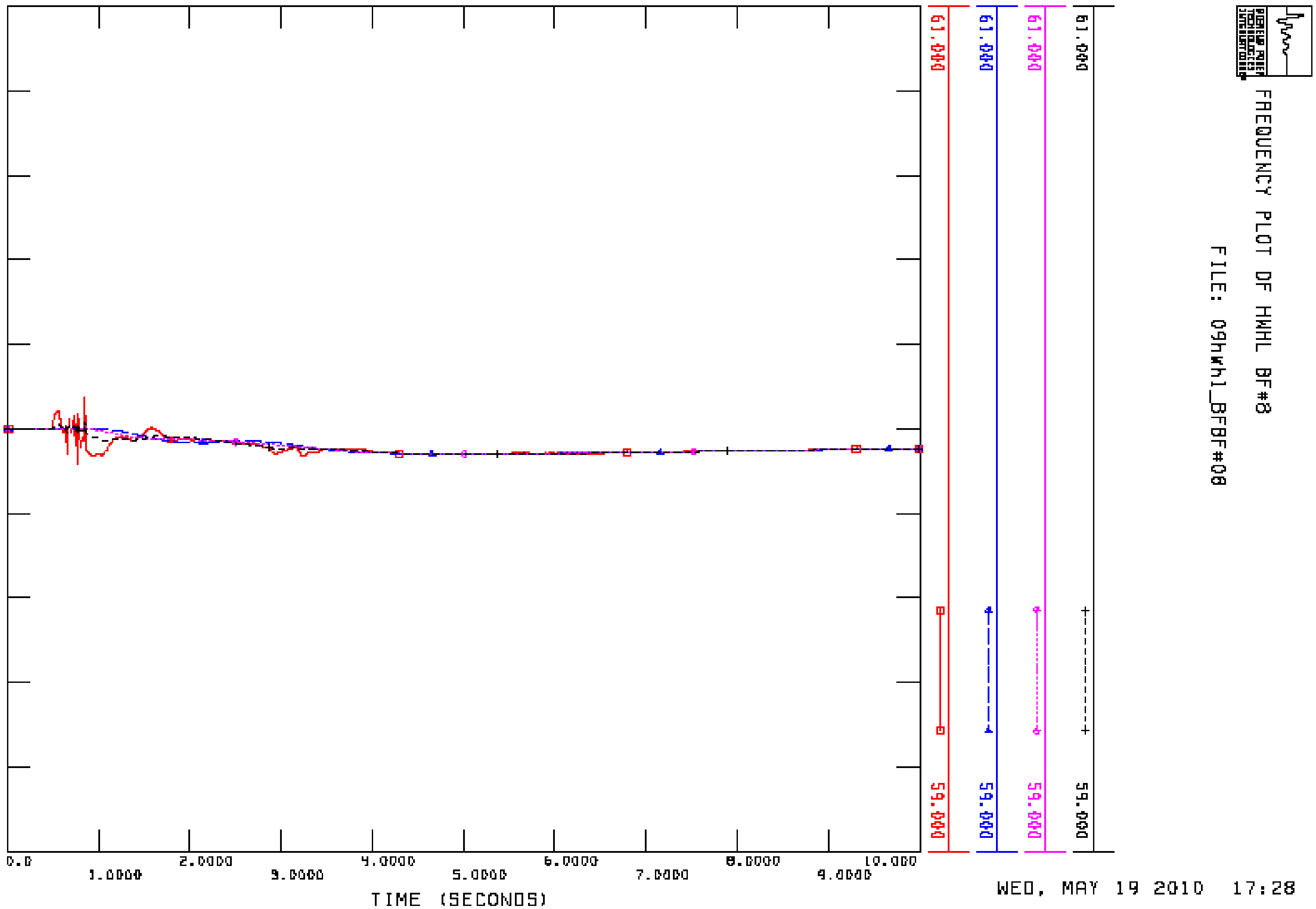

Exhibit 10-d: Frequency Response for all ERCOT Zones for BF#8 – HWHL Case

While the results associated with breaker failure events do not indicate any major reliability risks from a VRT standpoint for HWHL case, it is important to put the results in perspective. The dynamic simulation performed within PSS/E is done so purely in a positive sequence environment hence the need to specify fault shunt values describing sequence impedance parameters for unbalanced faults. This positive sequence voltage level can be easily calculated from the short circuit impedance and current values. However, if the sequence impedance and current values were utilized to calculate the faulted phase voltage level, it could be significantly lower than the positive sequence voltage.

In such a situation, it is important for ERCOT to ascertain from wind turbine manufacturers the reference associated with the under-voltage relay settings incorporating the VRT capability for various turbines. This comment is applicable for WGR trips initiated or not initiated within the PSS/E environment during the un-balanced system conditions only. This is so since PSS/E operates in a positive sequence environment from a dynamic simulation standpoint. As if often the case for S-L-G faults, the faulted phase voltage can be significantly lower than the positive sequence voltage during the period that the fault exists. Hence if the actual turbine voltage relay settings utilize the phase voltage directly to initiate WGR trips, PB deems that PSS/E may not adequately represent the initiation of WGR trips during the fault period. However, if the turbines utilize the phase voltages to determine the positive sequence voltage and the under-voltage relay settings correspond to positive sequence values then the representation of WGR trips during the fault period as obtained from PSS/E would represent actual system conditions more accurately.

5.4 HWLL Case Results

This sub-section discusses the results associated with the High Wind Low Load (HWLL) case for dynamic simulations associated with normal clearing and breaker failure events.

5.4.1 Normal Clearing Events

As in the case of HWHL, the normal clearing events for the HWLL case are also simulated with a fault clearing time of 6 cycles. Exhibits 11-a and 11-b depict the results associated with the WGR trips for each of the 65 normal clearing events for the HWLL case.

Contingency Number	MW Tripped as per HWLL Dispatch	MW Capacity Lost
CTG1	163.10	258.00
CTG2	104.90	177.00
CTG3	560.40	838.38
CTG4	354.20	542.46
CTG5	33.00	37.50
CTG6	222.80	531.00
CTG7	180.80	411.00
CTG8	0.00	0.00
CTG9	761.20	1274.70
CTG10	109.60	265.50
CTG11	0.00	0.00
CTG12	0.00	0.00
CTG13	82.70	142.50
CTG14	167.70	341.28
CTG15	0.00	0.00
CTG16	128.10	222.00
CTG17	412.50	991.42
CTG18	82.70	142.50
CTG19	0.00	0.00
CTG20	0.00	0.00
CTG21	33.00	37.50
CTG22	560.40	838.38
CTG23	77.20	188.28
CTG24	298.10	713.22
CTG25	82.70	142.50
CTG26	0.00	0.00
CTG27	144.30	348.00
CTG28	143.80	260.28
CTG29	0.00	0.00
CTG30	761.20	1274.70
CTG31	0.00	0.00
CTG32	345.90	832.82

Exhibit 11-a: WGR Trips for Normal Clearing Events – HWLL Case

Contingency Number	MW Tripped as per HWLL Dispatch	MW Capacity Lost
CTG33	130.10	220.50
CTG34	85.20	138.78
CTG35	85.20	138.78
CTG36	128.10	222.00
CTG37	0.00	0.00
CTG38	0.00	0.00
CTG39	15.70	38.28
CTG40	82.70	142.50
CTG41	15.70	38.28
CTG42	68.40	114.00
CTG43	0.00	0.00
CTG44	345.90	832.82
CTG45	298.10	713.22
CTG46	345.90	832.82
CTG47	0.00	0.00
CTG48	128.10	222.00
CTG49	0.00	0.00
CTG50	0.00	0.00
CTG51	126.00	180.90
CTG52	0.00	0.00
CTG53	128.10	222.00
CTG54	298.10	713.22
CTG55	163.30	392.22
CTG56	345.90	832.82
CTG57	232.30	552.72
CTG58	364.70	871.82
CTG59	82.70	142.50
CTG60	235.40	378.60
CTG61	235.40	378.60
CTG62	0.00	0.00
CTG63	405.40	575.28
CTG64	85.20	138.78
CTG65	120.60	215.28

Exhibit 11-b: WGR Trips for Normal Clearing Events – HWLL Case

Exhibits 11-a and 11-b depict the event, the HWLL dispatch level and capacity associated with the WGR trips for each of the 65 normal clearing events. As in the case of HWHL, CTG9 and CTG30 result in the maximum amount of WGR trips both in terms of HWLL WGR dispatch and WGR capacity lost. Both events result in 761 MW WGR trips as per the HWLL dispatch and approximately 1275 MW of WGR capacity lost by virtue of under-voltage trips for WGRs without VRT capability. The post-event frequency deviation associated with both these events for the HWLL case is about 0.08 Hz.

Both the events were re-run following the inclusion of the ERCOT LaaR models. However, no LaaR activation was observed for either event due to relatively low frequency post-event frequency deviation when compared to the LaaR model under-frequency settings. As in the case of HWHL case, most WGRs with no VRT capability trip during the voltage dip associated with CTG9 and CTG30.

In terms of reliability risks when assessed vis-à-vis the reliability metrics, the WGR trips for the most severe events for the HWLL case do not result in WGR trips exceeding the ERCOT RRS requirement (i.e. 2300 MW) either in terms of the case dispatch or the WGR capacity lost. The post-event frequency deviation was also observed to within acceptable limits.

No voltage recovery issues were observed and the post-event voltage levels in West Texas were deemed to be satisfactory. Exhibits 12-a through 12-d depict the plots associated with various power system quantities for dynamic simulation associated with CTG9 for the HWLL case.

The simulation results did not indicate any other normal clearing event simulated to pose a reliability risk stemming from the lack of WGR VRT capability for the HWLL case.

No PSS/E crash issues were witnessed for any normal clearing event for the HWLL case.

5.4.2 Breaker Failure Events

Exhibit 13 depicts the results associated with the WGR trips for each of the 31 breaker failure events simulated for the HWLL case. Exhibit 13 depicts the event, the HWLL dispatch level and capacity associated with the WGR trips for each of the 31 breaker failure events simulated.

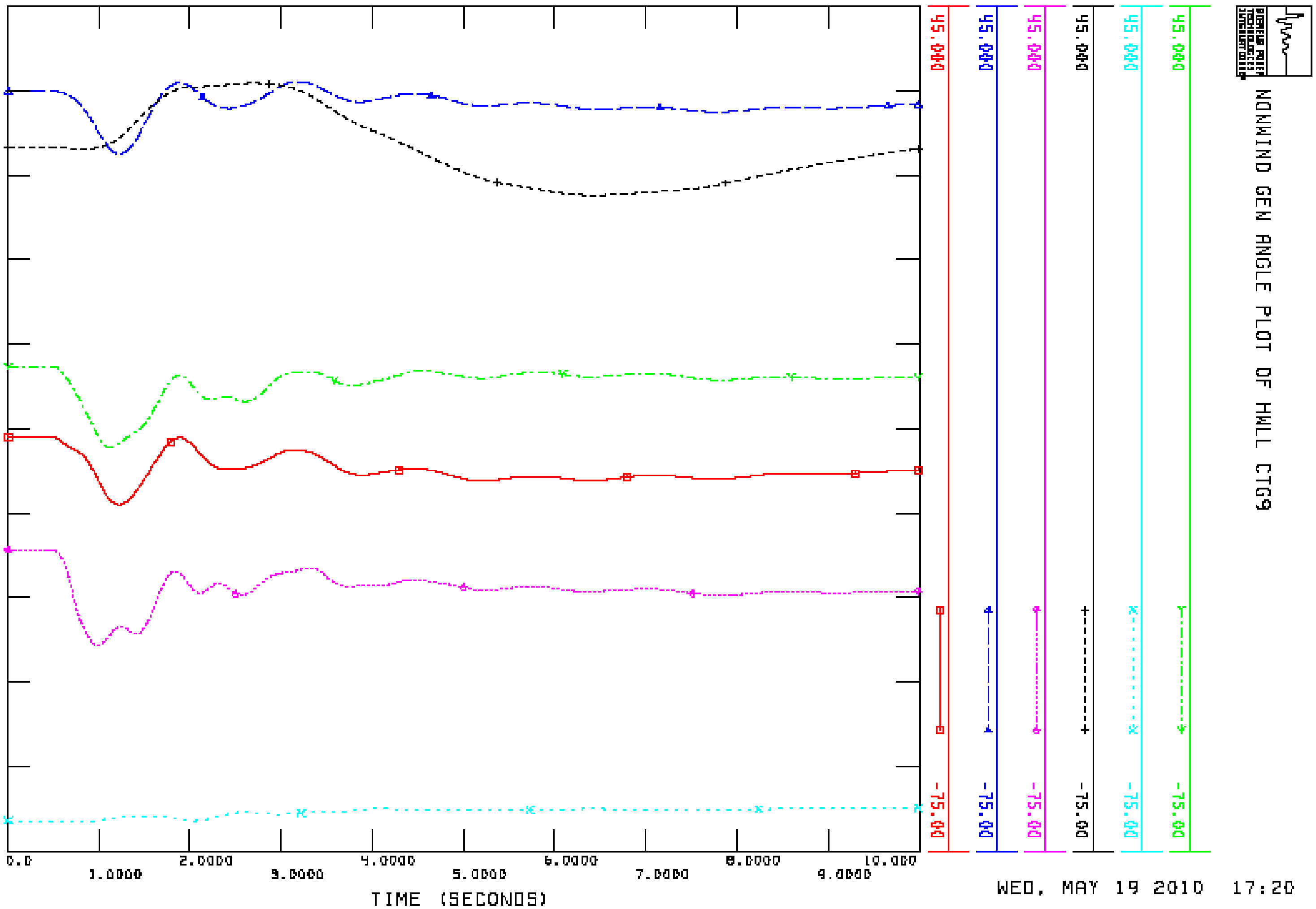

Exhibit 12-a: Rotor Angle Response for Conventional Generators for CTG9 – HWLL Case

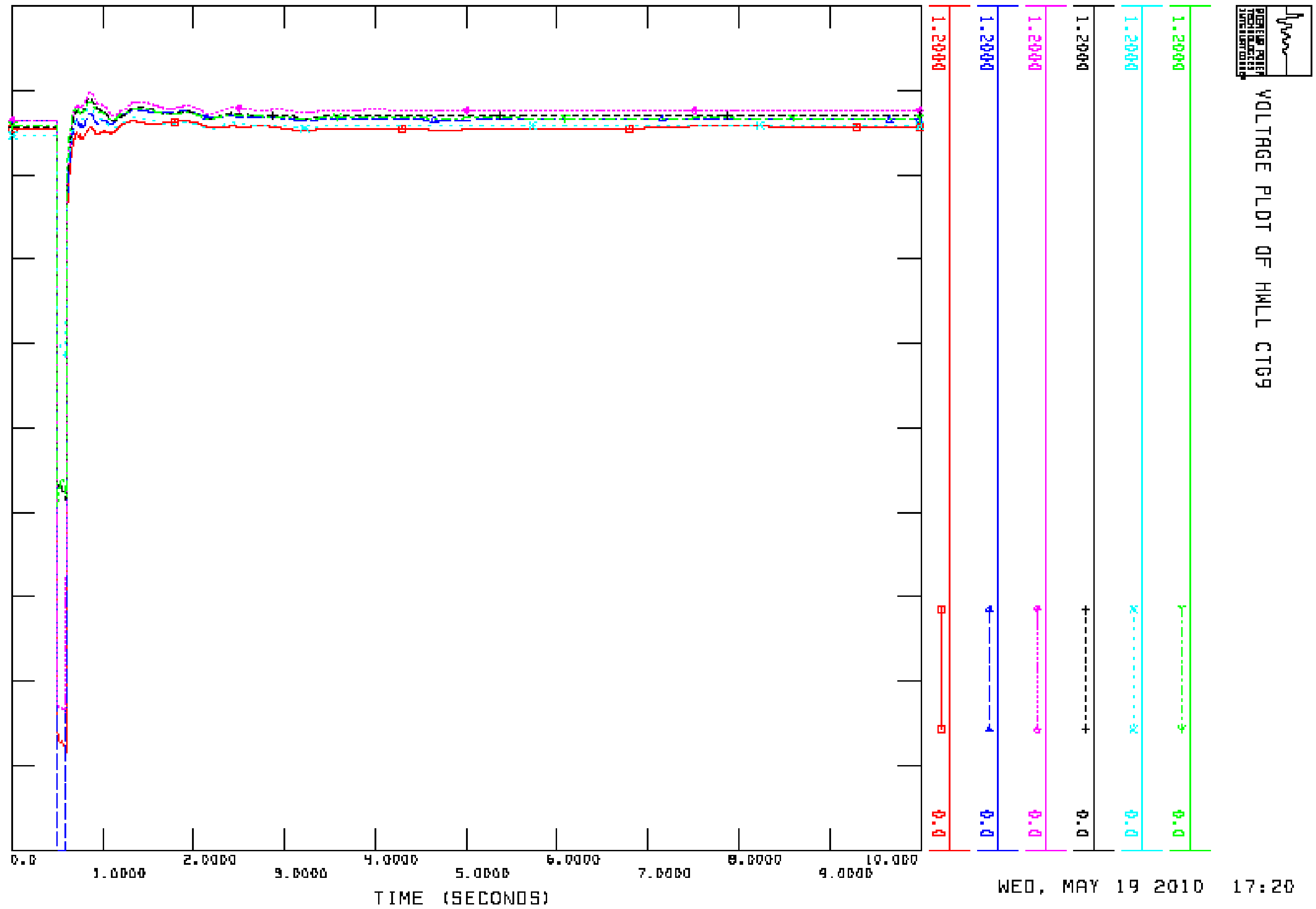

Exhibit 12-b: Voltage Response for 345 kV ERCOT West Stations for CTG9 – HWLL Case

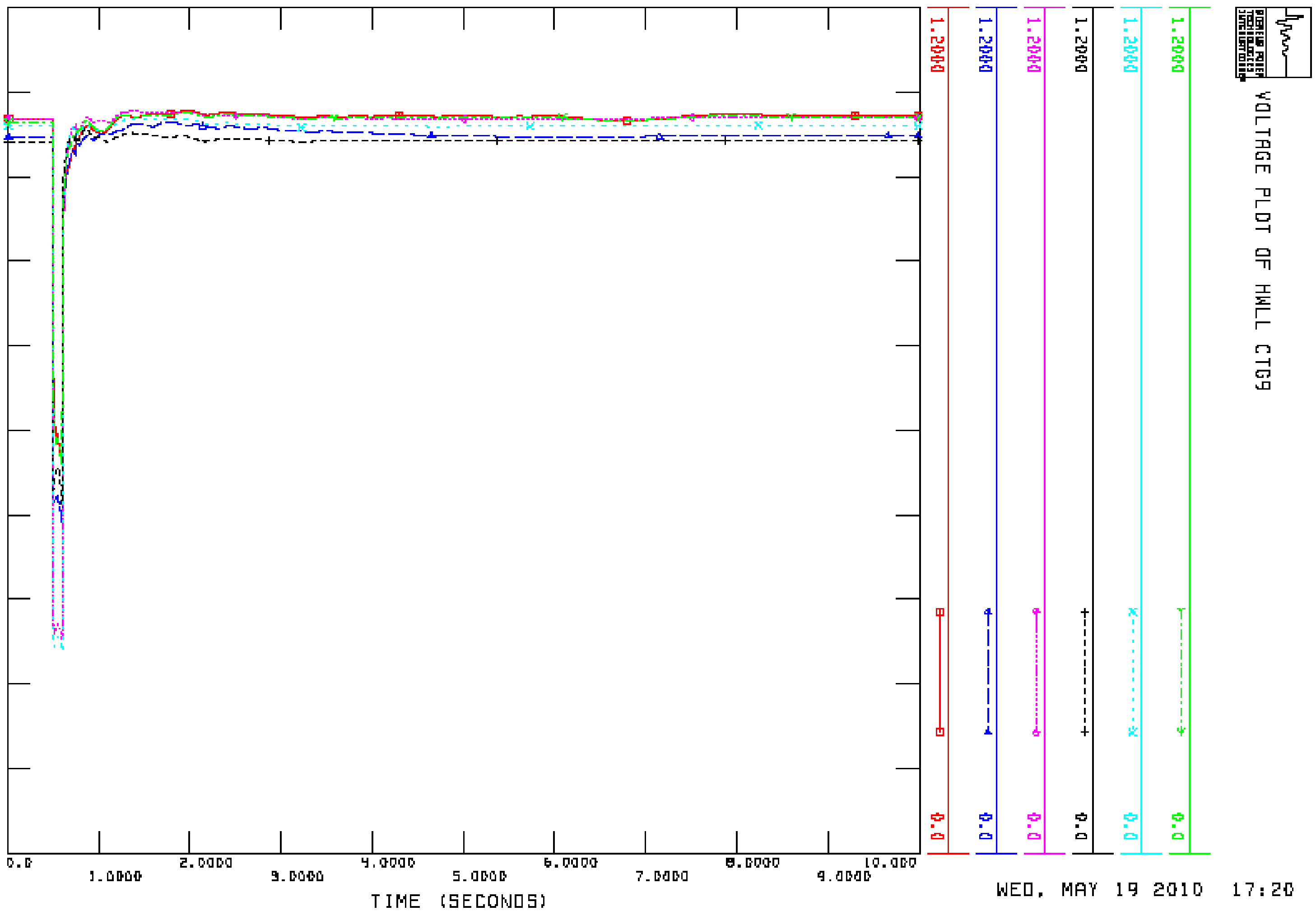

Exhibit 12-c: Voltage Response for 138 kV ERCOT West Stations for CTG9 – HWLL Case

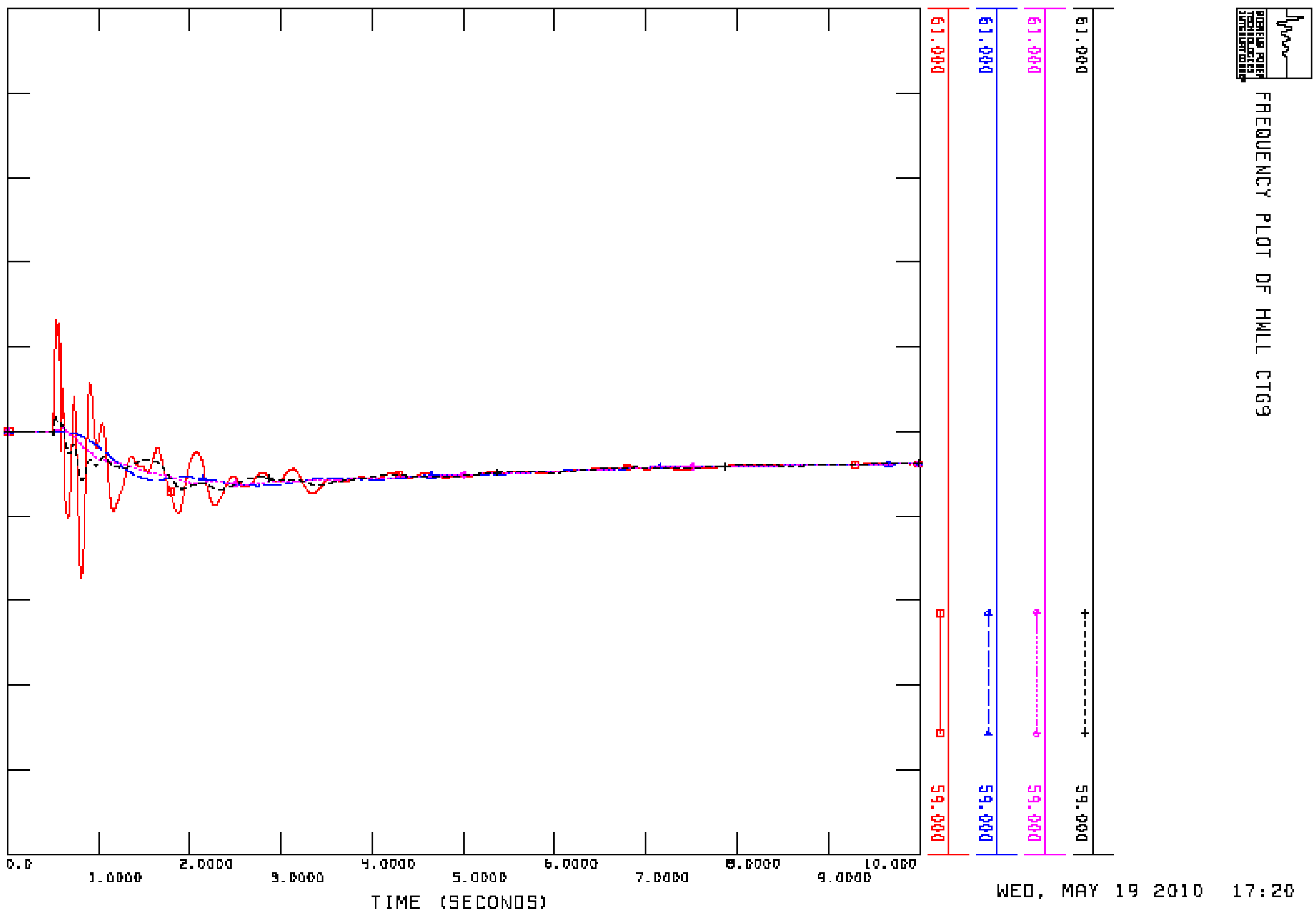

Exhibit 12-d: Frequency Response for all ERCOT Zones for CTG9 – HWLL Case

As evident from Exhibit 13, none of the breaker failure events simulated seem to pose any reliability risks associated with the lack of WGR VRT capability. The most severe breaker failure event for the HWLL case is BF#8 again resulting in WGR trips of approximately 277 MW as per the HWLL dispatch and 672 MW in terms of the WGR capacity lost. The frequency deviation associated with the event was identified to be around 0.03 Hz.

PB did not investigate potential LaaR activation for BF#8 for the HWLL case owing to the low number of WGR trips and relatively minimal frequency deviation.

In terms of reliability risks when assessed vis-à-vis the reliability metrics, the WGR trips for the most severe breaker failure events for the HWLL case do not result in WGR trips exceeding the ERCOT RRS requirement (i.e. 2300 MW) either in terms of the case dispatch or the WGR capacity lost.

No voltage recovery issues were observed and the post-event voltage levels in West Texas were deemed to be satisfactory. Exhibits 14-a through 14-d depict the plots associated with various power system quantities for dynamic simulation associated with BF#8 for the HWLL case.

No other breaker failure event simulated poses any reliability risks associated with the lack of WGR VRT capability for the HWLL case.

No PSS/E crash issues were witnessed for any breaker failure event for the HWLL case.

Breaker Failure Event	MW Tripped as per HWLL	MW Capacity Lost
BF1	0.00	0.00
BF2	0.00	0.00
BF3	68.40	114.00
BF4	0.00	0.00
BF5	163.90	186.30
BF6	163.90	186.30
BF7	0.00	0.00
BF8	276.90	672.32
BF9	0.00	0.00
BF10	0.00	0.00
BF11	0.00	0.00
BF12	125.40	313.50
BF13	0.00	0.00
BF14	143.80	260.28
BF15	143.80	260.28
BF16	143.80	260.28
BF17	143.80	260.28
BF18	143.80	260.28
BF19	143.80	260.28
BF20	143.80	260.28
BF21	143.80	260.28
BF22	61.50	150.00
BF23	61.50	150.00
BF24	0.00	0.00
BF25	127.30	310.50
BF26	127.30	310.50
BF27	127.30	310.50
BF28	127.30	310.50
BF29	127.30	310.50
BF30	175.10	430.10
BF31	175.10	430.10

Exhibit 13: WGR Trips for Beaker Failure Events – HWLL Case

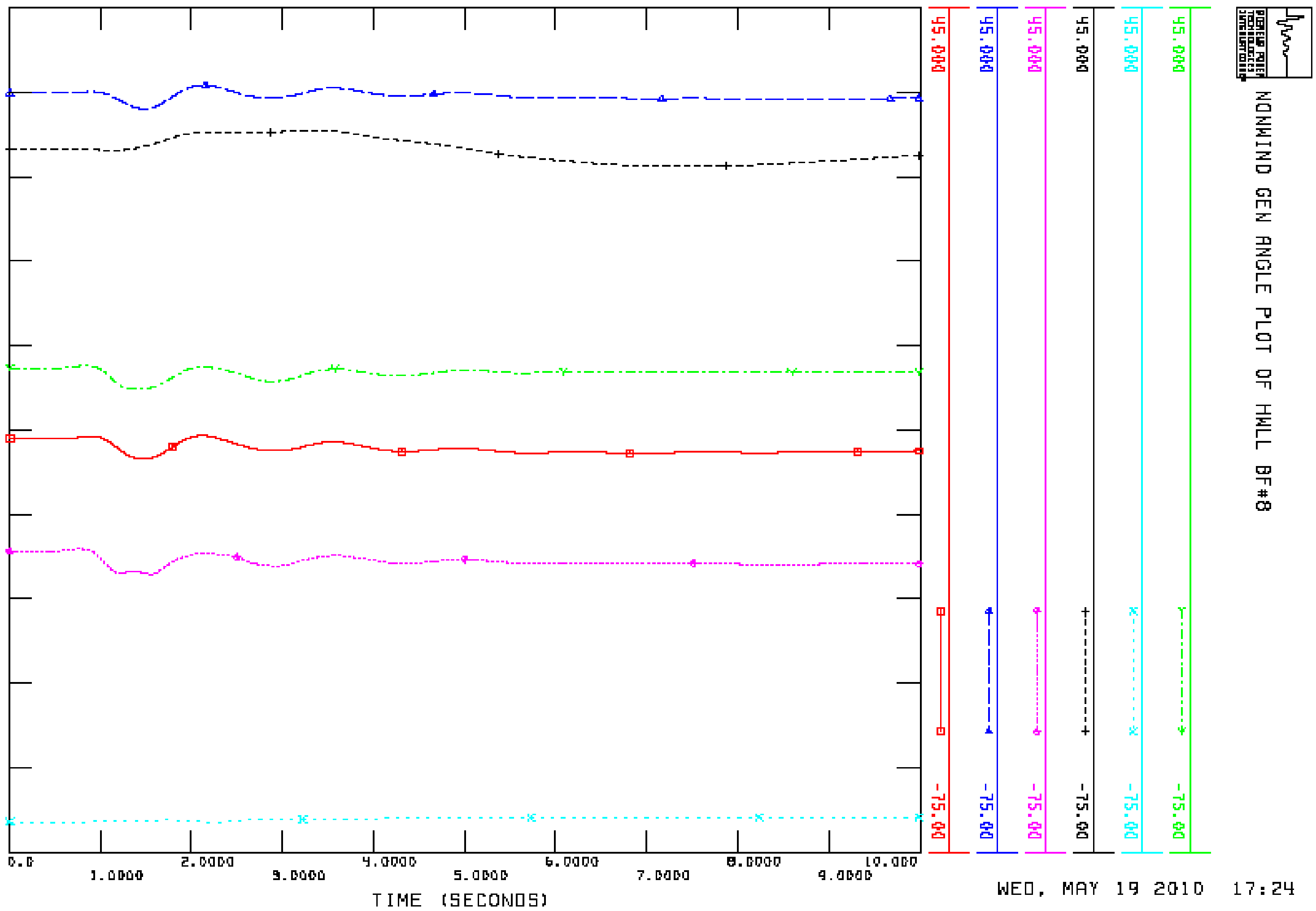

Exhibit 14-a: Rotor Angle Response for Conventional Generators for BF#8 – HWLL Case

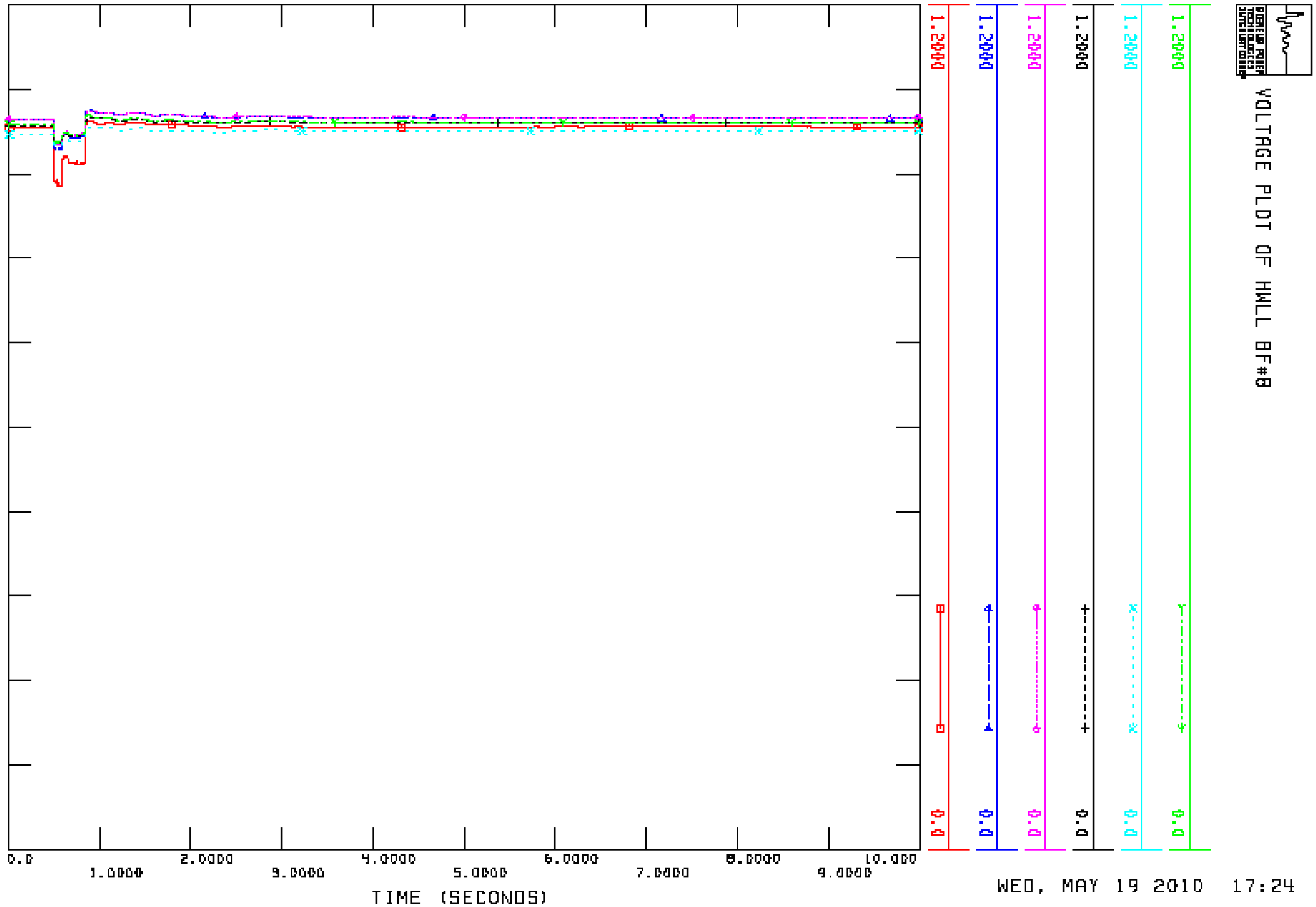

Exhibit 14-b: Voltage Response for 345 kV ERCOT West Stations for BF#8 – HWLL Case

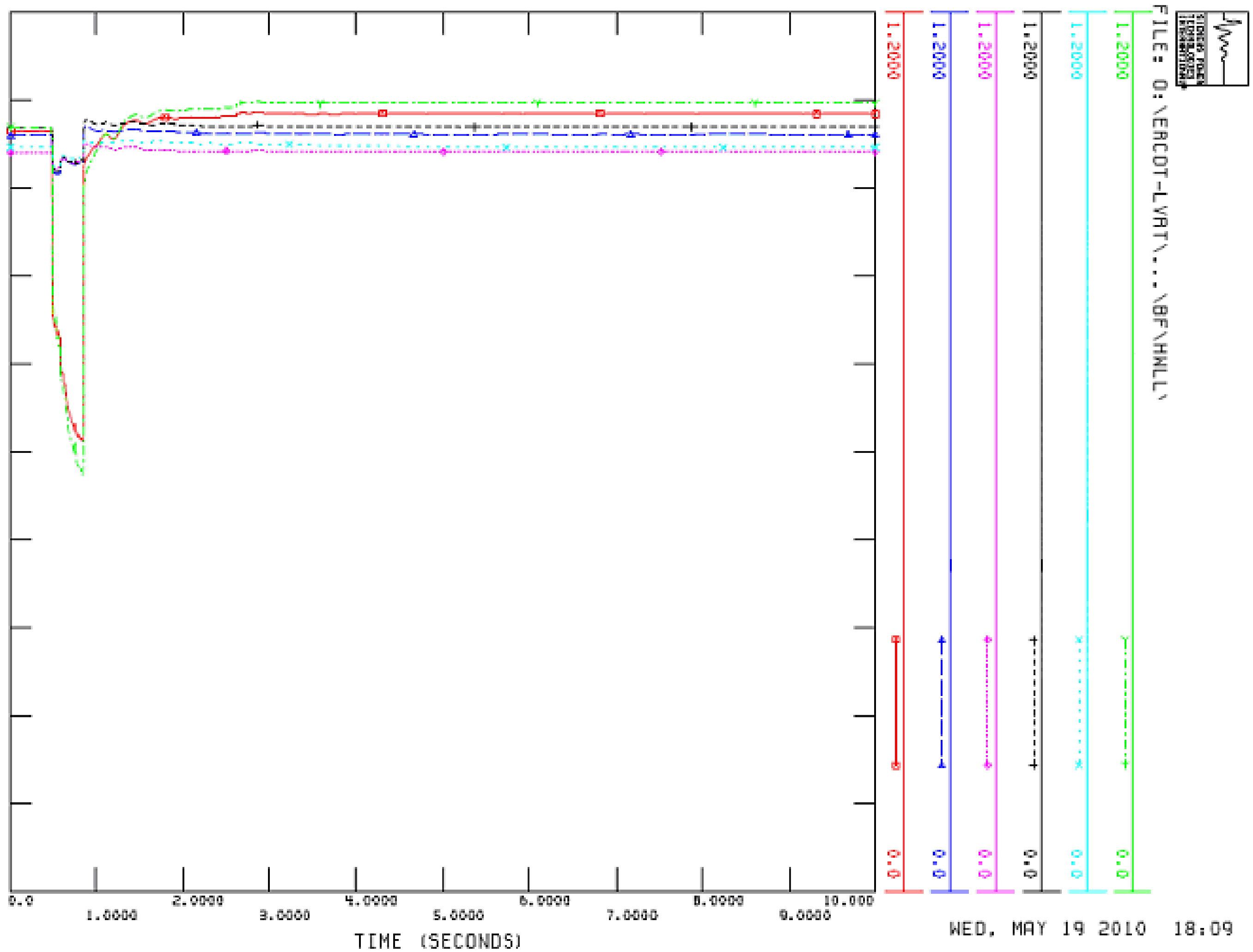

Exhibit 14-c: Voltage Response for 138 kV ERCOT West Stations for BF#8 – HWLL Case

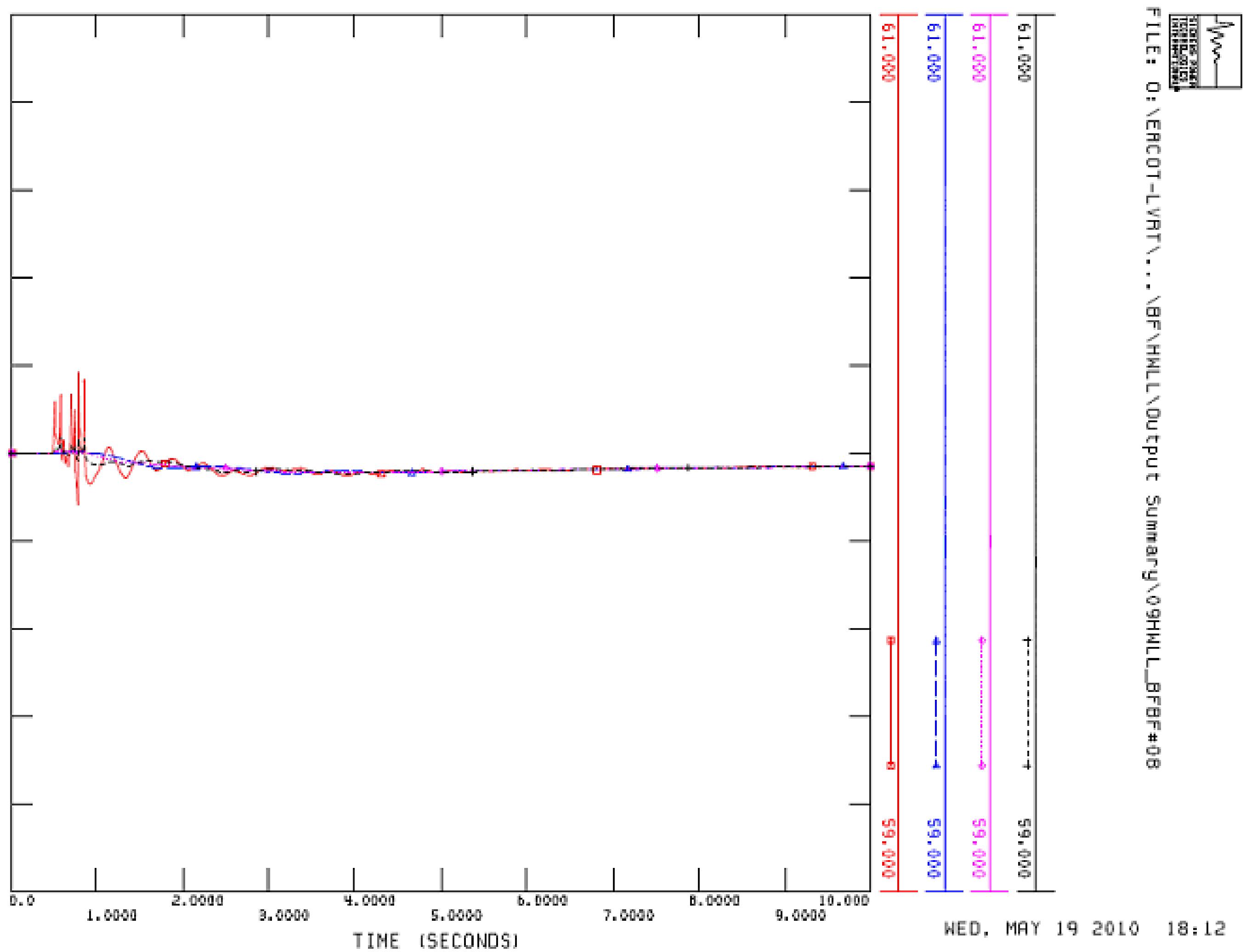

Exhibit 14-d: Frequency Response for all ERCOT Zones for BF#8 – HWLL Case

5.5 Observations

The following observations can be made from the dynamic simulation results associated with normal clearing and breaker failure events for the HWHL and HWLL cases:

- The normal clearing and breaker failure simulation results for the HWHL and HWLL cases are indicative of no reliability risks (for events simulated) associated with WGRs that may not comply with the ERCOT VRT requirements (as defined in Operating Guide 3.1.4.6.1) when assessed vis-à-vis the reliability metrics defined in Phase I and agreed upon by ERCOT. The above observation is drawn from the following:
    - No normal clearing and/or breaker failure event simulated results in WGR trips more than the ERCOT RRS requirement of 2300 MW for the HWHL/HWLL cases in terms of the case dispatch or the WGR capacity lost
    - None of the normal clearing and/or breaker failure events simulated is indicative of any LaaR activation owing to significant frequency deviations for the HWHL/HWLL case. The post-event frequency deviations are also observed to be within acceptable levels
    - No voltage recovery issues and/or post-event voltage level problems were witnessed for any normal clearing and/or breaker failure event simulated for the HWHL and HWLL cases
    - Simulations reflect wind plant performance as accurately as possible by incorporating updated wind plant models based on an extensive verification of wind plant modeling data (including wind plant VRT capability) with the WGR owners
- However, of the normal clearing events simulated, CTG9 and CTG30 present the most severe case in terms of WGR trips as per the case dispatch and the WGR capacity lost. Both events result in 1140 MW of WGR trips in terms of HWHL dispatch and 761 MW of WGR trips in terms of HWLL dispatch. In terms of WGR capacity, 1706 MW was tripped for the HWHL case and 1275 MW was tripped for the HWLL case for these events.
- All the WGR trips for normal clearing events for the HWHL/HWLL cases are based on 6 cycle fault duration. Based on the expected normal TSP fault clearing times, especially for the 345kV stations, the WGR trips may be lesser since most of the TSPs have indicated the ability to clear 345kV faults on their system within 4 cycles and 138kV faults on their system in 5 cycles.
- In terms of the breaker failure events, BF#8 is observed to be the most severe event for both the HWHL and the HWLL cases. BF#8 results in approximately

514 MW of WGR trips in terms of the HWHL dispatch and 277 MW in terms of the HWLL dispatch. In terms of WGR capacity, 831 MW was tripped for the HWHL case and 672 MW was tripped for the HWLL case for BF#8.

- It is important for ERCOT to ascertain from wind turbine manufacturers the reference associated with the under-voltage relay settings incorporating the VRT capability for various turbines. This comment is applicable for WGR trips initiated or not initiated within the PSS/E environment during the un-balanced system conditions only. This is so since PSS/E operates in a positive sequence environment from a dynamic simulation standpoint. As if often the case for S-L-G faults, the faulted phase voltage can be significantly lower than the positive sequence voltage during the period that the fault exists. Hence, if the actual turbine voltage relay settings utilize the phase voltage directly to initiate WGR trips, PB deems that PSS/E may not adequately represent the initiation of WGR trips during the fault period. However, if the turbines utilize the phase voltages to determine the positive sequence voltage and the under-voltage relay settings correspond to positive sequence values then the representation of WGR trips during the fault period as obtained from PSS/E would represent actual system conditions more accurately.

6 Simulation Results – Change Case 1

As described in Chapter 4, Change Case 1 was developed from the HWLL case by incrementally turning off conventional generation units in and around West Texas region. Additionally, the West Texas wind dispatch was scaled up from 4300 MW in the HWLL case to approximately 5100 MW in Change Case 1. In essence, the conditions modeled in Change Case 1 are representative of high wind conditions in the absence of any conventional voltage support and/or system inertia by virtue of the lack of conventional units in West Texas. The entire set of sixty five (65) normal clearing and thirty one (31) breaker failure events was simulated for Change Case 1 in order to assess the risk associated with lack of WGR VRT capability in the absence of conventional generation units in West Texas.

6.1 Normal Clearing Events

This sub-section discusses the results associated with the Change Case 1 for dynamic simulations associated with normal clearing events.

6.1.1 6 cycle fault duration

As in the case of HWHL/HWLL case, all the normal clearing events were first simulated with a 6 cycle fault duration (assuming a 1-2 cycle clearing margin for 345/138 kV system faults) to assess worst case situations in terms of WGR trips. Exhibits 15-a and 15-b depict the results associated with 65 normal clearing events with a 6 cycle fault duration for Change Case 1.

As evident from Exhibit 15, results associated with the following events are indicative of potential reliability risks to the ERCOT system as a whole:

- **CTG5**
    - WGR Trips as per Change Case 1 Dispatch – 2959.6 MW
    - WGR Trips as per Capacity – 4989.7 MW
- **CTG21**
    - WGR Trips as per Change Case 1 Dispatch – 1673.5 MW
    - WGR Trips as per Capacity – 2601.4 MW

Contingency Number	MW Tripped as per Change Case 1	MW Capacity Lost
CTG1	340.30	462.00
CTG2	366.40	518.28
CTG3	803.20	1147.38
CTG4	821.70	1197.38
CTG5	2959.60	4989.70
CTG6	348.30	730.50
CTG7	381.30	768.00
CTG8	0.00	0.00
CTG9	1309.20	2188.80
CTG10	190.90	411.00
CTG11	0.00	0.00
CTG12	82.70	142.50
CTG13	82.70	142.50
CTG14	618.00	884.28
CTG15	0.00	0.00
CTG16	128.10	222.00
CTG17	487.50	991.42
CTG18	82.70	142.50
CTG19	61.50	150.00
CTG20	0.00	0.00
CTG21	1673.50	2601.40
CTG22	883.20	1347.38
CTG23	113.70	251.28
CTG24	334.90	713.22
CTG25	82.70	142.50
CTG26	0.00	0.00
CTG27	256.70	571.50
CTG28	143.80	260.28
CTG29	15.70	38.28
CTG30	1229.20	1988.80
CTG31	0.00	0.00
CTG32	487.50	991.42

Exhibit 15-a: WGR Trips for Normal Clearing Events (6 cycle fault duration) – Change Case 1

Contingency Number	MW Tripped as per Change Case 1	MW Capacity Lost
CTG33	366.40	518.28
CTG34	618.00	884.28
CTG35	618.00	884.28
CTG36	128.10	222.00
CTG37	0.00	0.00
CTG38	0.00	0.00
CTG39	15.70	38.28
CTG40	82.70	142.50
CTG41	52.20	101.28
CTG42	643.20	876.04
CTG43	0.00	0.00
CTG44	401.90	832.82
CTG45	334.90	713.22
CTG46	487.50	991.42
CTG47	0.00	0.00
CTG48	128.10	222.00
CTG49	0.00	0.00
CTG50	0.00	0.00
CTG51	171.00	180.90
CTG52	171.00	180.90
CTG53	128.10	222.00
CTG54	401.90	832.82
CTG55	184.10	392.22
CTG56	487.50	991.42
CTG57	487.50	991.42
CTG58	420.50	871.82
CTG59	82.70	142.50
CTG60	361.60	441.60
CTG61	361.60	441.60
CTG62	0.00	0.00
CTG63	712.90	1041.18
CTG64	427.90	668.28
CTG65	427.90	668.28

Exhibit 15-b: WGR Trips for Normal Clearing Events (6 cycle fault duration) – Change Case 1

Of the 2 events identified above, CTG5 is of special concern since the WGR trips exceed the ERCOT RRS of 2300 MW both in terms of WGR dispatch and the WGR capacity lost. The over-all frequency deviation associated with the event is about 0.3 Hz. Based on all these observations, CTG5 does present a reliability risk for 6 cycle fault duration. Exhibits 16-a through 16-d depict the plots for various power system quantities for CTG5 assuming a 6 cycle fault duration for Change Case 1. CTG5 has also been highlighted in Exhibit 15-a since the simulation crashes prior to the entire 10 sec duration. The LaaR models were not implemented due to PSS/E crashing within the first few seconds of the simulation.

A closer look at the voltage plots associated with various 345 and/or 138kV stations in West Texas for CTG5 indicate an imminent voltage collapse assuming a 6 cycle fault duration which is primarily avoided due to reduced West-North transfer by virtue of the large amount of WGR trips. The voltage plots depicted in Exhibits 16-b and 16-c are clearly indicative of the inability of resulting transmission system (after the loss of transmission circuits characterizing CTG5) to handle the West-North transfer modeled in Change Case 1. The situation seems to be exacerbated due to the absence of any conventional generation in West Texas thereby preventing any dynamic voltage support to the system during and immediately after the event. The second voltage dip identified in Exhibits 16-b and 16-c is accompanied with frequency swings in West & North regions that are out of phase or "out-of-step" with each other.

While some of the wind turbines not possessing VRT capability do trip by virtue of under-voltage trips, a majority of the WGRs employing a specific Type III machine trip by virtue of over-frequency due to the large frequency swing in the West following the isolation of that part of the ERCOT system. The behavior of the system as indicated in the plots in Exhibits 16-a through 16-d seems to suggest the problem stemming from the West-North voltage stability limit for CTG5 in the absence of conventional generation units in West Texas. The reliability risk associated with this event cannot be attributed to the lack of WGR VRT capability primarily due to the following reasons:

- While the event witnesses numerous WGR trips, a majority of the trips are by virtue of over-frequency due to the large un-inhibited frequency swing in West Texas. There could be a few likely explanations associated with the exaggerated frequency swing observed for CTG5 for Change Case 1. The phenomenon and associated causes are explored in detail in Change Case 5.
- The number of WGR trips during or immediately after the fault are not substantial. The initiation of the second voltage dip occurs after the loss of transmission circuits comprising CTG5 due to the inability of the resulting transmission system to handle the West-North transfer levels modeled in Change Case 1.

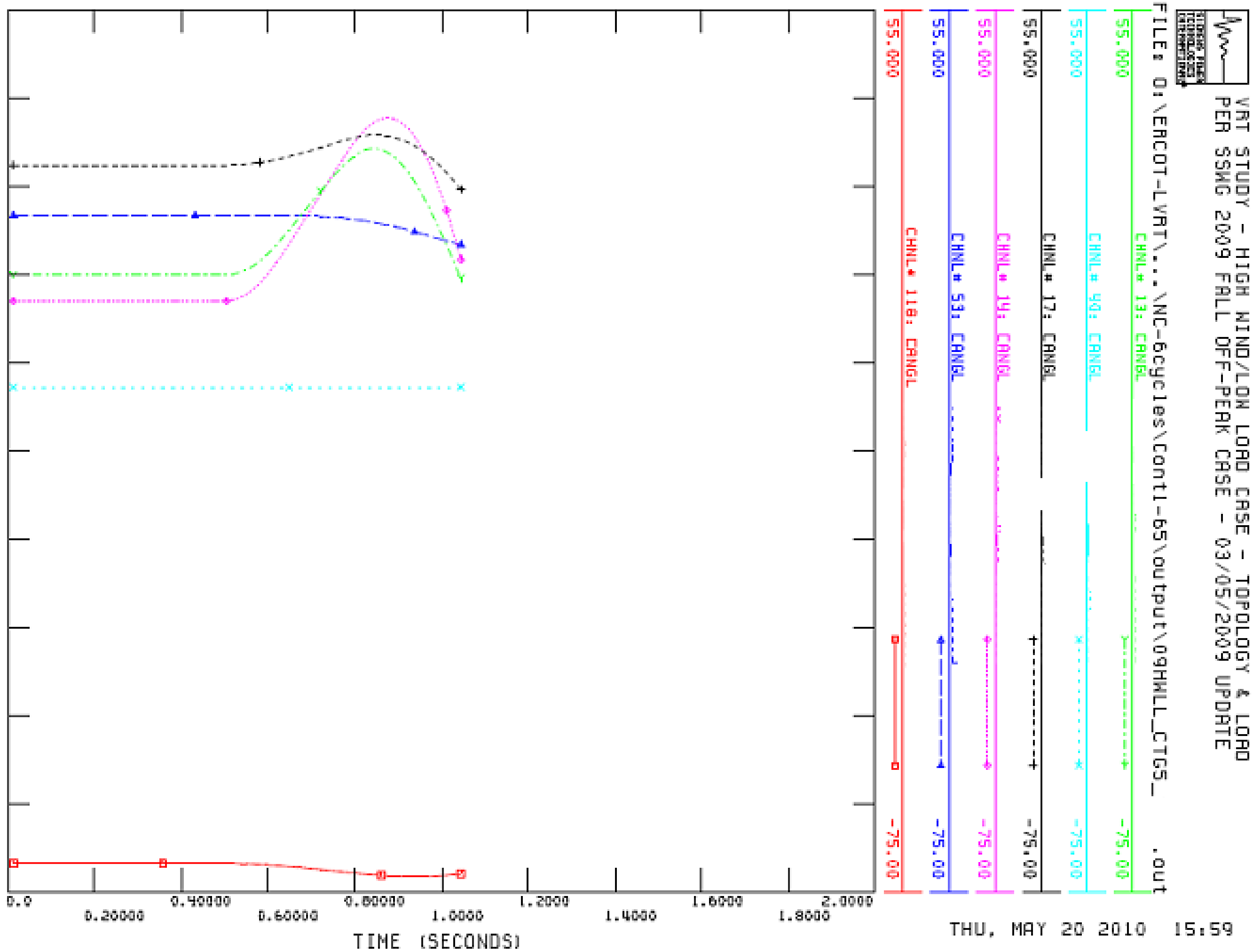

Exhibit 16-a: Rotor Angle Response for Conventional Generators for CTG5 (6 cycle fault duration) – Change Case 1

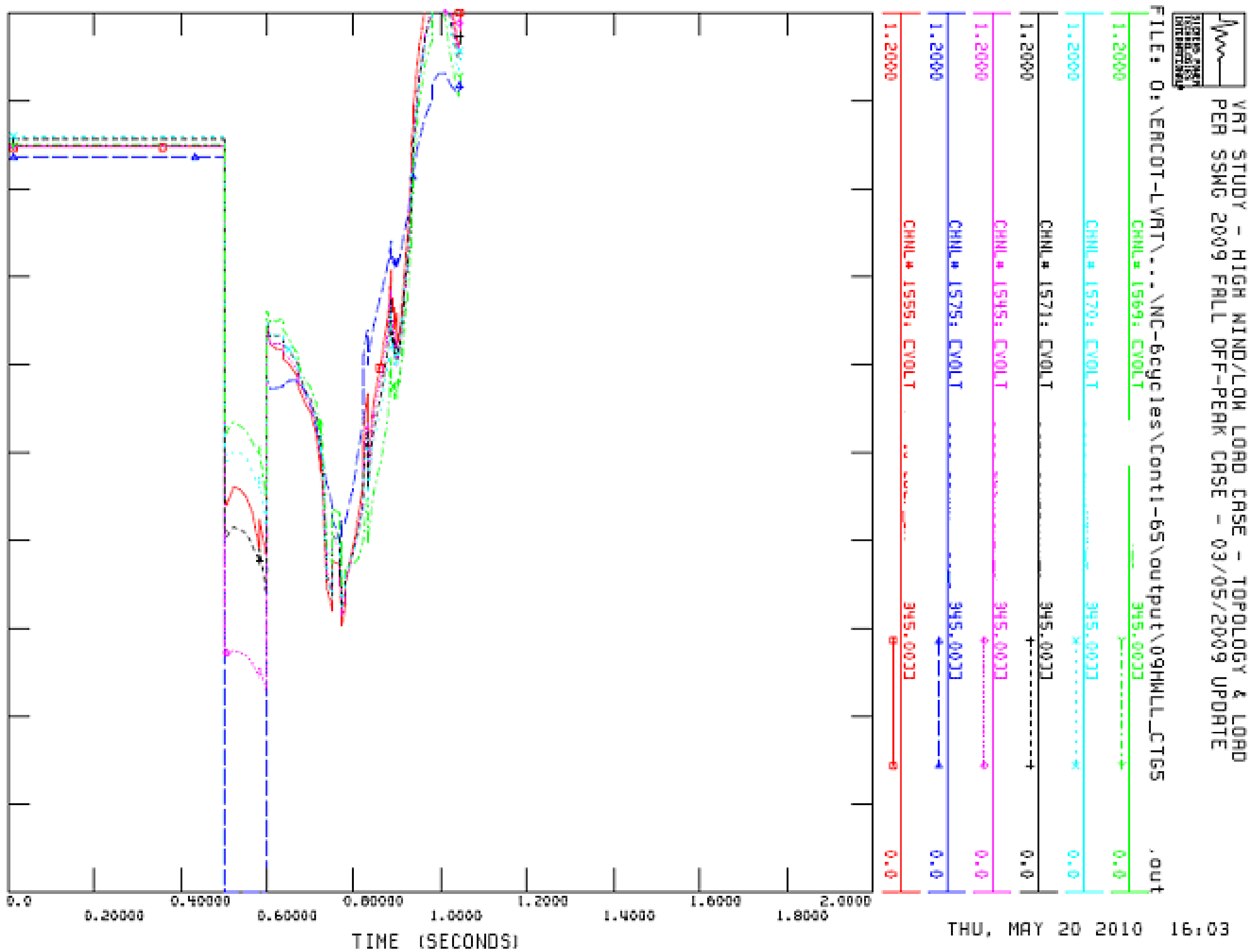

Exhibit 16-b: Voltage Response for 345 kV ERCOT West Stations for CTG5 (6 cycle fault duration) – Change Case 1

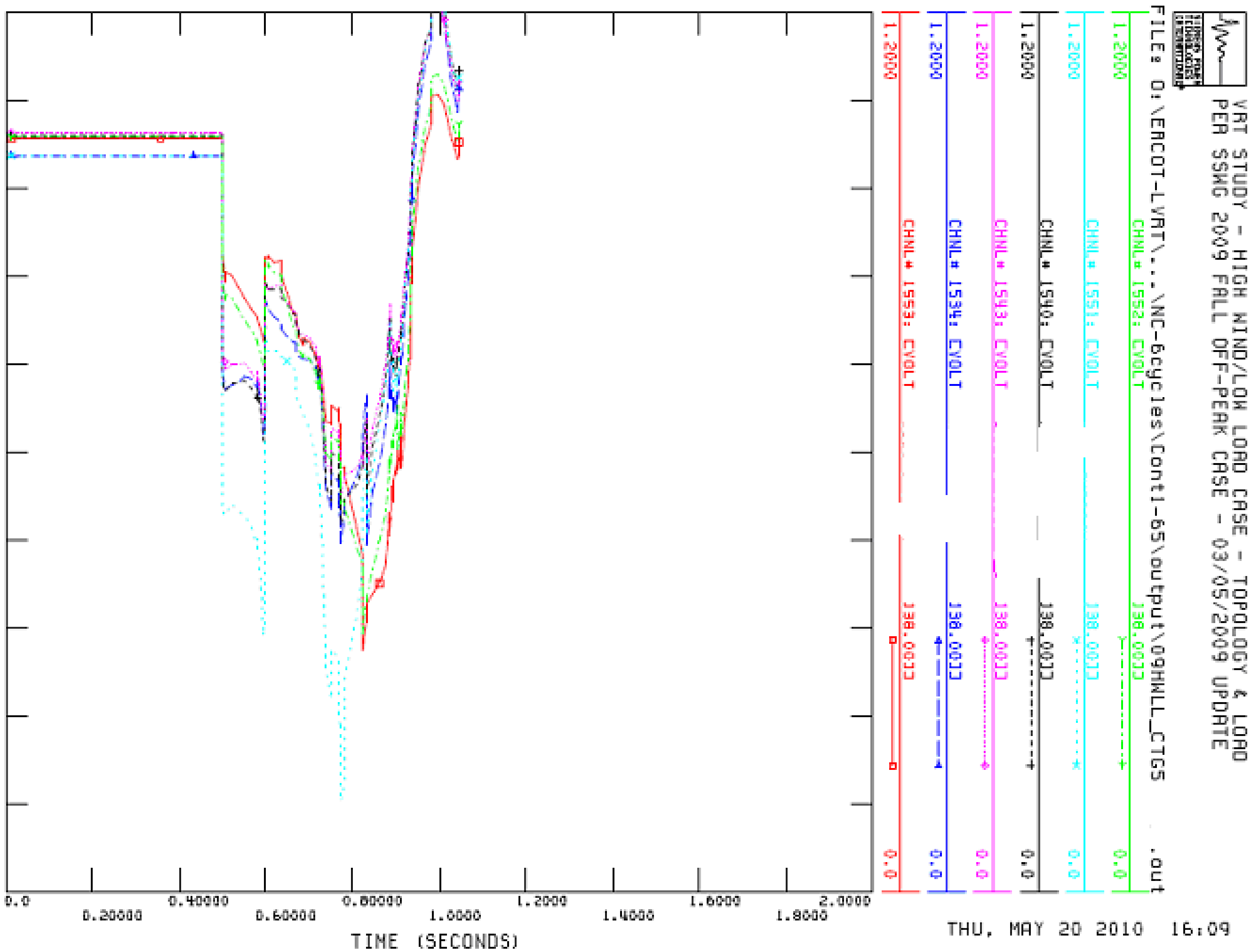

Exhibit 16-c: Voltage Response for 138 kV ERCOT West Stations for CTG5 (6 cycle fault duration) – Change Case 1

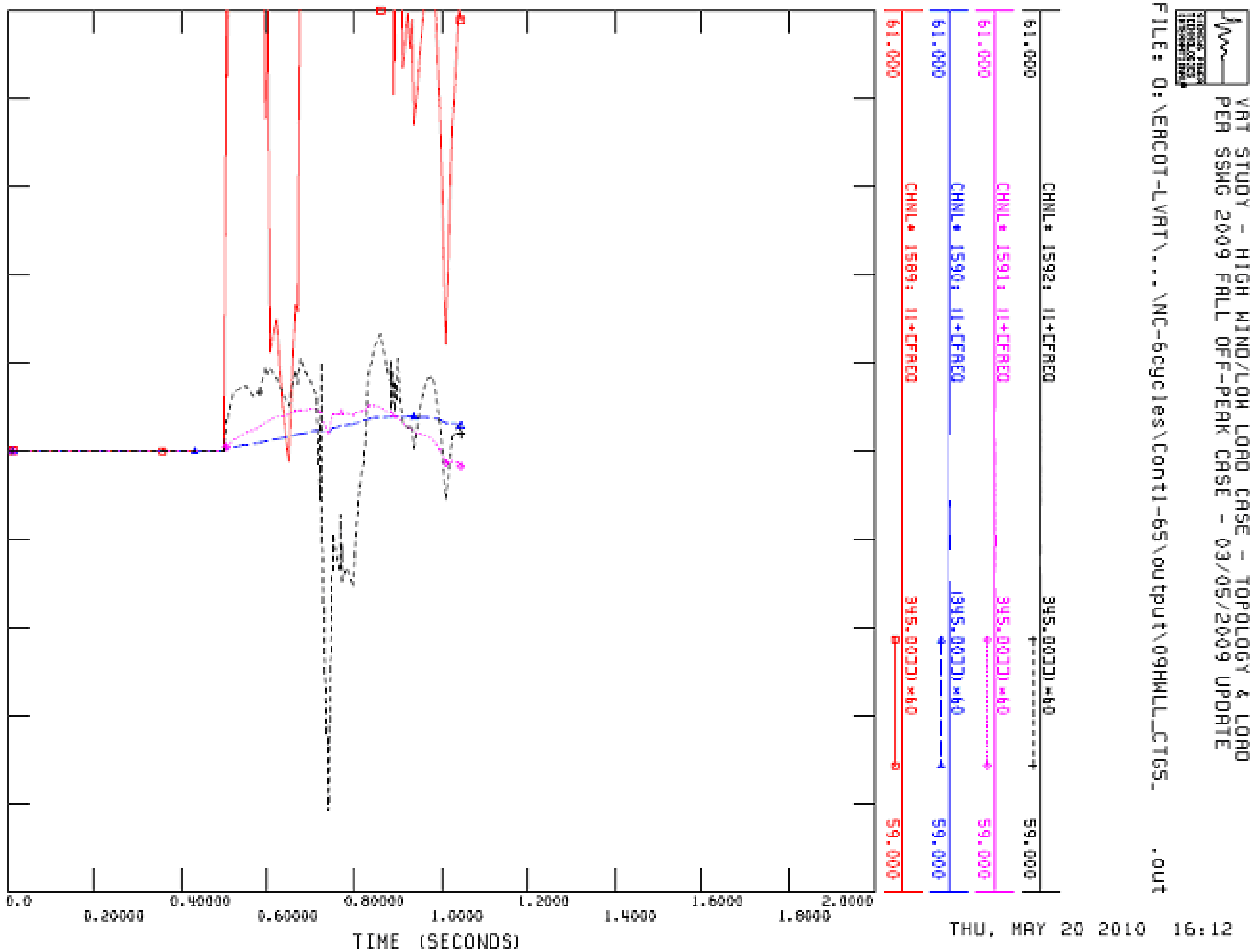

Exhibit 16-d: Frequency Response for all ERCOT Zones for CTG5 (6 cycle fault duration) – Change Case 1

The PSS/E crash is simply an indication of the numerical non-convergence of the dynamic dataset following the voltage instability.

Based on the results associated with normal clearing events for a 6 cycle fault duration for Change Case 1, all the events were simulated with the expected normal TSP fault clearing times to assess the impact of the fault duration on the WGR trips. Of special interest were CTG5 and CTG21, the events that result in WGR trips indicative of potential reliability risks for ERCOT. The ensuing sub-section discusses the simulation results associated with normal clearing events with the expected normal TSP fault clearing times utilized.

6.1.2 TSP fault duration

As discussed in the previous sub-section, certain normal clearing events result in widespread WGR trips when simulated with 6 cycle fault duration. As a result, all 65 normal clearing events for Change Case 1 were simulated with expected TSP normal fault clearing times as identified in Exhibit 5.

Exhibits 17-a and 17-b depict the WGR trips associated with normal clearing events with expected normal TSP fault clearing times for Change Case 1. As evident from Exhibit 17, the reduction of the fault duration has a profound impact on the results associated with CTG5 and CTG21 for Change Case 1. As expected, CTG5 still remains the most severe event albeit with reduced WGR trips. CTG5 results in 734 MW of WGR trips in terms of Change Case 1 dispatch and 977 MW in terms of WGR capacity lost. The frequency deviation associated with the event is about 0.08 Hz. These results correspond to the normal expected fault duration of 4 cycles for CTG5 as provided by ERCOT. The total WGR trips and associated frequency deviation are indicative of no LaaR model activation and do not seem to pose reliability risks associated with the lack of WGR VRT capability. Another indication that the phenomenon associated with CTG5 for 6 cycle fault duration stems from voltage stability (rather than the lack of WGR VRT capability) is the impact of fault duration on system behavior. Reduced fault duration and/or faster fault clearing are known to have an alleviating impact on voltage stability as is observed to be the case with CTG5 for Change Case 1.

In terms of reliability risks when assessed vis-à-vis the reliability metrics, the WGR trips for CTG5 with the normal expected fault duration do not result in WGR trips exceeding the ERCOT RRS requirement (i.e. 2300 MW) either in terms of the case dispatch or the WGR capacity lost for Change Case 1.

While the voltage recovery was observed to be delayed, owing to the absence of conventional voltage support in West Texas, no voltage recovery concerns were observed. Exhibits 18-a through 18-d depict the plots associated with various power system quantities for dynamic simulation associated with CTG5 with 4 cycle fault duration for Change Case 1.

Contingency Number	MW Tripped as per Change Case 1	MW Capacity Lost
CTG1	69.50	100.50
CTG2	432.80	535.50
CTG3	531.90	679.50
CTG4	531.90	679.50
CTG5	734.60	977.90
CTG6	98.00	213.00
CTG7	131.00	250.50
CTG8	0.00	0.00
CTG9	725.50	1065.00
CTG10	98.00	213.00
CTG11	0.00	0.00
CTG12	82.70	142.50
CTG13	82.70	142.50
CTG14	510.70	687.00
CTG15	0.00	0.00
CTG16	128.10	222.00
CTG17	487.50	991.42
CTG18	82.70	142.50
CTG19	0.00	0.00
CTG20	0.00	0.00
CTG21	483.60	597.00
CTG22	531.90	679.50
CTG23	98.00	213.00
CTG24	334.90	713.22
CTG25	82.70	142.50
CTG26	0.00	0.00
CTG27	98.00	213.00
CTG28	128.10	222.00
CTG29	0.00	0.00
CTG30	725.50	1065.00
CTG31	0.00	0.00

Exhibit 17-a: WGR Trips for Normal Clearing Events (TSP Fault Clearing Times) – Change Case 1

Contingency Number	MW Tripped as per Change Case 1	MW Capacity Lost
CTG32	487.50	991.42
CTG33	69.50	100.50
CTG34	449.20	537.00
CTG35	449.20	537.00
CTG36	128.10	222.00
CTG37	0.00	0.00
CTG38	0.00	0.00
CTG39	0.00	0.00
CTG40	82.70	142.50
CTG41	52.20	101.28
CTG42	259.10	321.00
CTG43	0.00	0.00
CTG44	401.90	832.82
CTG45	334.90	713.22
CTG46	487.50	991.42
CTG47	0.00	0.00
CTG48	70.90	123.00
CTG49	0.00	0.00
CTG50	0.00	0.00
CTG51	171.00	180.90
CTG52	171.00	180.90
CTG53	128.10	222.00
CTG54	401.90	832.82
CTG55	61.50	150.00
CTG56	487.50	991.42
CTG57	487.50	991.42
CTG58	420.50	871.82
CTG59	82.70	142.50
CTG60	259.10	321.00
CTG61	259.10	321.00
CTG62	0.00	0.00
CTG63	531.90	679.50
CTG64	427.90	668.28
CTG65	427.90	668.28

Exhibit 17-b: WGR Trips for Normal Clearing Events (TSP Fault Clearing Times) – Change Case 1

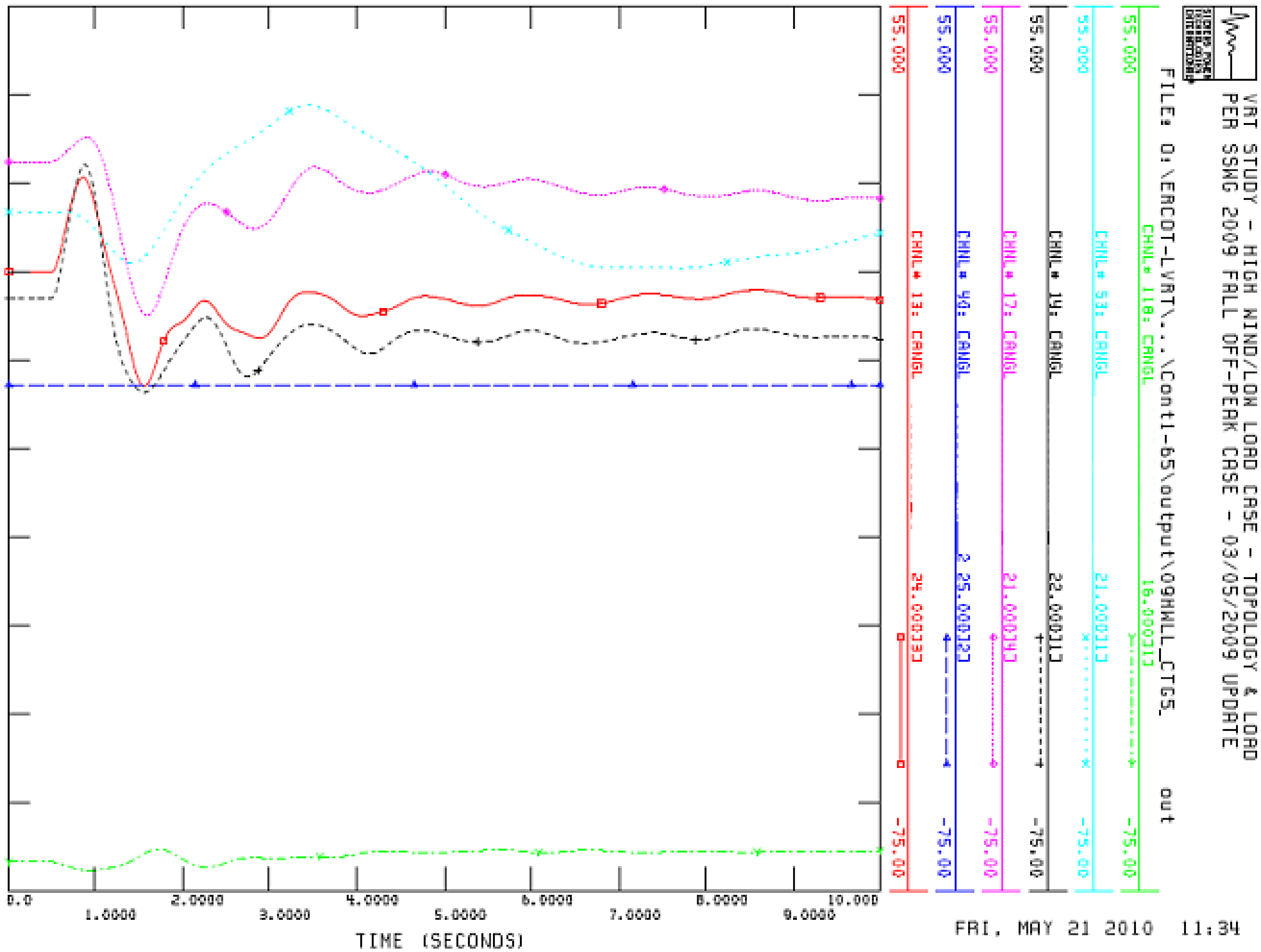

Exhibit 18-a: Rotor Angle Response for Conventional Generators for CTG5 (4 cycle fault duration) – Change Case 1

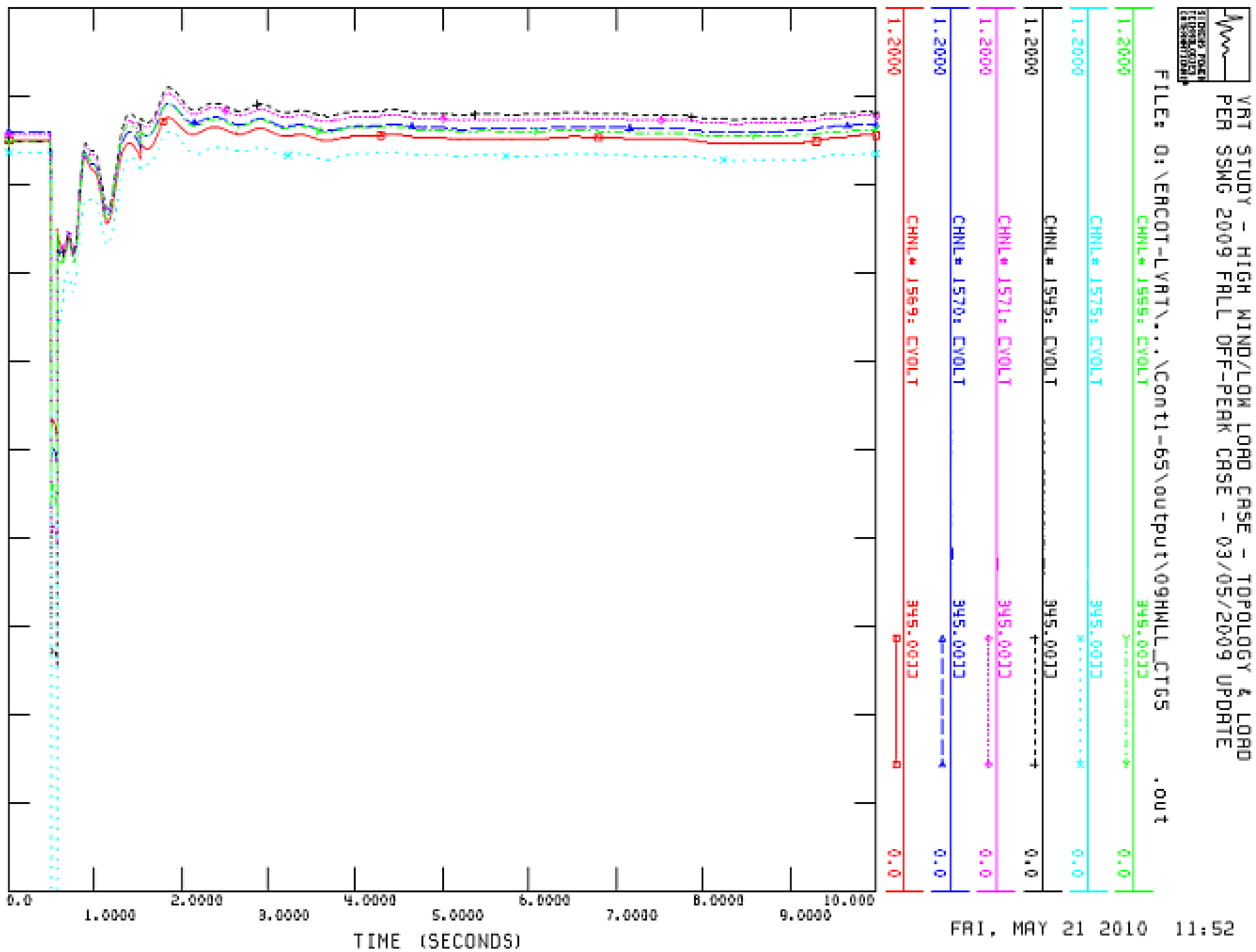

Exhibit 18-b: Voltage Response for 345 kV ERCOT West Stations for CTG5 (4 cycle fault duration) – Change Case 1

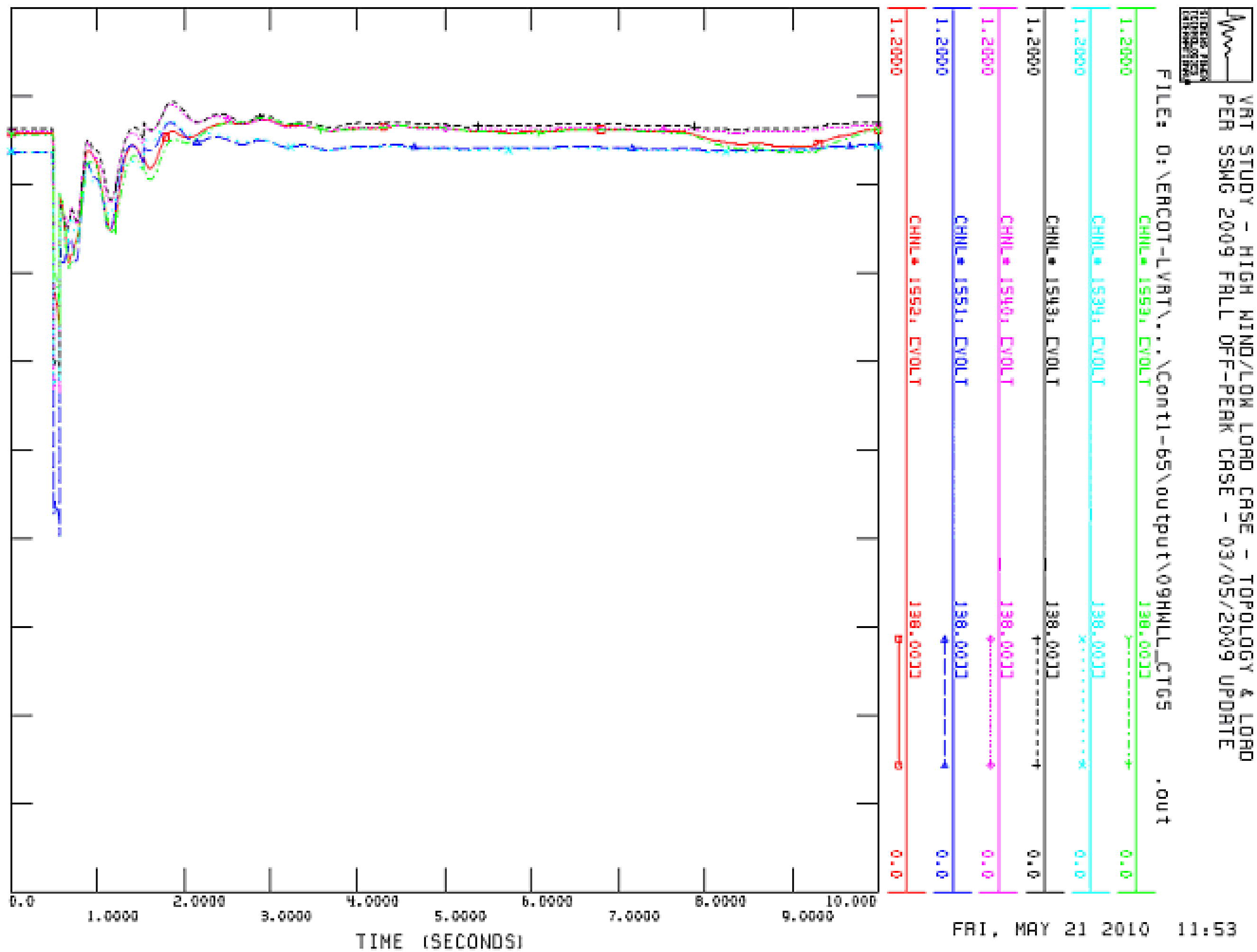

Exhibit 18-c: Voltage Response for 138 kV ERCOT West Stations for CTG5 (4 cycle fault duration) – Change Case 1

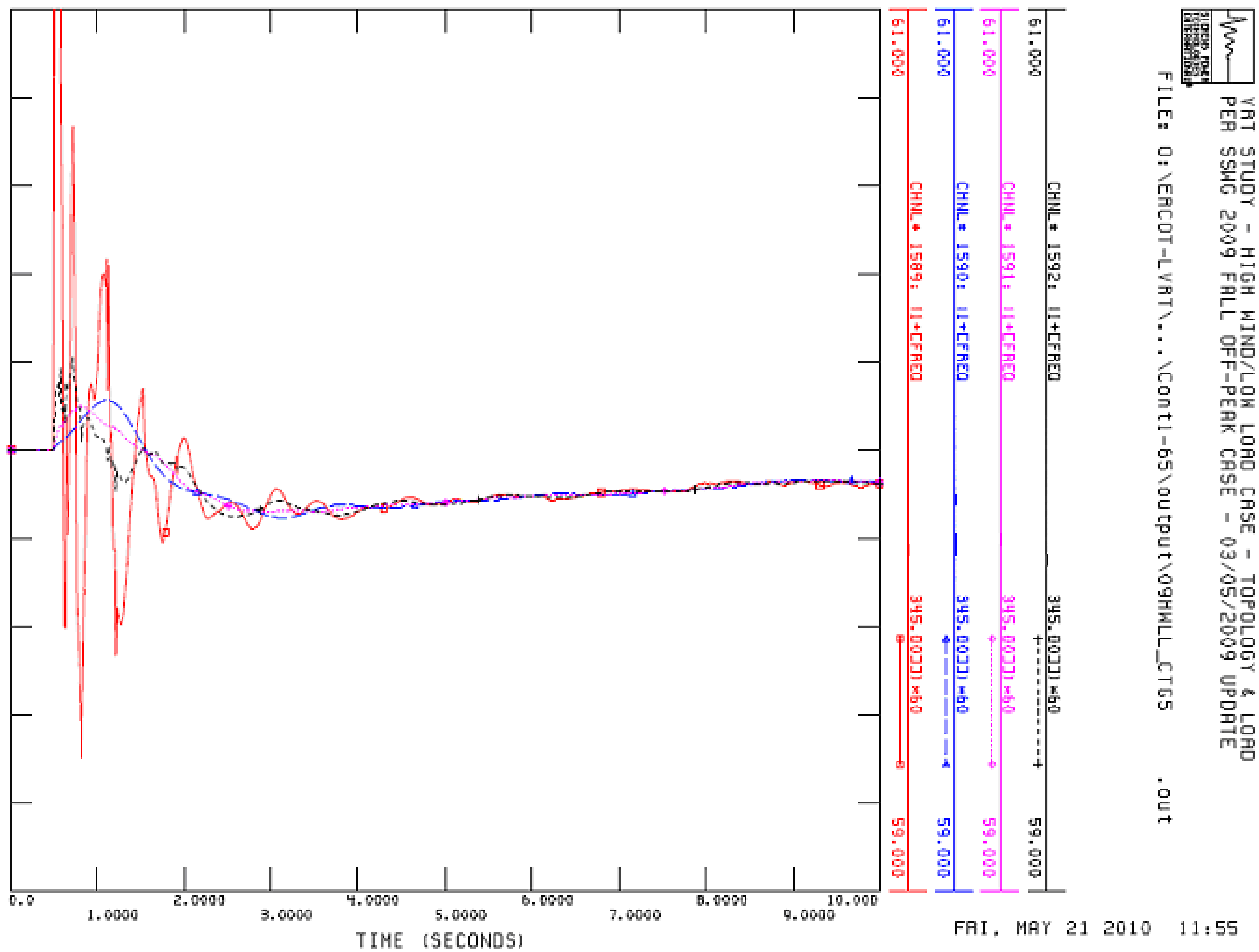

Exhibit 18-d: Frequency Response for all ERCOT Zones for CTG5 (4 cycle fault duration) – Change Case 1

No other normal clearing event simulated poses reliability risks associated with the lack of WGR VRT capability for Change Case 1 when utilizing expected normal TSP fault clearing times.

6.2 Breaker Failure Events

This sub-section discusses the results associated with the Change Case 1 for dynamic simulations associated with the 31 breaker failure events as described in the previous chapter.

The breaker failure events are simulated with the TSP provided clearing times for the primary and the back-up breaker isolation events. Exhibit 19 depicts the WGR trips associated with the 31 breaker failure events simulated for Change Case 1. As evident from Exhibit 19, BF#17 presents the most severe event from the 31 breaker failure events simulated for Change Case 1. BF#17 results in 835 MW of WGR trips in terms of Change Case 1 dispatch and 1307 MW in terms of WGR capacity lost. Exhibits 20-a through 20-d depict the plots for various power system quantities for BF#17 for Change Case 1. The frequency response and post-event frequency deviation associated with BF#17 is observed to be within acceptable limits. Exhibits 20-b and 20-c do not indicate any voltage recovery issues associated with BF#17 for Change Case 1.

Additionally, none of the breaker failure events simulated for Change Case 1 seem to present reliability risks due to lack of WGR VRT capability vis-à-vis the following reliability metrics:

- WGR trips in terms of case dispatch exceed ERCOT RRS requirement of 2300 MW
- WGR trips in terms of capacity lost exceed ERCOT RRS requirements of 2300 MW
- System frequency response and post-event frequency deviations
- Voltage excursions and post-event voltage levels

However, care has to be taken to ensure that the fault shunt admittance values utilized for performing S-L-G fault breaker failure simulations for Change Case 1 are reflective of no conventional generation in West Texas. All the results presented in this sub-section associated with breaker failure assessment for Change Case 1 correspond to altered fault shunt admittance values to reflect the absence of conventional generation units in West Texas.

Contingency Number	MW Tripped as per Change Case 1	MW Capacity Lost
BF1	539.40	680.60
BF2	539.40	680.60
BF3	273.50	301.50
BF4	378.30	421.10
BF5	163.90	186.30
BF6	163.90	186.30
BF7	0.00	0.00
BF8	316.90	672.32
BF9	0.00	0.00
BF10	196.20	282.60
BF11	171.00	180.90
BF12	256.60	313.50
BF13	0.00	0.00
BF14	601.10	976.12
BF15	791.50	1256.44
BF16	767.20	1271.60
BF17	835.00	1307.58
BF18	644.60	1029.38
BF19	644.60	1029.38
BF20	732.50	1189.10
BF21	597.00	1031.00
BF22	127.30	310.50
BF23	279.90	588.70
BF24	218.40	438.70
BF25	313.60	648.00
BF26	313.60	648.00
BF27	267.10	560.58
BF28	312.50	643.08
BF29	267.10	560.58
BF30	127.30	310.50
BF31	127.30	310.50

Exhibit 19: WGR Trips for Breaker Failure Events – Change Case 1

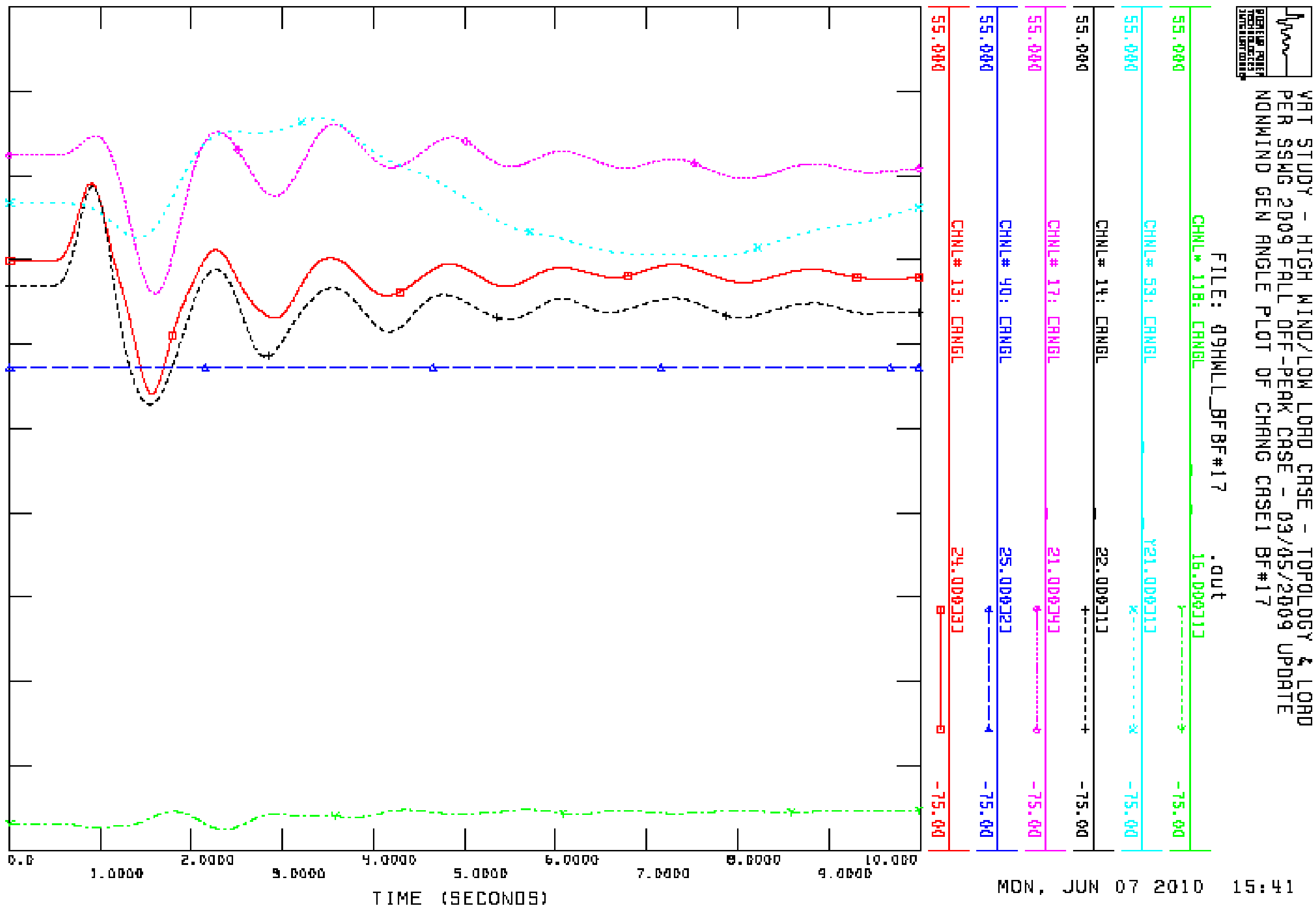

Exhibit 20-a: Rotor Angle Response for Conventional Units for BF#17 – Change Case 1

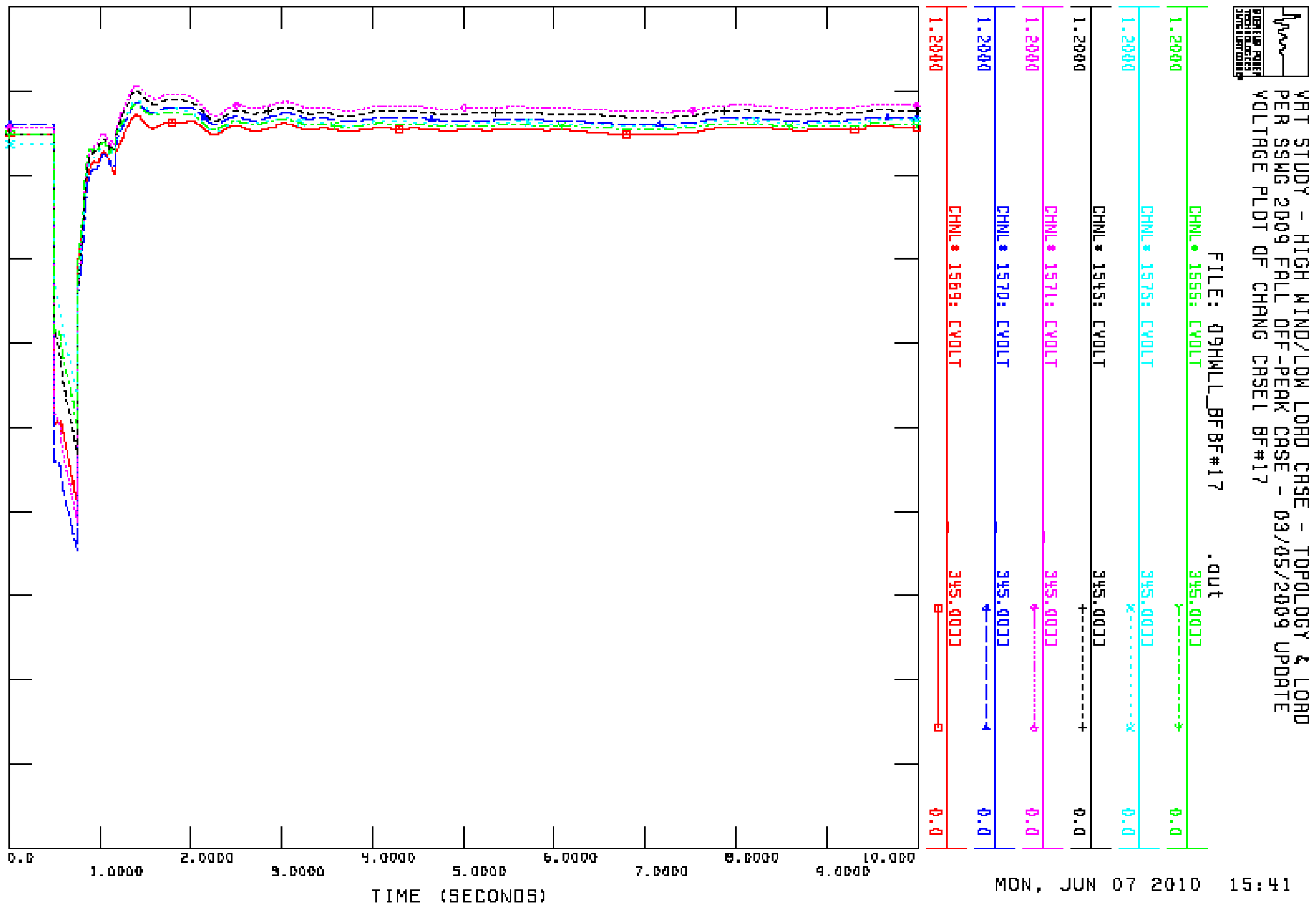

Exhibit 20-b: Voltage Response for 345 kV ERCOT West Stations for BF#17 – Change Case 1

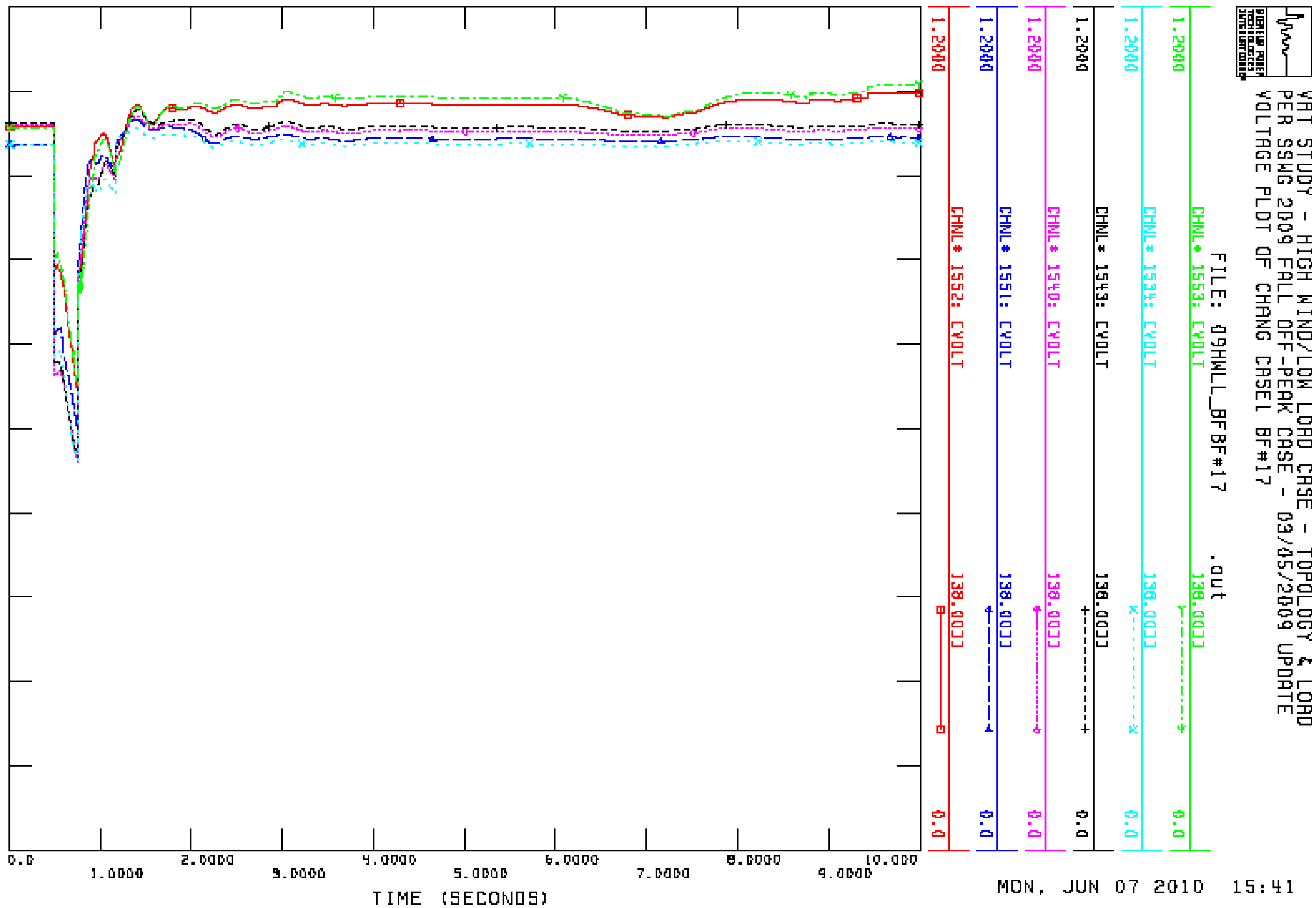

Exhibit 20-c: Voltage Response for 138 kV ERCOT West Stations for BF#17 – Change Case 1

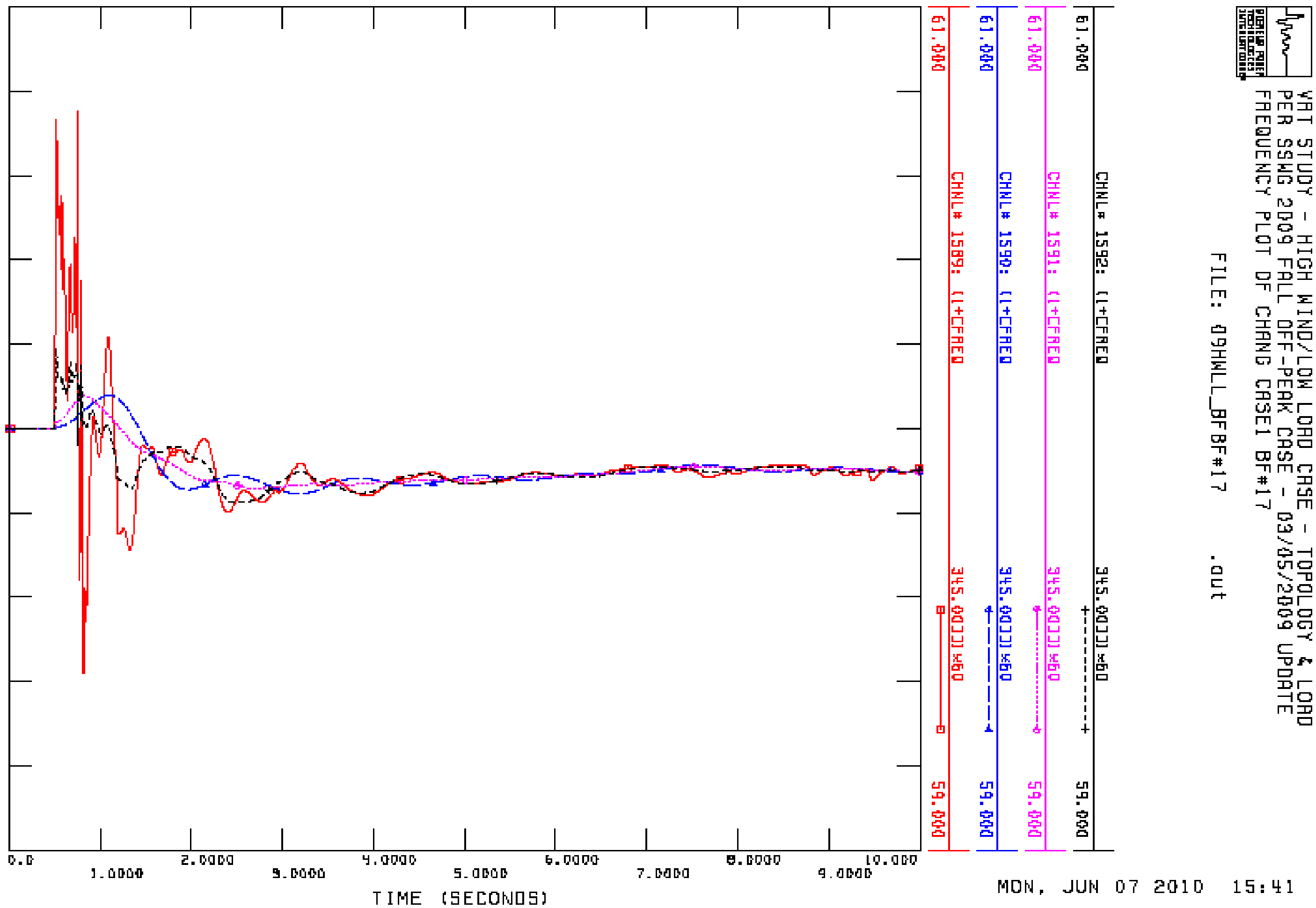

Exhibit 20-d: Frequency Response for all 4 ERCOT Zones for BF#17 – Change Case 1

6.3 Observations

Based on the results of the dynamic simulations performed for normal clearing and breaker failure events for Change Case 1, the following observations can be made with respect to the reliability risks associated with lack of WGR VRT capability:

- CTG5 results in voltage instability and potential subsequent voltage collapse for Change Case 1 when simulated with 6 cycle fault duration. The event leads to WGR trips of 2959 MW in terms of Change Case 1 dispatch and 4989 MW in terms of WGR capacity lost. A majority of the WGR trips, however, are initiated from over-frequency issues immediately after the event.
- The results of the simulation are indicative of the West-North transfer limit resulting in imminent voltage collapse for CTG5 when simulated for 6 cycle fault duration which is avoided primarily due to reduced West-North transfer by virtue of WGR trips. The fact that a majority of the WGR trips happen by virtue of over-frequency also seems to suggest that the risks stemming from the event may not be related to the lack of WGR VRT capability.
- When CTG5 was re-simulated with the expected normal TSP fault clearing time of 4 cycles, the amount of WGR trips were reduced to 734 MW in terms of Change Case 1 dispatch and 977 MW in terms of WGR capacity lost. The results are on expected lines as reduced fault duration typically has an alleviating impact on the voltage stability. The reduction in the fault duration results in reduced WGR trips with little or no over-frequency trips.
- Overall the simulation of CTG5 for Change Case 1 is suggestive of the case being near the West-North Voltage stability limit in terms of the transfer modeled in the case.
- No other normal clearing event simulated poses reliability risks associated with the lack of WGR VRT capability (as outlined in ERCOT Operating guides Section 3.1.4.6.1) when simulated with the expected normal TSP fault cycle duration.
- In terms of the breaker failure event simulation, BF#17 presents the most severe case resulting in 835 MW of WGR trips in terms of Change Case 1 dispatch and approximately 1307 MW in terms of WGR capacity lost for Change Case 1. However no reliability risks associated with the lack of WGR VRT capability are observed for BF#17 when assessed vis-à-vis the reliability metrics outlined for the study.
- None of the other breaker failure events simulated pose reliability risks associated with the lack of WGR VRT capability for Change Case 1.

7 Simulation Results – Change Case 2

As described in Chapter 4, Change Case 2 was developed from the HWHL case by the incremental addition of the dynamic load models for West Texas. No changes to the wind dispatch in West Texas or status of the conventional generation units was made to the HWHL case in order to obtain Change Case 2. While details associated with the dynamic load model representation for ONCOR, AEP and LCRA for their West Texas region loads has been discussed in previous chapters, a summary is presented below. It should be noted that for dynamic load modeling purposes, several smaller TSPs serving load in and around West Texas were included in the ONCOR footprint. These include Rayburn Country Electric Cooperative, Brazos Electric Power Cooperative, Texas-New Mexico Power, City of Denton, City of Garland and Greenville Electric.

The load models associated with ONCOR utilized the WECC "CIMWOW" Induction motor model for representing the large and small induction motor loads at their stations in West Texas. The ABB "C5LSOW" load model was utilized to model AC motor loads due to its ability to represent motor stalling during exacerbated voltage dips. While the specification of the load split into large induction motor, small induction motor, AC motor and constant impedance load was made at each bus level, the dynamic data associated with the large, small and AC motor models was provided at the owner level. In other words, individual bus level load composition was utilized to identify the percentage of large, small and AC motor load and the constant impedance load. However, the nature of the large induction motors across the entire ONCOR footprint was modeled utilizing the same model and parameters. The same applies to small and AC motor load models. All the ONCOR load models are modeled at the low voltage side with a nominal voltage of 12.47 kV and an intermediate distribution transformer and feeder modeled.

The load models associated with AEP utilized the ABB "C5LSOW" induction motor model for representing large, small and AC motor loads at their stations in West Texas. Unlike ONCOR, AEP load category percentage was specified by owner identifying 60% concentration of large induction motor load in West Texas for high load conditions. The remaining was identified to be constant impedance load while no small and/or AC motor load was modeled at AEP stations in West Texas. Similar to the ONCOR load models, the AEP load models were also included at the low voltage side with nominal voltage of 12.47 kV and an intermediate distribution transformer and feeder modeled.

The load models associated with LCRA were based on individual bus load with specific bus-based dynamic data provided for the motor and constant impedance load modeled at each bus. However, unlike AEP and ONCOR, the load models for LCRA have not been modeled at the low side. No distribution transformer and/or feeder have been modeled for the LCRA loads.

The entire set of 65 normal clearing and 31 breaker failure events were simulated for Change Case 2 in order to assess the risk associated with lack of WGR VRT capability following the addition of the dynamic load models.

The resulting dynamic dataset following the addition of the dynamic load models was tested to ensure acceptable flat start to confirm acceptable dynamic initialization of the load models prior to dynamic simulation. The ensuing sub-sections provide discussion associated with the results for normal clearing and breaker failure events for Change Case 2.

7.1 Normal Clearing Events

This sub-section discusses the results associated with the Change Case 2 for dynamic simulations associated with normal clearing events. As in the case of HWHL/HWLL cases, all the normal clearing events were first simulated with a 6 cycle fault duration (assuming a 1-2 cycle clearing margin for 345/138 kV system faults) to assess worst case situations in terms of WGR trips. Exhibits 21-a and 21-b depict the results associated with 65 normal clearing events with a 6 cycle fault duration for Change Case 2.

As evident from Exhibits 21-a and 21-b, CTG9 represents the most severe event for Change Case 2 resulting in approximately 1190 MW of WGR trips in terms of Change Case 2 dispatch and 1788 MW in terms of WGR capacity lost. The number of WGR trips is close to that observed for the same event in the HWHL case. In other words, the dynamic load models and associated voltage response during and immediately after the fault event does not have a major impact in terms of WGR trips by virtue of lack of VRT capability. The relatively lightly loaded conditions and lower concentration of motor loads in West Texas seem to be the probable causes for the minimal impact. The same is confirmed by observing the plots associated with the 138kV and 345kV voltage response depicted in Exhibit 22. The addition of the dynamic load models does not have a significant impact on the post-fault voltage recovery in West Texas primarily due to the low levels and lower concentration of the motor loads. Most of the WGR trips are the same as those observed for CTG9 for the HWHL case and correspond to WGR with machines that lack VRT capability. The plots associated with various power system quantities for CTG5 are presented in Exhibits 22-a through 22-d for Change Case 2.

The frequency deviation associated with the event was observed to be close to 0.12 Hz. The event was re-run with the addition of the LaaR models but no LaaR model activation was observed.

Contingency Number	MW Tripped as per Change Case 2	MW Capacity Lost
CTG1	37.49	220.50
CTG2	44.10	63.00
CTG3	332.58	657.60
CTG4	121.00	221.10
CTG5	215.10	243.90
CTG6	741.17	1088.68
CTG7	691.67	1006.18
CTG8	0.00	0.00
CTG9	1190.25	1788.70
CTG10	105.00	150.00
CTG11	0.00	0.00
CTG12	0.00	0.00
CTG13	65.55	142.50
CTG14	217.35	310.50
CTG15	0.00	0.00
CTG16	155.40	222.00
CTG17	610.31	991.42
CTG18	65.55	142.50
CTG19	0.00	0.00
CTG20	0.00	0.00
CTG21	44.10	63.00
CTG22	332.58	657.60
CTG23	149.10	213.00
CTG24	610.31	991.42
CTG25	65.55	142.50
CTG26	0.00	0.00
CTG27	159.05	227.22
CTG28	326.40	402.90
CTG29	0.00	0.00
CTG30	1140.75	1706.20
CTG31	0.00	0.00
CTG32	610.31	991.42

Exhibit 21-a: WGR Trips for Normal Clearing Events, 6 cycle fault duration – Change Case 2

Contingency Number	MW Tripped as per Change Case 2	MW Capacity Lost
CTG33	0.00	0.00
CTG34	86.10	123.00
CTG35	44.10	63.00
CTG36	326.40	402.90
CTG37	0.00	0.00
CTG38	0.00	0.00
CTG39	0.00	0.00
CTG40	65.55	142.50
CTG41	33.30	38.28
CTG42	79.80	114.00
CTG43	0.00	0.00
CTG44	499.29	832.82
CTG45	610.31	991.42
CTG46	610.31	991.42
CTG47	0.00	0.00
CTG48	155.40	222.00
CTG49	0.00	0.00
CTG50	0.00	0.00
CTG51	171.00	180.90
CTG52	171.00	180.90
CTG53	155.40	222.00
CTG54	610.31	991.42
CTG55	159.05	227.22
CTG56	362.60	552.72
CTG57	362.60	552.72
CTG58	610.31	991.42
CTG59	65.55	142.50
CTG60	88.14	341.10
CTG61	88.14	341.10
CTG62	0.00	0.00
CTG63	244.44	316.50
CTG64	44.10	63.00
CTG65	44.10	63.00

Exhibit 21-b: WGR Trips for Normal Clearing Events, 6 cycle fault duration – Change Case 2

The overall WGR trips associated with the most severe event (CTG9) do not exceed the ERCOT RRS requirements of 2300 MW either in terms of the case dispatch or in terms of the WGR capacity lost. No post-fault voltage recovery issues were observed for this event for Change Case 2.

The post-event over-voltages on 138kV system depicted in Exhibit 22-c are a manifestation of the turbine side capacitors staying online even after the associated WGR has tripped as explained in previous chapters.

No other normal clearing event simulated poses reliability risks associated with the lack of WGR VRT capability for Change Case 2 when compared to the reliability metrics outlined in Phase I.

7.2 Breaker Failure Events

The entire set of 31 breaker failure events were simulated for Change Case 2 to assess the impact of the inclusion of the dynamic load models in West Texas on delayed clearing breaker failure events from a VRT standpoint. Exhibit 23 depicts the results associated with breaker failure events for Change Case 2 in terms of WGR trips. The results clearly indicate BF#20 to be the most severe event in terms of WGR trips with 824 MW of WGR trips in terms of Change Case 2 dispatch and approximately 1189 MW in terms of WGR capacity lost. The breaker failure event BF#20 is accompanied with a frequency deviation of about 0.09 Hz. Change Case 2 was simulated again for BF#20 with the inclusion of the LaaR models provided by ERCOT but no LaaR model activation was witnessed.

Exhibits 24-a through 24-d depict the plots for various power system quantities for BF#20 for Change Case 2. In summary, the addition of the dynamic load models in West Texas do not result in any reliability concerns from a VRT standpoint as far as breaker failure events are concerned.

The impact of the dynamic load models on the voltage recovery is more clearly visible in the 138kV system voltage response following BF#20 as depicted in Exhibit 24-c. Exhibit 24-c depicts a slight delay in voltage recovery following the event and as expected it is more visible on the lower voltage levels. However, the voltage recovery delay is not very pronounced due to the low load levels in West Texas and the lower concentration of motor loads in West Texas. The comment associated with post-event voltage being higher by virtue of turbine side capacitors staying online for tripped WGRs is also applicable for Exhibit 24-c.

No other breaker failure event simulated results in WGR trips that could be indicative of reliability risks stemming from the lack of WGR VRT capability for Change Case 2.

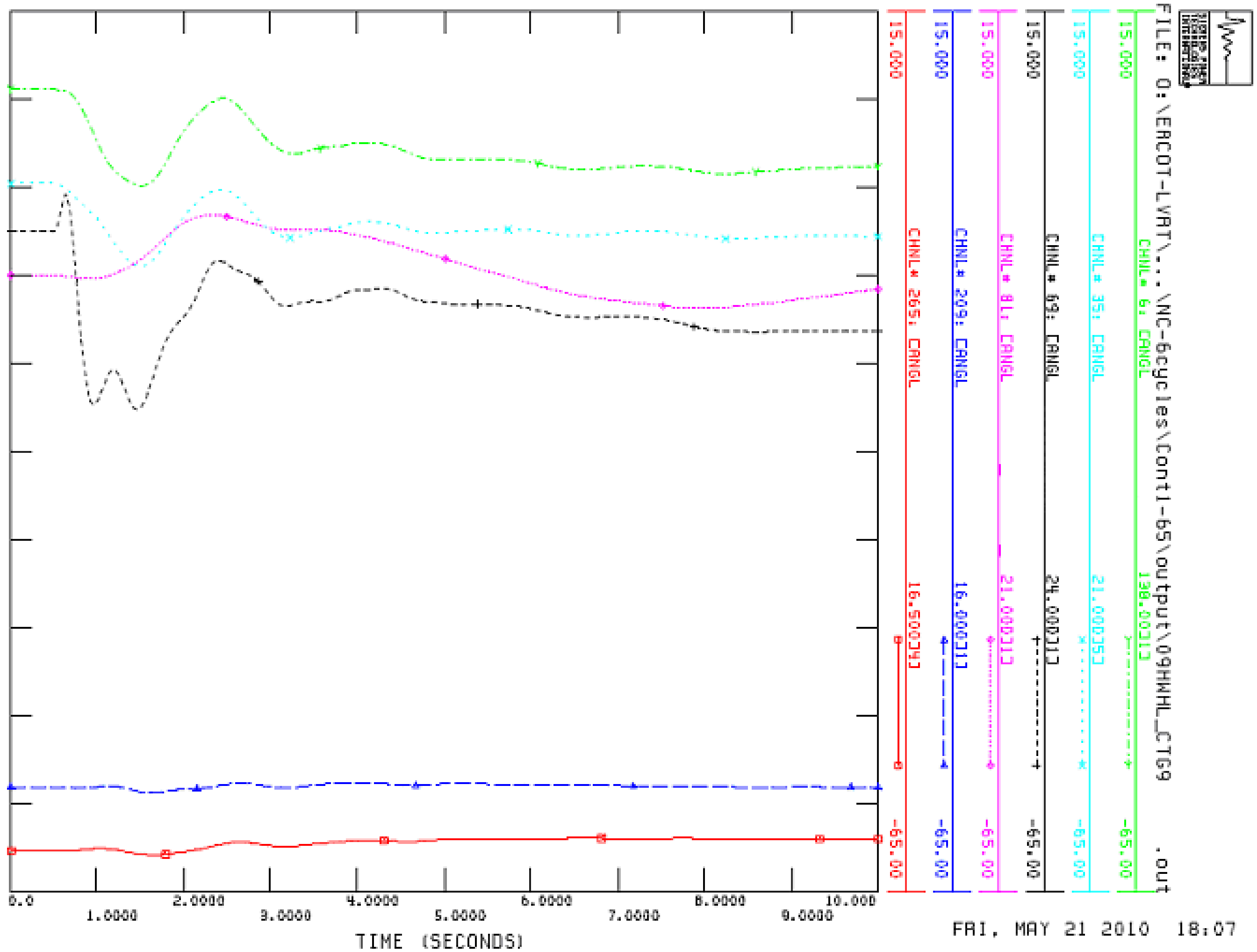

Exhibit 22-a: Rotor Angle Response for Conventional Generators for CTG9 (6 cycle fault duration) – Change Case 2

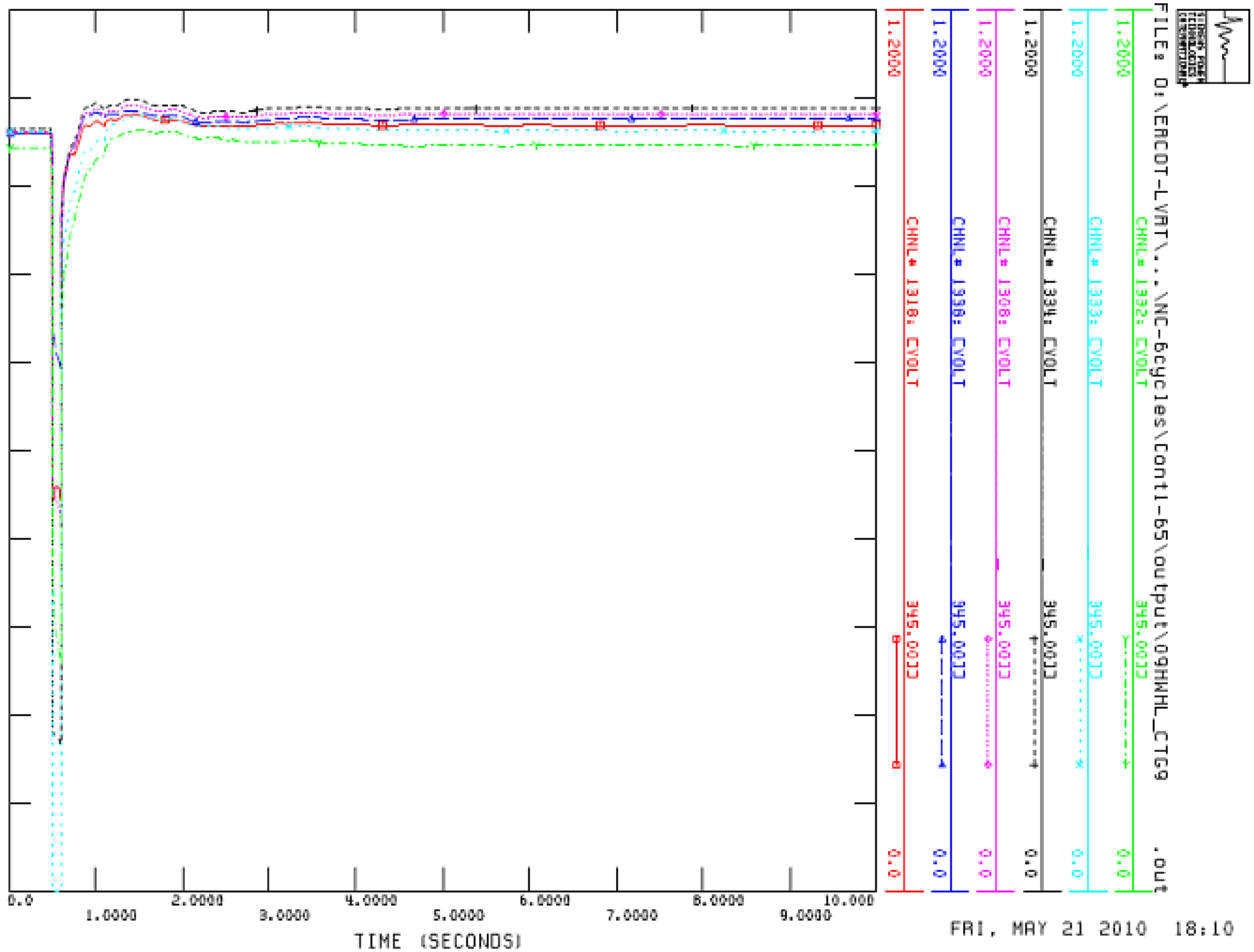

Exhibit 22-b: Voltage Response for 345 kV ERCOT West stations for CTG9 (6 cycle fault duration) – Change Case 2

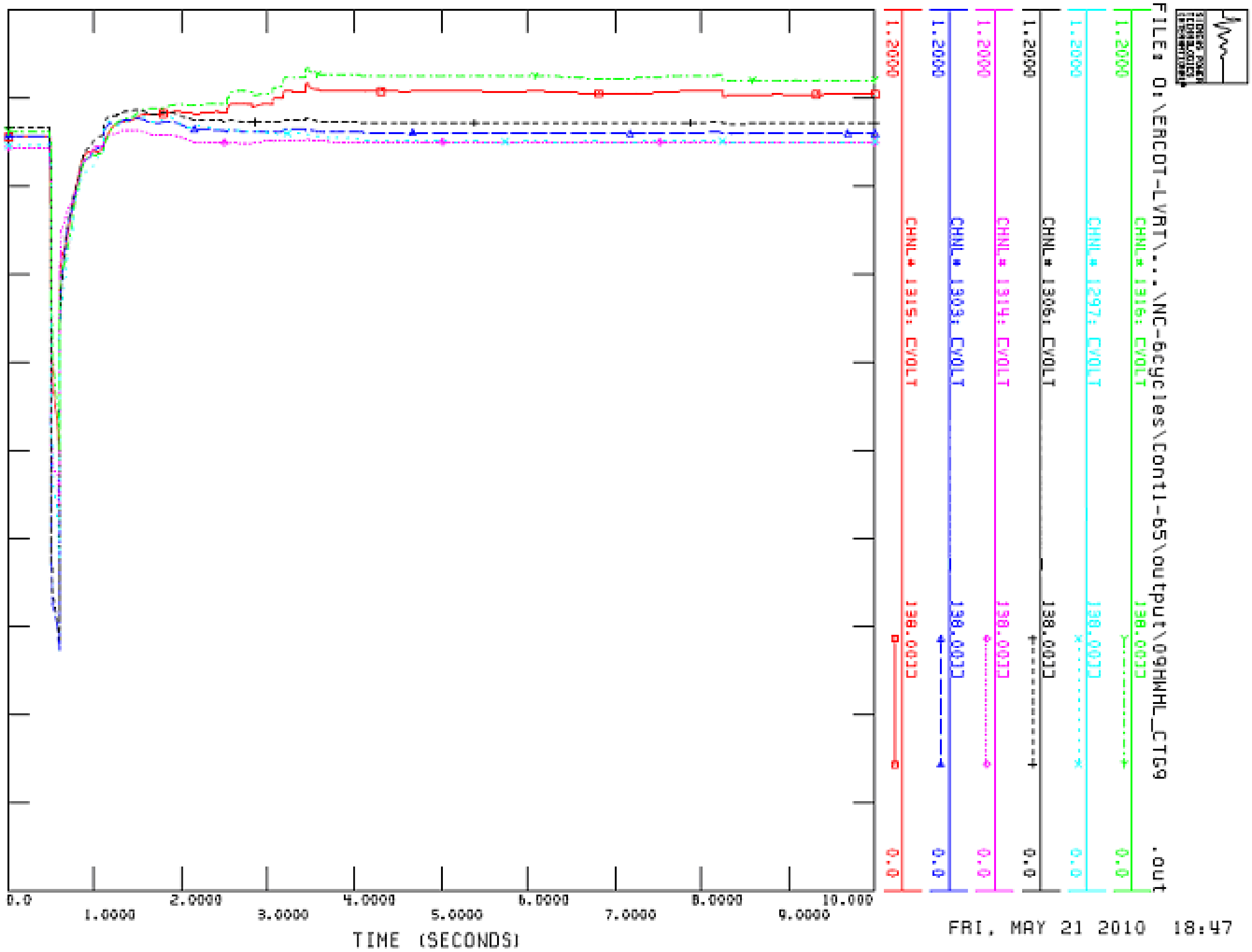

Exhibit 22-c: Voltage Response for 138 kV ERCOT West stations for CTG9 (6 cycle fault duration) – Change Case 2

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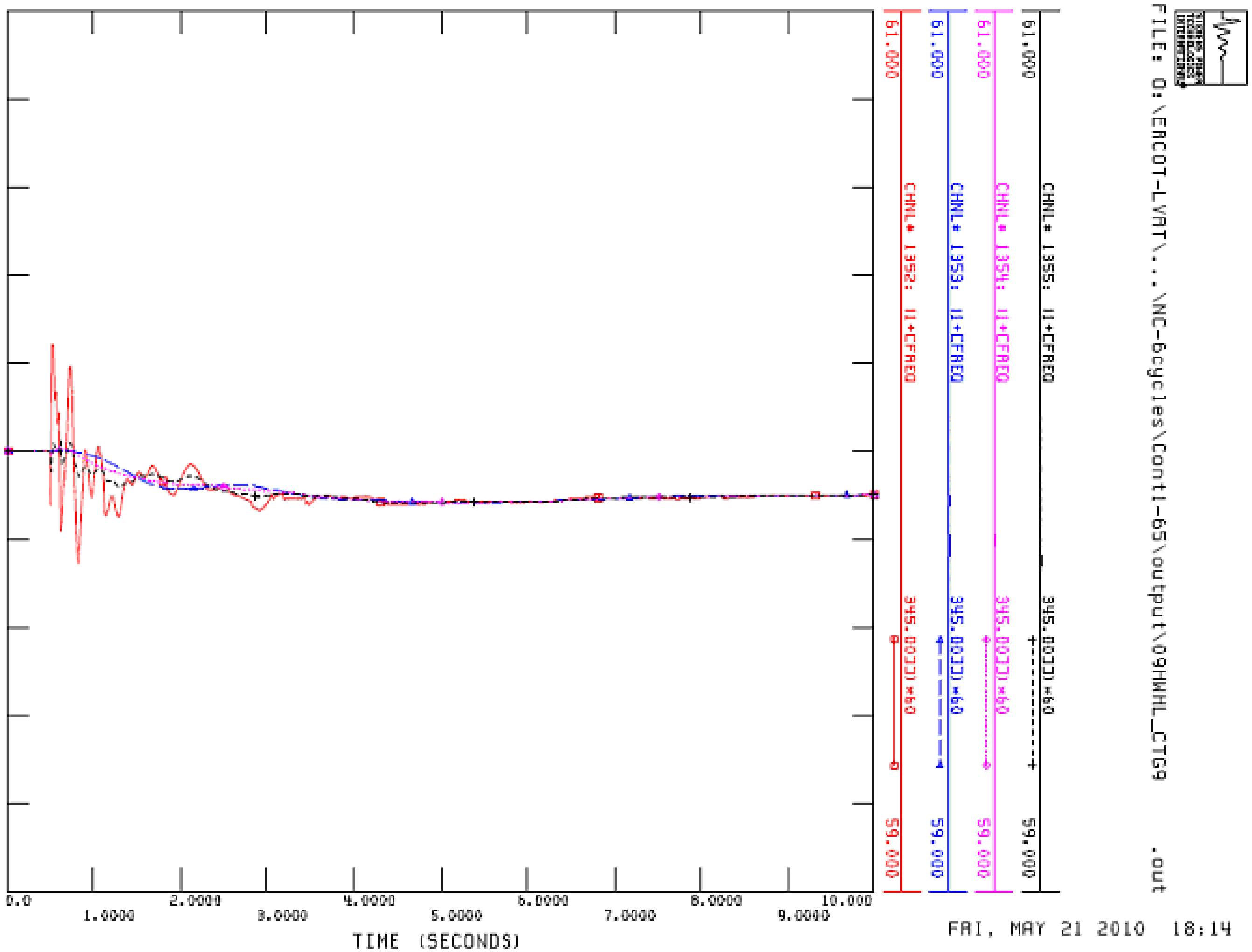

Exhibit 22-d: Frequency Response for all 4 ERCOT zones for CTG9 (6 cycle fault duration) – Change Case 2

Contingency Number	MW Tripped as per Change Case 2	MW Capacity Lost
BF1	0.00	0.00
BF2	0.00	0.00
BF3	0.00	0.00
BF4	0.00	0.00
BF5	148.53	186.30
BF6	148.53	186.30
BF7	0.00	0.00
BF8	514.01	830.92
BF9	0.00	0.00
BF10	0.00	0.00
BF11	0.00	0.00
BF12	178.70	313.50
BF13	0.00	0.00
BF14	338.46	416.76
BF15	802.97	1165.18
BF16	338.46	416.76
BF17	338.46	416.76
BF18	338.46	416.76
BF19	338.46	416.76
BF20	824.21	1189.60
BF21	802.97	1165.18
BF22	105.00	150.00
BF23	105.00	150.00
BF24	0.00	0.00
BF25	635.51	929.32
BF26	635.51	929.32
BF27	635.51	929.32
BF28	635.51	929.32
BF29	635.51	929.32
BF30	635.51	929.32
BF31	635.51	929.32

Exhibit 23: WGR Trips for Breaker Failure Events – Change Case 2

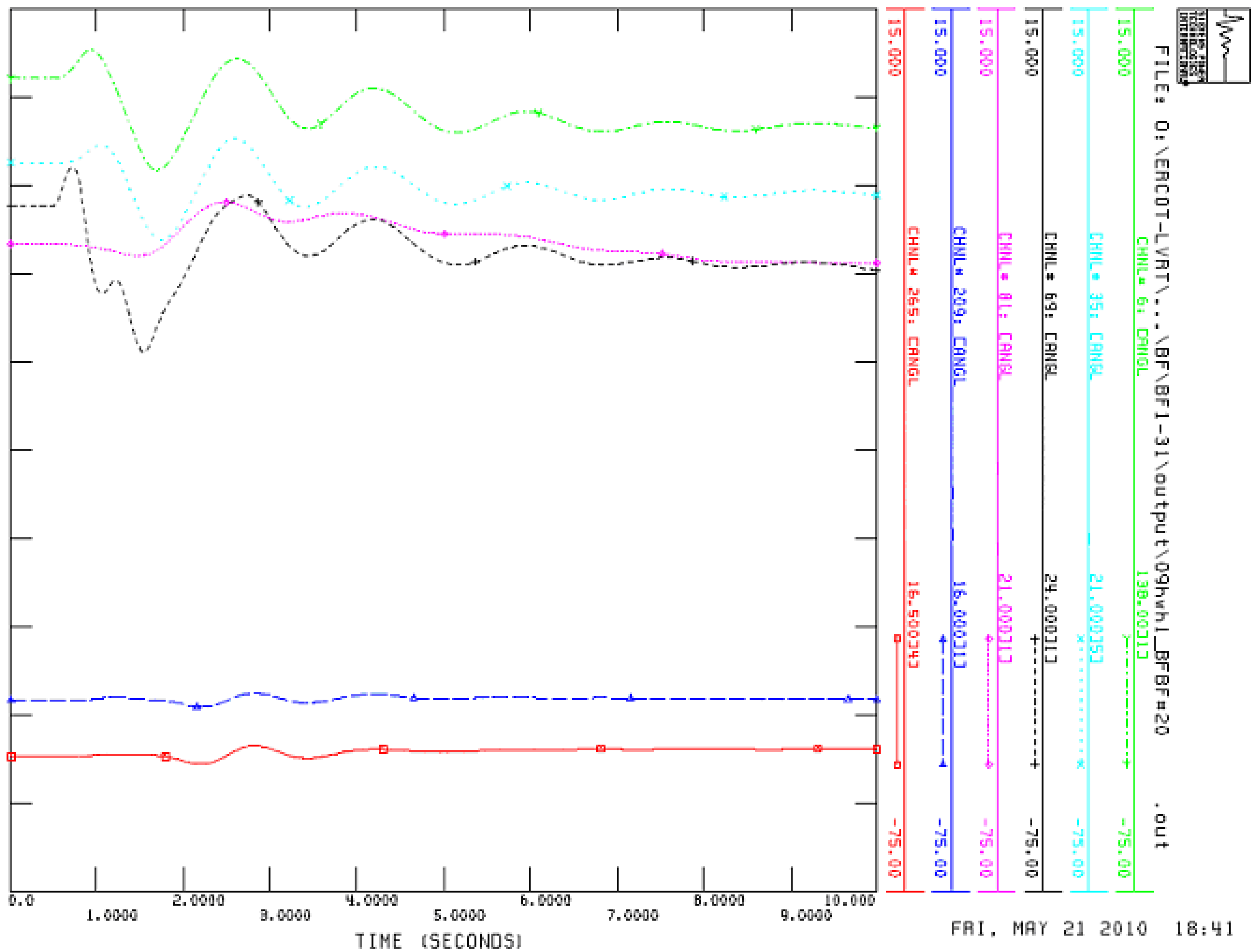

Exhibit 24-a: Rotor Angle Response for Conventional Generators for BF#20 – Change Case 2

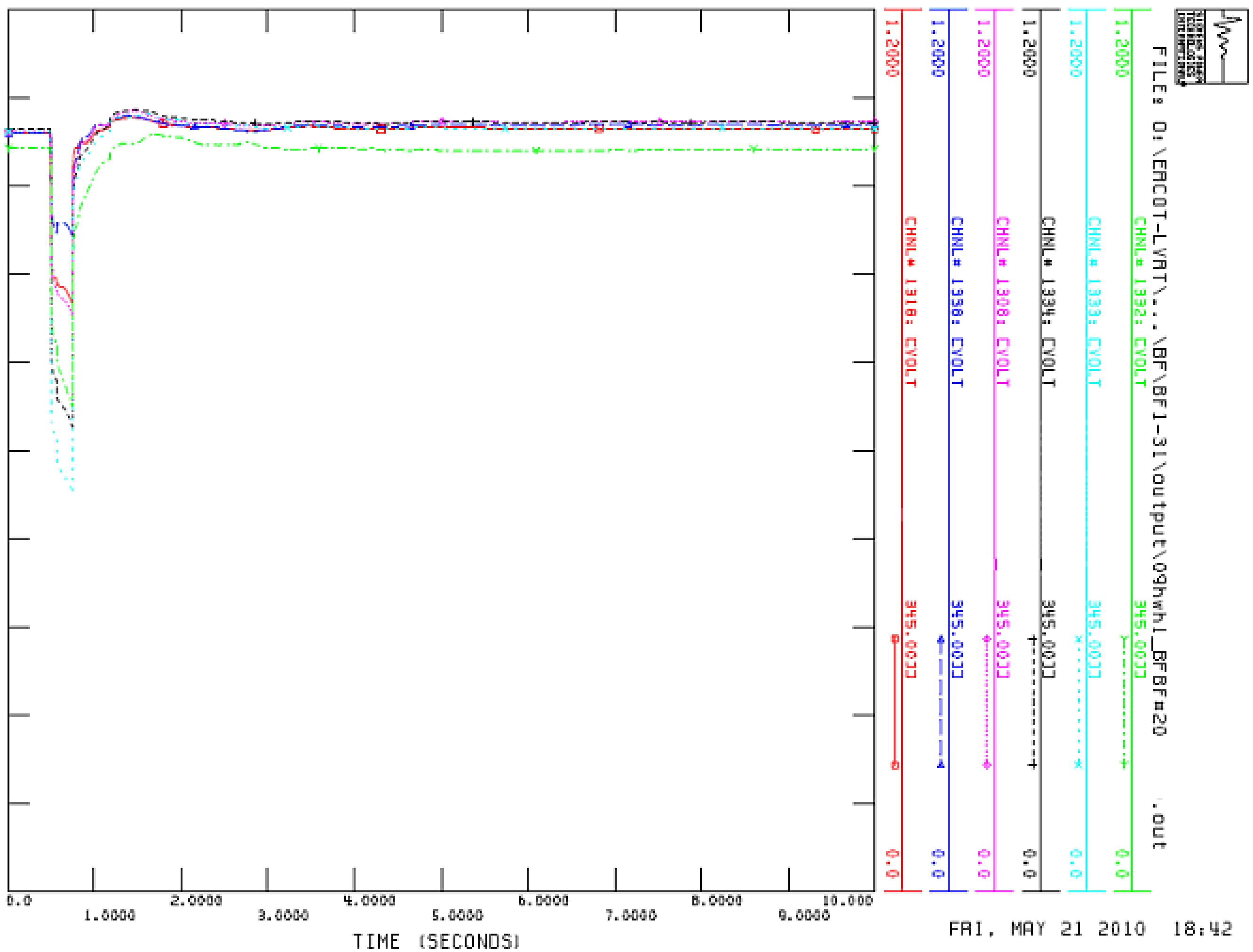

Exhibit 24-b: Voltage Response for 345 kV ERCOT West Stations for BF#20 – Change Case 2

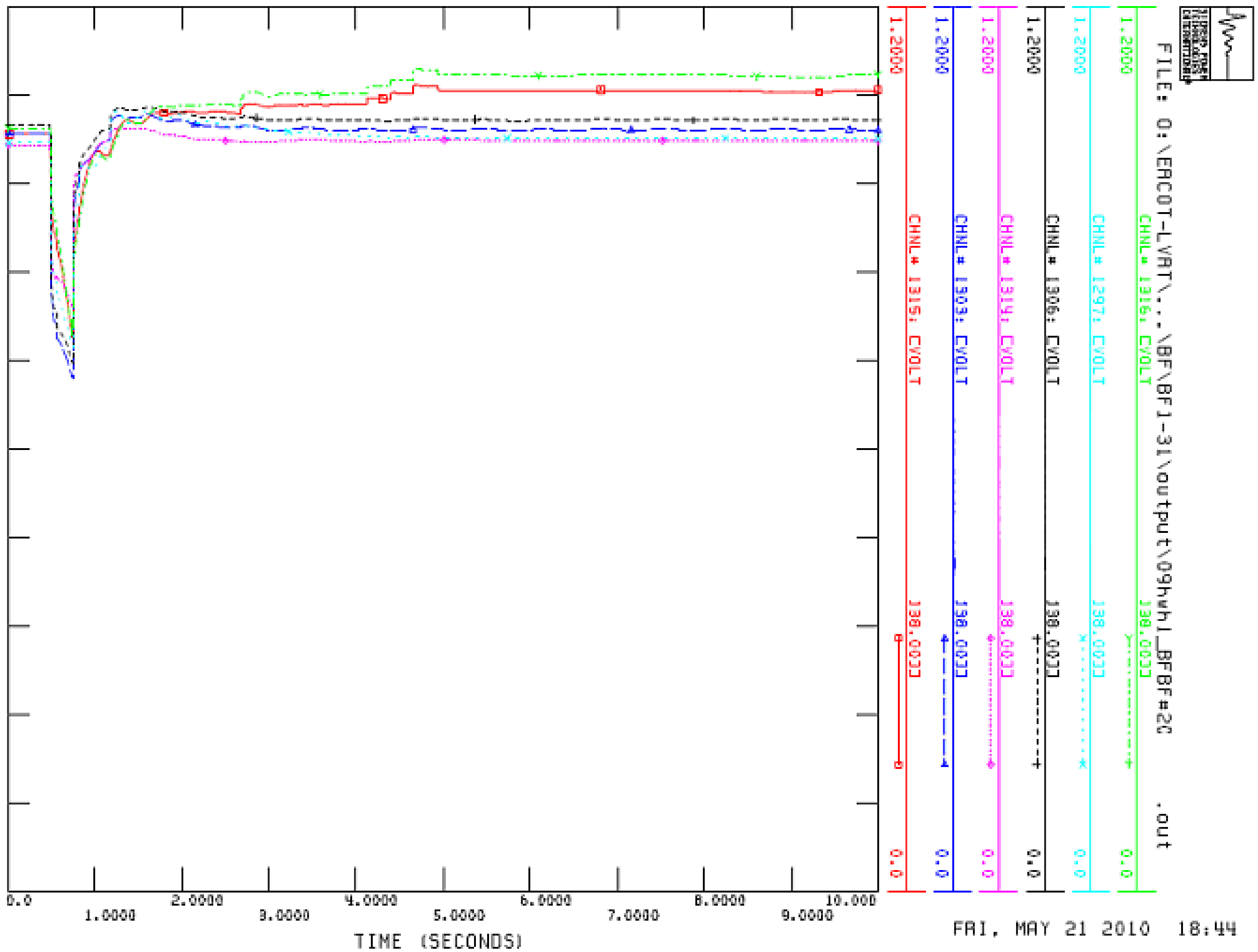

Exhibit 24-c: Voltage Response for 138 kV ERCOT West Stations for BF#20 – Change Case 2

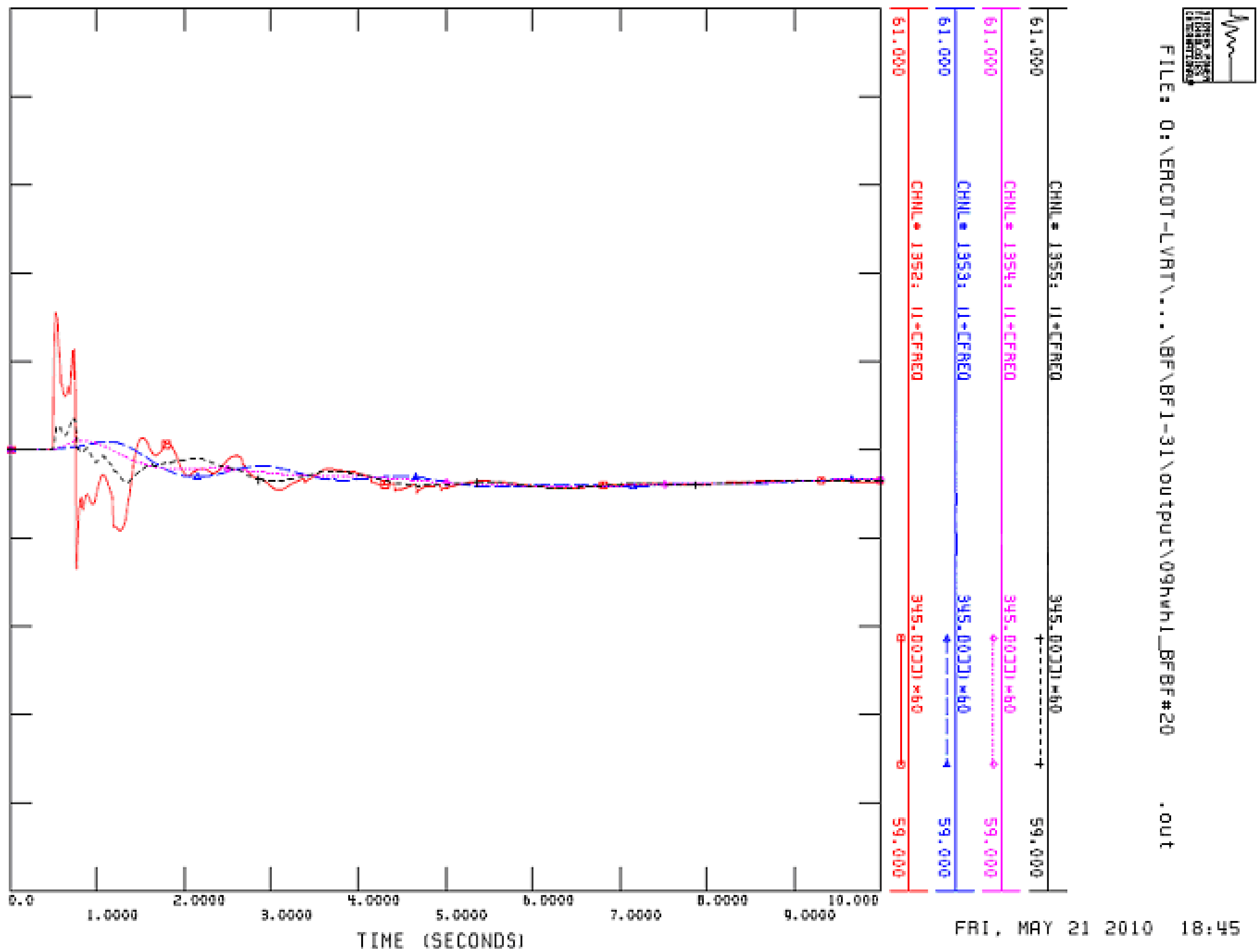

Exhibit 24-d: Frequency Response for all ERCOT zones for BF#20 – Change Case 2

7.3 Observations

Based on the results of the normal clearing and breaker failure event simulations performed for Change Case 2, the following observations can be made with respect to the reliability risks due to lack of WGR VRT capability:

- CTG9 represents the most serve normal clearing event (out of the simulated events) for Change Case 2 resulting in 1190 MW of WGR trips in terms of Change Case 2 dispatch and approximately 1788 MW in terms of WGR capacity lost. However, when compared to the reliability metrics outlined in Phase I, the WGR trips associated with CTG9 do not exceed the 2300 MW of ERCOT RRS requirement. The frequency deviation associated with the event was observed to be 0.12 Hz and no LaaR model activation was witnessed.
- The frequency response and post-event frequency deviation associated with CTG9 were deemed to be within acceptable limits for Change Case 2.
- Although the inclusion of the dynamic load models in West Texas do introduce a slight delay in voltage recovery, no major concerns from a voltage recovery and/or post-event voltage levels were observed for any normal clearing events simulated.
- None of the simulated normal clearing events pose any reliability risks associated with WGR VRT capability for Change Case 2.
- Normal clearing events for Change Case 2 were simulated for 6 cycle fault duration. Most of the TSP fault clearing times associated with 3-Phase faults on 345kV stations are identified to be 4 cycles thereby indicating that the WGR trips by virtue of under-voltage would tend to be lesser.
- In terms of breaker failure events, BF#20 is identified to be the most severe event for Change Case 2 resulting in 824 MW of WGR trips in terms of case dispatch and approximately 1189 MW of WGR trips in terms of capacity lost. However, when compared to the reliability metrics outlined in Phase I, the WGR trips associated with BF#20 do not exceed the 2300 MW of ERCOT RRS requirement. The frequency deviation associated with the event also does not result in any LaaR model activation
- None of the simulated breaker failure events pose any reliability risks associated with WGR VRT capability for Change Case 2.
- The inclusion of dynamic load models is found to have a minor impact on the post-fault voltage response and/or voltage recovery primarily due to the low load levels in West Texas and relatively low concentration of motor loads. However, as will be observed in the ensuing chapters dynamic load modeling parameters

are bound to impact conditions associated with high wind and the absence of conventional generators in West Texas.

- The results documented in this section are based on the dynamic load models/parameters and load category concentrations provided to PB by ERCOT. It is important for ERCOT to understand that accurate modeling of dynamic load behavior includes multiple parameter tuning and identification of accurate motor load parameters for each bus/region.

8 Simulation Results – Change Case 3

As described in Chapter 4, Change Case 3 is a derivative of Change Case 1 characterized by the incremental addition of the dynamic load models for West Texas. The details associated with the incremental addition of the dynamic load models to develop Change Case 3 are consistent with that described in Chapters 4 and 7. The only change made to the dynamic load models was in terms of the percentage of various load categories in order to reflect light load conditions corresponding to Change Case 1. As can be recalled from the previous chapter, the ONCOR load category percentage was specified at individual bus level and the same was altered to reflect light load conditions at each ONCOR bus in West Texas. LCRA provided a dedicated “min load” dynamic data file to be utilized to represent light load conditions associated with their loads in West Texas region. AEP provided altered percentages of the motor load concentration in West Texas corresponding to light load conditions. No change was made to the generation dispatch and/or load levels to obtain Change Case 3 when compared to Change Case 1. Change Case 3 was designed to assess the combined impact of no conventional generation units in West Texas and dynamic load behavior on the ability of WGRs to ride-through voltage dips simulated in the form of normal clearing and breaker failure events.

The ensuing sub-sections in this chapter present the results associated with normal clearing and breaker failure event simulations for Change Case 3.

8.1 Normal Clearing Events

Since Change Case 3 was originally derived from Change Case 1 which had exhibited large WGR trips when normal clearing events were simulated with 6 cycle fault duration, normal clearing events for Change Case 3 were directly simulated with expected normal TSP fault clearing times. Exhibits 25-a and 25-b depict the results associated with the 65 normal clearing events (TSP fault clearing times) for Change Case 3 in terms of WGR trips.

As evident from Exhibit 25, the lone event that causes WGR trips indicative of potential reliability risks is CTG5. It may be recalled that CTG5 was the lone event resulting in similar amount of WGR trips for Change Case 1 for 6 cycle fault duration. Subsequently, the reduction in the fault duration did result in alleviation of the WGR trips. Like Change Case 1, a majority of the WGR trips for CTG5 for Change Case 3 also result from over-frequency trips.

Contingency Number	MW Tripped as per Change Case 3 Dispatch	MW Capacity Lost
CTG1	69.50	100.50
CTG2	69.50	100.50
CTG3	531.90	679.50
CTG4	449.20	537.00
CTG5	3965.00	6214.00
CTG6	98.00	213.00
CTG7	98.00	213.00
CTG8	0.00	0.00
CTG9	685.00	988.50
CTG10	98.00	213.00
CTG11	0.00	0.00
CTG12	0.00	0.00
CTG13	82.70	142.50
CTG14	207.60	337.50
CTG15	0.00	0.00
CTG16	128.10	222.00
CTG17	487.50	991.42
CTG18	82.70	142.50
CTG19	0.00	0.00
CTG20	0.00	0.00
CTG21	578.00	690.90
CTG22	531.90	679.50
CTG23	98.00	213.00
CTG24	487.50	991.42
CTG25	82.70	142.50
CTG26	0.00	0.00
CTG27	98.00	213.00
CTG28	128.10	222.00
CTG29	0.00	0.00
CTG30	685.00	988.50
CTG31	0.00	0.00
CTG32	487.50	991.42

Exhibit 25-a: WGR Trips for Normal Clearing Events (Expected Normal TSP Fault Clearing Times) – Change Case 3

Contingency Number	MW Tripped as per Change Case 3 Dispatch	MW Capacity Lost
CTG33	36.50	63.00
CTG34	146.10	187.50
CTG35	146.10	187.50
CTG36	128.10	222.00
CTG37	0.00	0.00
CTG38	0.00	0.00
CTG39	0.00	0.00
CTG40	82.70	142.50
CTG41	52.20	101.28
CTG42	259.10	321.00
CTG43	0.00	0.00
CTG44	401.90	832.82
CTG45	487.50	991.42
CTG46	487.50	991.42
CTG47	0.00	0.00
CTG48	128.10	222.00
CTG49	0.00	0.00
CTG50	0.00	0.00
CTG51	171.00	180.90
CTG52	171.00	180.90
CTG53	128.10	222.00
CTG54	487.50	991.42
CTG55	61.50	150.00
CTG56	487.50	991.42
CTG57	487.50	991.42
CTG58	487.50	991.42
CTG59	82.70	142.50
CTG60	259.10	321.00
CTG61	259.10	321.00
CTG62	0.00	0.00
CTG63	449.20	537.00
CTG64	427.90	668.28
CTG65	427.90	668.28

Exhibit 25-b: WGR Trips for Normal Clearing Events (Expected Normal TSP Fault Clearing Times) – Change Case 3

As evident from Exhibit 25, CTG5 results in 3965 MW of WGR trips in terms of Change Case 3 dispatch and approximately 6214 MW in terms of WGR capacity lost. As in Change Case 1, a majority of the WGR trips are by virtue of over-frequency. However, unlike Change Case 1, the widespread WGR trips occur for 4 cycle fault duration (as opposed to 6 cycle fault duration for Change Case 1). It may be recalled that one of the likely causes attributed for the short-term voltage instability and potentially subsequent voltage collapse associated with CTG5 (for a 6 cycle fault duration) for Change Case 1 was the West-North transfer limit and the inability of the resulting system to handle the transfer modeled in the case following the loss of transmission circuits characterizing CTG5. As expected, the fault duration was found to have an alleviating effect on the voltage stability thereby preventing such a phenomenon upon the reduction of the fault duration for Change Case 1. However, for Change Case 3, the inclusion of the dynamic load models results in similar amount of widespread WGR trips at 4 cycle fault duration. Exhibits 26-a through 26-d depict the plots for various power system quantities for CTG5 for Change Case 3.

A closer look at the voltage and frequency plots depicted in Exhibit 26 lead to the following observations:

- A combination of the West-North transfer modeled in Change Case 3 and the inclusion of dynamic load model results in a second voltage dip immediately after the fault is cleared. This condition is reflective of the inability of the resulting transmission system to handle the transfer modeled in Change Case 3 following the loss of transmission circuits characterizing CTG5.
- The second voltage dip associated with the outage of the transmission circuits characterizing CTG5 also coincides with the exaggerated over-frequency swing wherein the resulting West & North zone frequencies are observed to be swinging “out-of-step” with respect to each other. The over-frequency swing results in numerous WGR trips by virtue of over-frequency thereby reducing the West-North transfer.
- The WGR trips by virtue of over-frequency (and the reduced West-North transfer thereof) coupled with dynamic voltage support of the un-tripped WGR models assists voltage recovery following the phenomenon.
- However after the transient conditions have settled and the system voltage has recovered, the loss of WGRs manifests itself in the form of very low system frequency with the system frequency dropping as low as 59.15 Hz. The post-event frequency deviation is observed to be beyond acceptable limits for CTG5 for Change Case 3.
- The system over-voltages witnessed after the transient conditions have settled are merely a reflection of the WGR switched shunt models being on-line despite the WGR trips. This is purely restricted to the model and simulation environment.

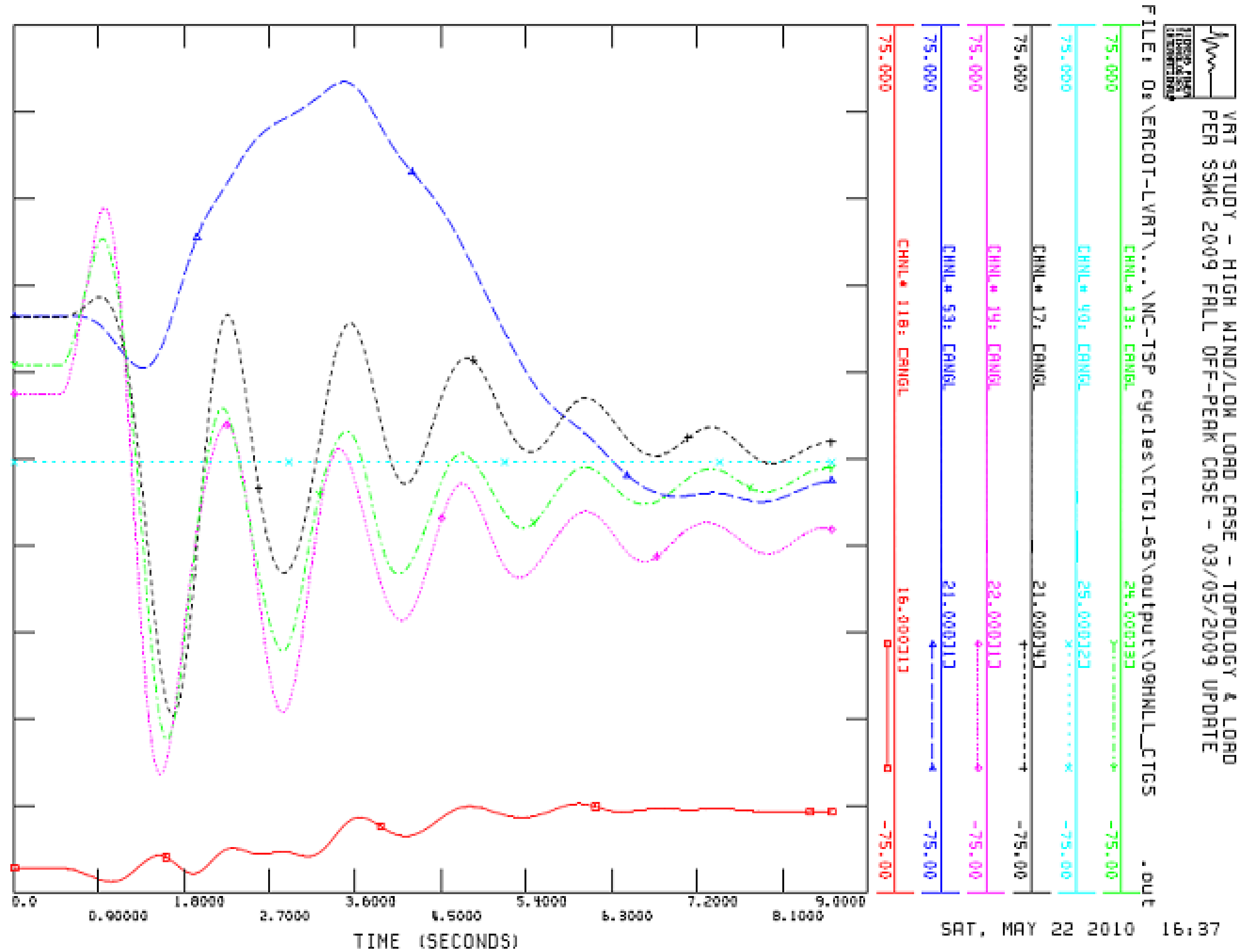

Exhibit 26-a: Rotor Angle Response for Conventional Generators for CTG5 (4 cycle fault duration) – Change Case 3

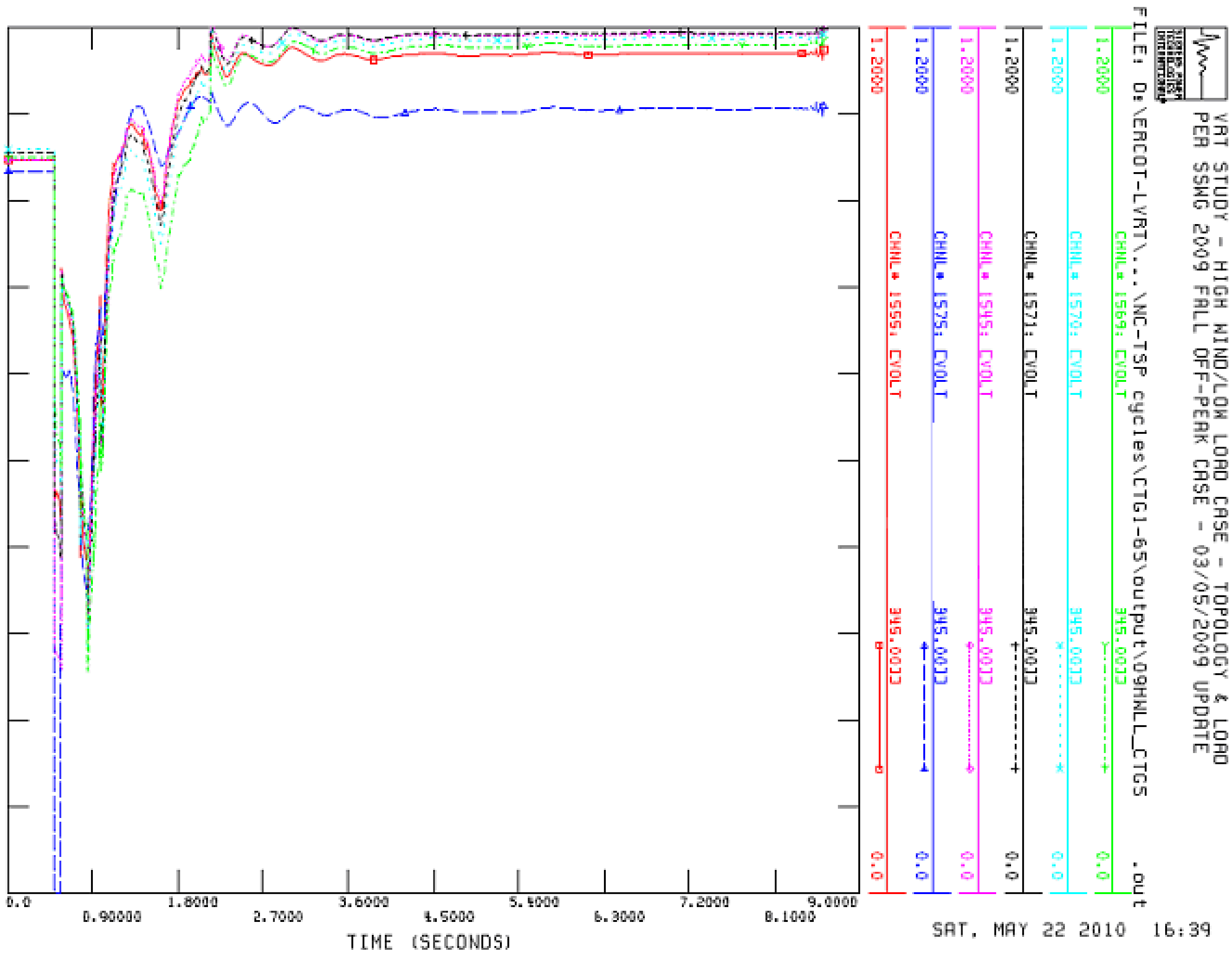

Exhibit 26-b: Voltage Response for 345 kV ERCOT West Stations for CTG5 (4 cycle fault duration) – Change Case 3

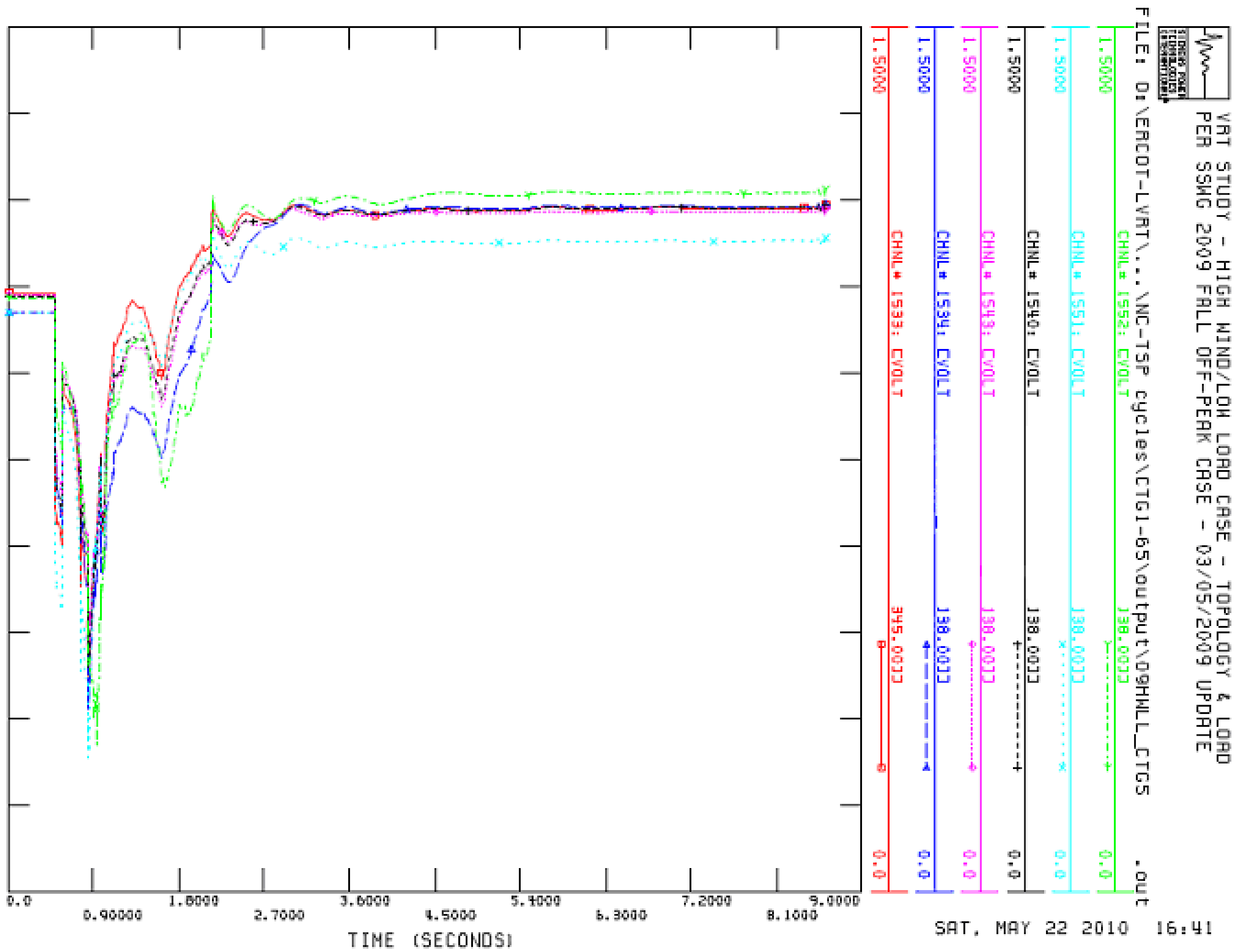

Exhibit 26-c: Voltage Response for 138 kV ERCOT West Stations for CTG5 (4 cycle fault duration) – Change Case 3

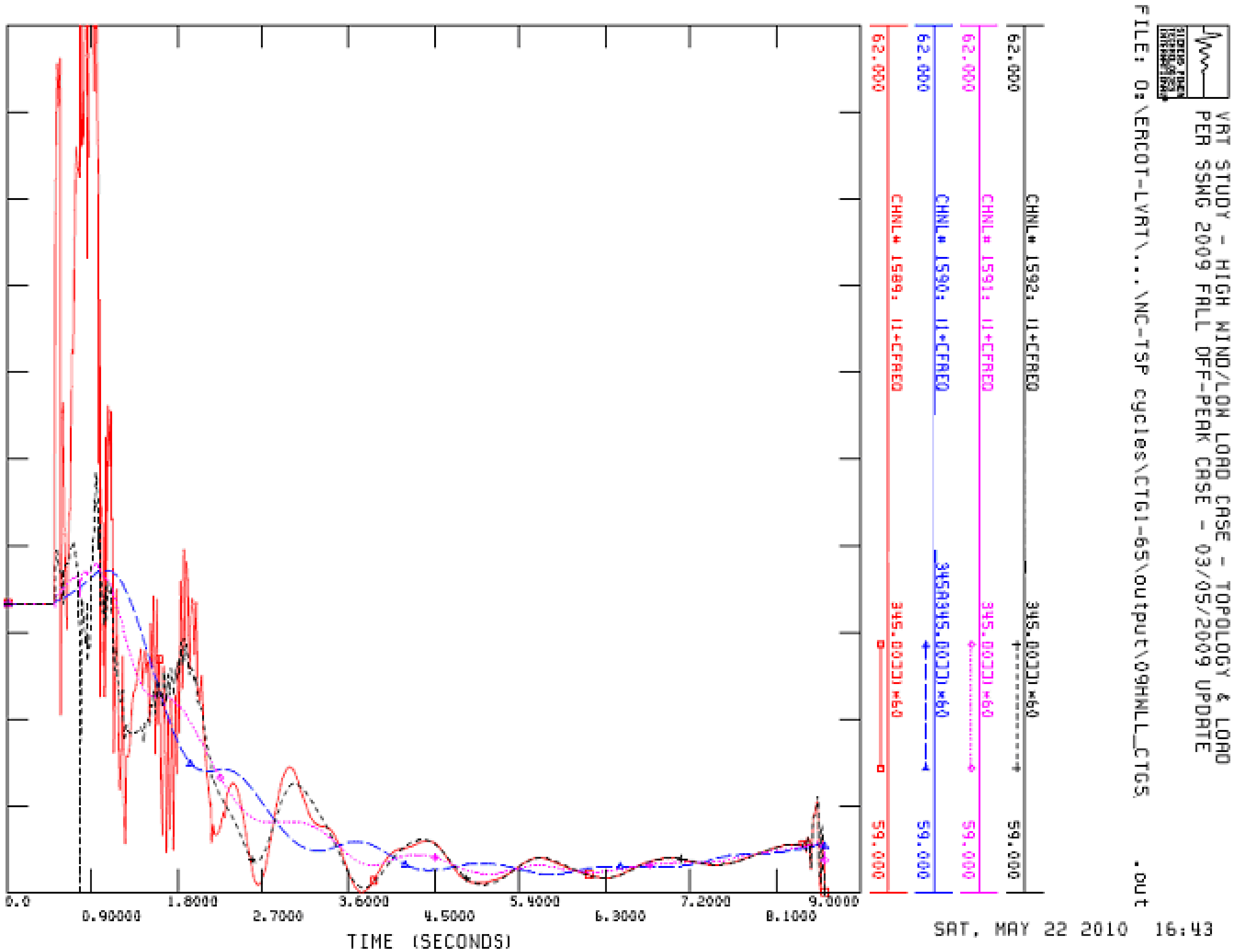

Exhibit 26-d: Frequency Response for all ERCOT zones for CTG5 (4 cycle fault duration) – Change Case 3

As mentioned in Chapter 6, the event associated with CTG5 does pose reliability risks for the ERCOT system as a whole. The fact is reiterated from the results obtained for CTG5 for Change Case 3 for 4 cycle fault duration. While it is clear from the results presented in this chapter and Chapter 6 that CTG5 does pose reliability risks for the ERCOT system as a whole for conditions modeled in Change Cases 1 and 3, the potential cause of the reliability issues needs to be established. To that effect, the aspects associated with CTG5 requiring further investigation include:

- Impact of West-North transfers modeled in Change Cases 1 and 3 on West-North stability limit during CTG5
  - With WGR models
  - Without WGR models
- Impact of inclusion of dynamic load models in West Texas in terms of exacerbating and/or expediting the voltage collapse phenomenon observed for CTG5 for Change Cases 1 and 3
- Role of lack of WGR VRT capability on the reliability risks stemming from CTG5 for Change Cases 1 and 3
- Potential lack of frequency reference for WGR models in West Texas (in the absence of any conventional units) there by leading to over-frequency trips that maybe purely restricted to modeling and/or simulation

All these aspects are investigated in elaborate detail in Change Case 5 thereby identifying the likely cause of the reliability risks stemming from CTG5 for conditions modeled in Change Cases 1 and 3.

8.2 Breaker Failure Events

The entire set of 31 S-L-G fault-based breaker failure events was simulated for Change Case 3. Exhibit 27 depicts the results for WGR trips associated with the breaker failure event simulations for Change Case 3.

As evident from Exhibit 27, BF#16 presents the most severe event in terms of WGR trips both in terms of Change Case 3 dispatch and WGR capacity lost. As depicted in Exhibit 27, BF#16 results in 1193 MW of WGR trips in terms of Change Case 3 dispatch and 1903 MW in terms of WGR capacity lost. A majority of the WGR trips are by virtue of under-voltage thereby clearly indicating the lack of WGR VRT capability as the probable cause for WGR trips.

Contingency Number	MW Tripped as per Change Case 3	MW Capacity Lost
BF1	951.00	1236.62
BF2	506.40	643.10
BF3	273.50	301.50
BF4	440.70	641.60
BF5	163.90	186.30
BF6	163.90	186.30
BF7	0.00	0.00
BF8	402.50	830.92
BF9	0.00	0.00
BF10	401.60	523.50
BF11	275.80	300.50
BF12	256.60	313.50
BF13	0.00	0.00
BF14	777.90	1269.48
BF15	860.10	1393.50
BF16	1193.20	1903.56
BF17	1036.40	1586.05
BF18	880.40	1390.08
BF19	922.90	1467.30
BF20	922.90	1467.30
BF21	787.40	1309.20
BF22	127.30	310.50
BF23	325.30	671.20
BF24	218.40	438.70
BF25	682.60	1189.60
BF26	682.60	1189.60
BF27	220.90	484.08
BF28	516.10	883.58
BF29	483.50	823.98
BF30	127.30	310.50
BF31	127.30	310.50

Exhibit 27: WGR Trips for Breaker Failure Events – Change Case 3

The WGR trips associated with BF#16 do not indicate reliability risks vis-à-vis the metrics outlined for the study either in terms of Change Case 3 dispatch or WGR capacity lost. The post-event frequency deviation associated with BF#16 is observed to be approximately 0.1 Hz. While the voltage recovery is delayed primarily due to lack of conventional voltage support and the presence of the dynamic load models, no concerns associated with voltage recovery and/or post-event voltage levels is witnessed.

Exhibits 28-a through 28-d depict the plots for various power system quantities associated with BF#16 for Change Case 3.

As in the case of Change Case 1, the results presented in this sub-section correspond to altered fault shunt admittance values to reflect the absence of conventional generation in West Texas. No other breaker failure event out of the simulated events seems to be indicative of reliability risks from a VRT standpoint.

8.3 Observations

Based on the results of normal clearing and breaker failure simulations for Change Case 3, the following observations can be made with respect to the reliability risks associated with the ERCOT system as a whole for the conditions modeled in the case:

- Amongst the normal clearing events, only CTG5 results in WGR trips indicative of reliability risks to the ERCOT system as a whole. The results are on expected lines since Change Case 3 is a derivative of Change Case 1 wherein CTG5 resulted in similar observations for 6 cycle fault duration. As in Change Case 1, a majority of the WGR trips for CTG5 are by virtue of over-frequency trips for Change Case 3.
- As pointed out in the observations made in Chapter 6, further investigation associated with CTG5 (in the absence of conventional generation in West Texas and inclusion of dynamic load models in West Texas) needs to be carried out. The aspects to be explored as part of the investigation include:
    - Impact of West-North transfers modeled in Change Case 3 on West-North stability limit during CTG5
        - With WGR models
        - Without WGR models
    - Impact of inclusion of dynamic load models in West Texas in terms of exacerbating and/or expediting the voltage collapse phenomenon observed for CTG5 for Change Case 3
    - Role of lack of WGR VRT capability on the reliability risks stemming from CTG5 for Change Case 3

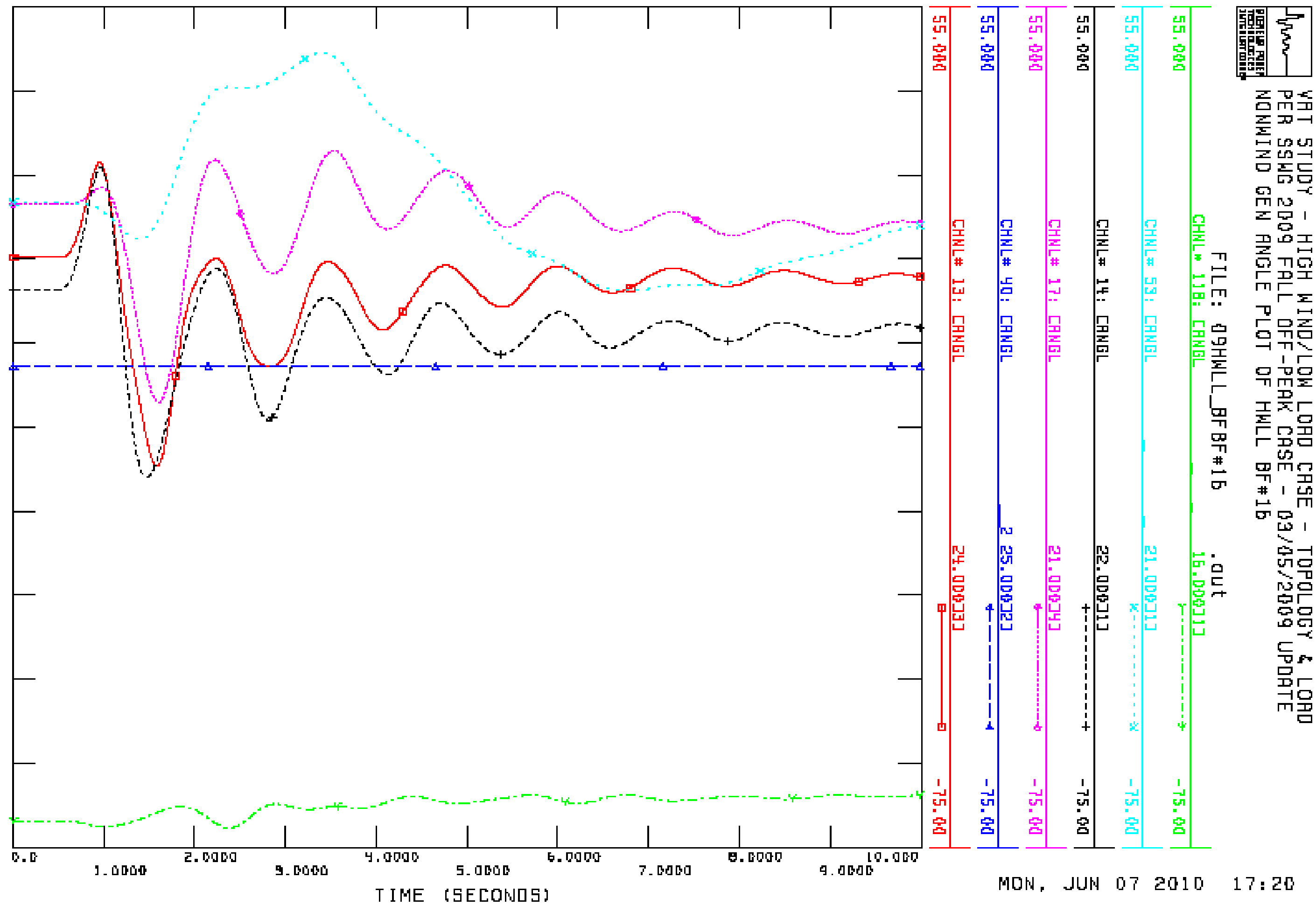

Exhibit 28-a: Rotor Angle Response for Conventional Generation Units for BF#16 – Change Case 3

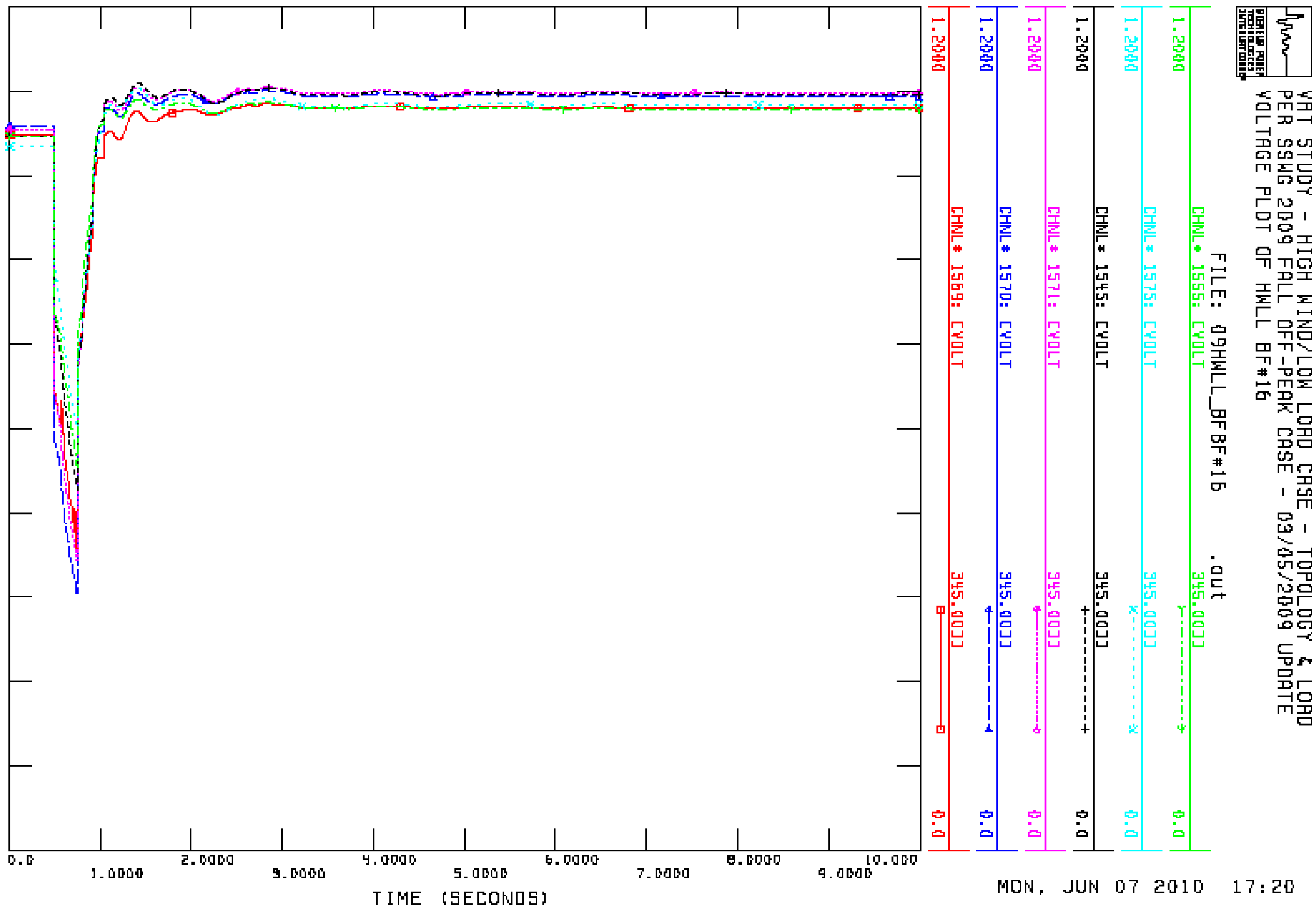

Exhibit 28-b: Voltage Response for 345 kV ERCOT West Stations for BF#16 – Change Case 3

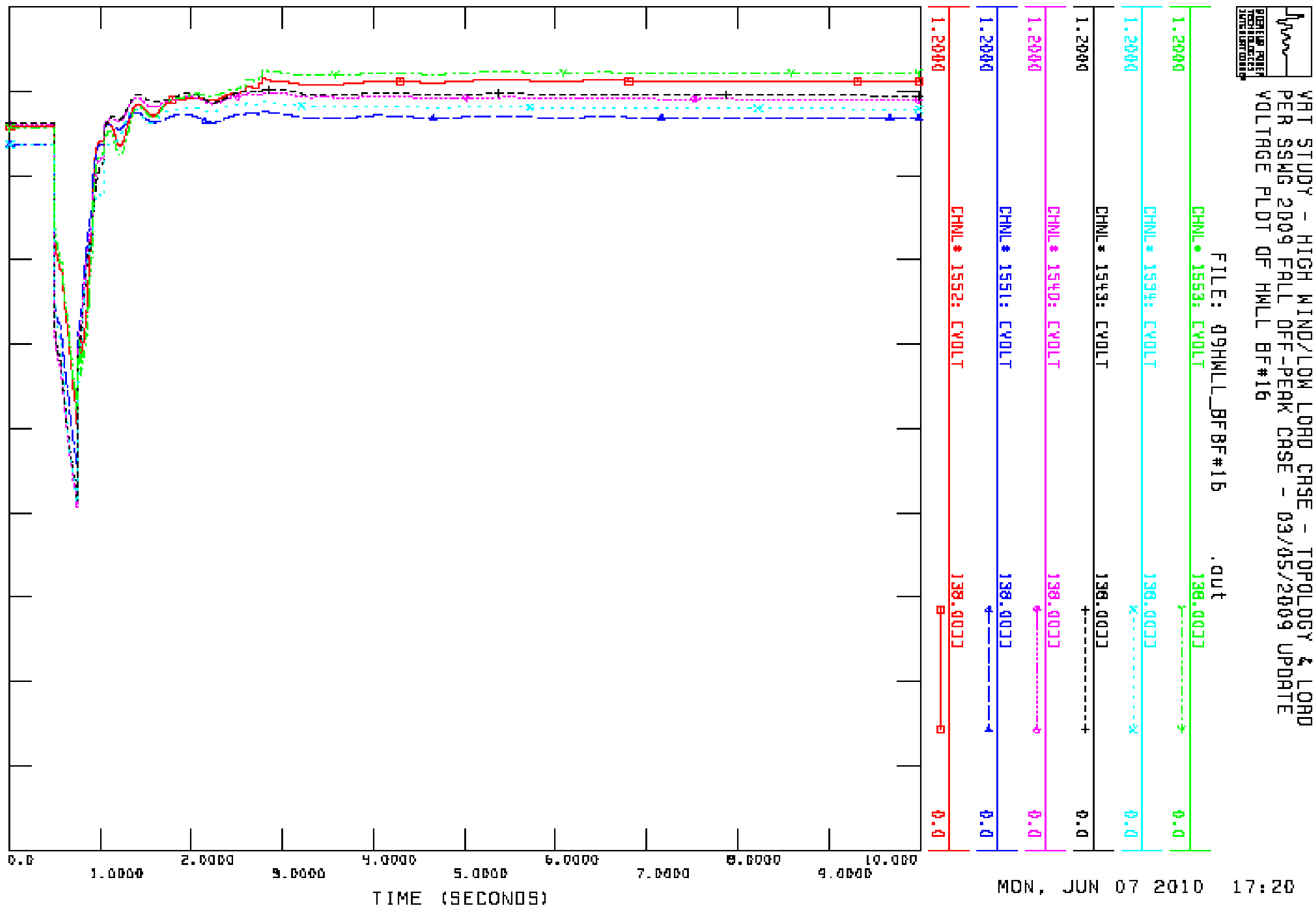

Exhibit 28-c: Voltage Response for 138 kV ERCOT West Stations for BF#16 – Change Case 3

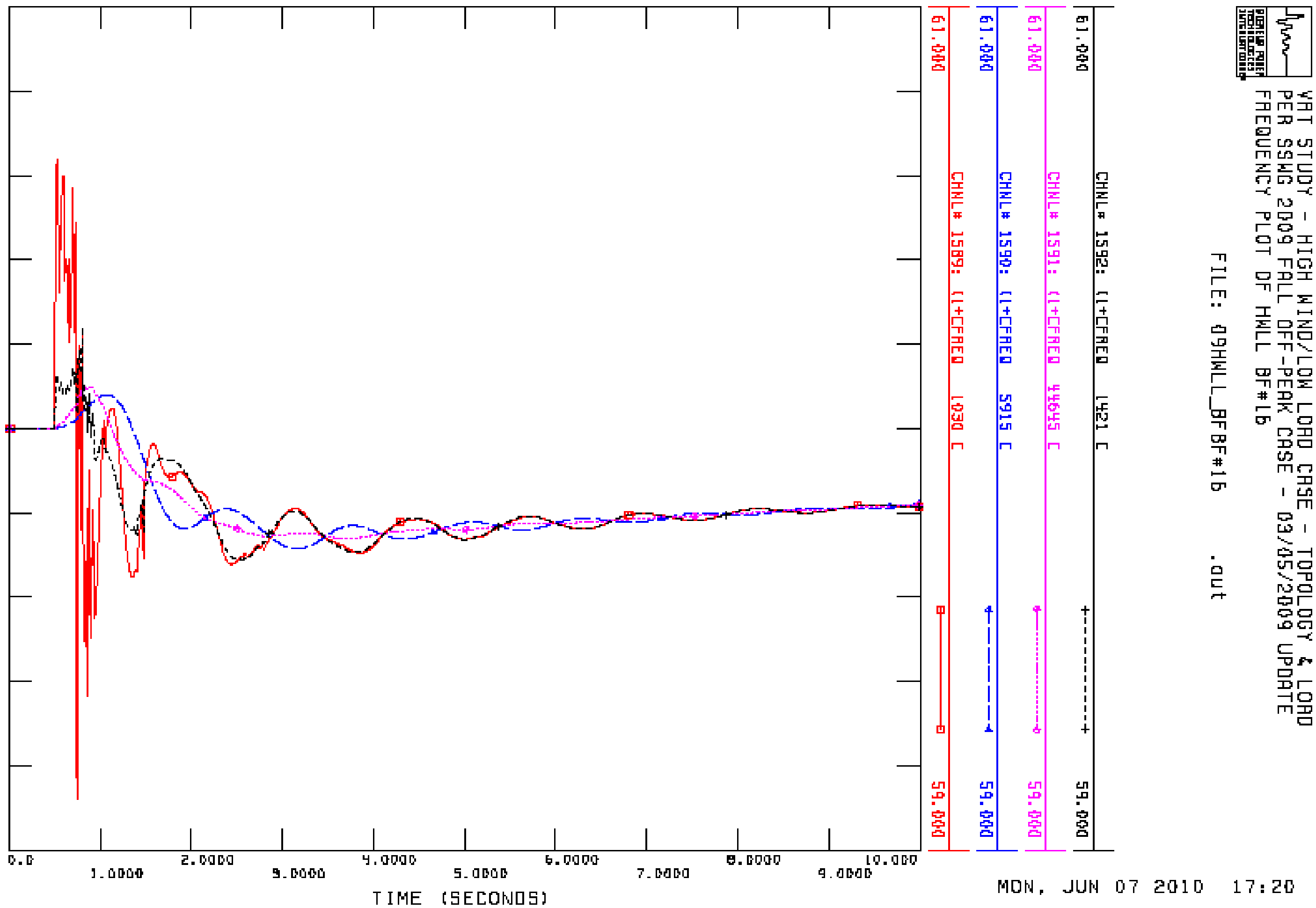

Exhibit 28-d: Frequency Response for all 4 ERCOT Zones for BF#16 – Change Case 3

   - Potential lack of frequency reference for WGR models in West Texas (in the absence of any conventional units) thereby leading to over-frequency trips that maybe purely restricted to modeling and/or simulation

- All the aforementioned aspects associated with CTG5 for Change Case 3 are investigated in detail as part of Change Case 5. A final conclusion on the role of WGR VRT capability in the reliability risks stemming from CTG5 for Change Cases 1 and 3 is presented in Change Case 5.
- No other normal clearing event simulated poses reliability risks associated with the lack of WGR VRT capability for Change Case 3.
- In terms of breaker failure events, BF#16 presents the most severe case in terms of WGR trips. The event associated with BF#16 results in 1193 MW of WGR trips in terms of Change Case 3 dispatch and approximately 1903 MW in terms of WGR capacity lost.
- The WGR trips associated with BF#16 do not exceed the ERCOT RRS requirement of 2300 MW. Furthermore, the post-event frequency deviation does not seem to present any reliability concerns stemming from the lack of WGR VRT capability.
- The voltage recovery is observed to be delayed by virtue of the lack of conventional voltage support and presence of dynamic load models in Change Case 3. However no voltage recovery and/or post-event voltage level concerns are witnessed for BF#16 for Change Case 3.
- It is important to bear in mind the need to alter the fault shunt admittance values in order to reflect the absence of conventional generation units in West Texas for Change Case 3.
- None of the breaker failure events simulated pose reliability risks associated with the lack of WGR VRT capability for Change Case 3.

9 Simulation Results – Change Case 4

Unlike the previous change cases discussed in Chapters 5 through 8, Change Case 4 was specifically designed to assess the impact of WGR modeling variations on WGR trips by virtue of VRT capability or the lack thereof. The following aspects associated with the modeling of WGRs and their impact on the WGR trips was investigated in detail as part of Change Case 4:

- **Impact of low pre-fault WGR terminal voltage**

While the voltage at the transmission bus (POI) associated with a WGR is almost always maintained within acceptable limits under normal operating and contingency conditions by means of external voltage control devices, the collector system voltage could be operating at lower levels prior to the occurrence of a dynamic event. The voltage at the POI is adjusted with the sub-station level capacitor banks and/or LTC control of the sub-station transformer to meet prevalent reactive standards associated with the host grid, independent of having the collector system voltages at lower operational levels. This operational situation is especially important for WGRs employing Type I and Type II machines without advanced VRT capabilities. Change Case 4 is designed to investigate the impact of low pre-fault voltage at the WGR turbine terminals, especially for WGRs utilizing turbines with no VRT capability, while maintaining the transmission bus voltage within acceptable operating limits as per incumbent TSP voltage criteria.

The ensuing sub-sections in this chapter present the results and observations associated with aforementioned investigation. Strategically chosen normal clearing and/or breaker failure events are utilized to demonstrate the results of the investigation.

9.1 Impact of low pre-fault voltage on WGR Trips

Sensitivity studies are indicative of pre-fault voltage at the WGR turbine terminals prior to the dynamic event to have a profound impact on the ability of the turbine to ride through voltage dips. This is especially true for WGRs utilizing Type I and Type II turbines with no VRT capability since the ability of these turbines to ride through voltage dips during dynamic events would be impacted by the pre-fault voltage level. To this effect, the impact of low pre-fault voltage for select WGRs was studied as a sensitivity scenario as part of Change Case 4.

As mentioned earlier, specific dynamic events (identified to be severe in terms of WGR trips based on the results presented in the previous chapters) associated with specific cases have been utilized to study the sensitivity associated with low pre-fault voltage. The objectives of the sensitivity study documented in this sub-section are as follows:

- Assess the impact of low pre-fault WGR terminal voltages while maintaining transmission bus voltages within acceptable levels especially for WGRs utilizing turbines with no VRT capability
- Assess impact of the same on WGR trips by virtue of lack of VRT capability and the reliability risks associated with over-all WGR trips for the event, if any

9.1.1 HWHL Case

CTG9, previously identified as the most severe event for HWHL case, was selected for performing the sensitivity study for the HWHL case. PB identified certain WGRs that do not possess VRT capability but do not trip for CTG9 for HWHL case. The pre-fault terminal voltage for these WGRs, as depicted in Exhibit 29, was altered to a lower value while maintaining the transmission bus voltage at the original value as modeled in the HWHL case. A combination of changing the sub-station capacitor bank status and the sub-station LTC was utilized to alter the terminal voltages of the WGRs without affecting the transmission bus voltage. If a low pre-fault voltage associated with the terminals of these WGRs does result in their tripping, the over-all WGR trips would exceed the ERCOT RRS requirement of 2300 MW in terms of WGR capacity lost thereby posing a reliability risk by virtue of lack of VRT capability.

Wind Farm	VRT Capability	ORIGINAL PRE-FAULT VOLTAGE (p.u)	NEW PRE-FAULT VOLTAGE (p.u)
WGR A	No LVRT	1.056	0.984
WGR B	No LVRT	1.013	0.989
WGR C	No LVRT	1.026	0.976
WGR D	No LVRT	1.040	0.967
WGR E	No LVRT	1.043	0.969
WGR F	No LVRT	1.053	0.979
WGR G	No LVRT	1.015	0.956
WGR H	No LVRT	1.024	0.964
WGR I	No LVRT	1.048	0.976
WGR J	No LVRT	1.039	0.980
WGR K	No LVRT	1.013	0.984

Exhibit 29: WGRs selected for low pre-fault terminal voltage sensitivity, HWHL case

The normal clearing event CTG9 was simulated for the HWHL case with the altered WGR pre-fault terminal voltages. Exhibit 30 depicts the amount of WGR trips associated with CTG9 for the HWHL case with the original and lowered pre-fault terminal voltages for WGRs depicted in Exhibit 29. The following incremental WGR trips are observed by virtue of low pre-fault terminal voltages modeled in the simulation:

- WGR A – The WGR utilizes Type II wind turbines which have no VRT capability and hence can withstand a voltage below 0.75 pu for less than 0.08s as per the turbine voltage relay settings. In the original HWHL case, the voltage drops below 0.75 pu but recovers to above that value within 0.08s thereby preventing the WGR trip. However with a lower pre-fault voltage and a fault duration of 0.1s (6 cycles) the voltage does not recover to above 0.75 pu within 0.08s leading to WGR trip. Exhibit 31-a depicts the voltage response associated with the WGR aggregated model with the original and lowered pre-fault terminal voltage.
- WGR C – The WGR utilizes Type III machines with the standard drop-out option and no additional VRT capability thereby implying an instantaneous trip if the voltage goes below 0.7 pu as per the voltage relay settings. In the original HWHL case, the WGR voltage is marginally higher than 0.7 pu thereby preventing the trip. However with the lower pre-fault terminal voltage, the voltage goes below 0.7 pu thereby triggering an instantaneous trip (barring breaker operation time). Exhibit 31-b depicts the voltage response associated with the WGR aggregated model with the original and lowered pre-fault terminal voltage.

Both of these WGRs are part of the list of WGRs for which the pre-fault terminal voltages were lowered, per Exhibit 29, as part of the sensitivity study. As for the other WGRs listed in Exhibit 29 that do not trip, the no trips are explained as follows:

- WGR B – The WGR utilizes Type I machines that do not possess any VRT capability. However, the relay settings associated with the wind turbine model are indicative of the turbine possessing the capability of withstanding a voltage below 0.85 pu for 5 seconds. Thus the turbines do not trip for the event even with lower pre-fault WGR terminal voltages.
- WGR D & WGR E: These WGRs employ Type III turbines with the standard drop out option and no additional VRT capability. The machines do not trip for the original HWHL case for CTG9 due to the WGRs being electrically distant from the fault location thereby preventing a pronounced voltage dip from being experienced at the turbine terminals. The machines do not trip for the HWHL case with lower pre-fault terminal voltages since the voltage still does not fall below the standard dropout voltage threshold. However, the lowering of the pre-fault terminal voltage does make these WGRs marginal in terms of tripping as can be seen from Exhibit 32. As evident from Exhibit 32, the lowering of the pre-fault terminal voltage for WGR D & WGR E does result in a more pronounced voltage dip for CTG9.

Wind Farm	Machine Type	Trip Reason	HWHL MW Dispatch	MW Capacity Lost
Total WGR Trips with original pre-fault voltage			**1140.75**	**1706.20**
Incremental WGR Trips due to lowered pre-fault voltage				
WGR A	Type II	VTGDCA		
WGR C	Type III	VTGDCA		
Total WGR Trips with lowered pre-fault voltage			**1227.74**	**2009.20**

Exhibit 30: WGR Trips for CTG9 with original and lowered pre-fault terminal voltages – HWHL case

- WGRs F through K: These WGRs employ a specific Type I turbine. This same turbine is also utilized for WGR L. The voltage response of these WGRs is analyzed together as follows:

Of these WGRs, the only WGR that trips for CTG9 in the original HWHL case or the case with lowered pre-fault terminal voltage at all the aforementioned WGRs is WGR L. In order to understand this, it is important to state the under-voltage relay settings associated with the Type I machines:

- Under-Voltage Setting #1: Voltage below 0.85 pu for 0.5 s
- Under-Voltage Setting #2: Voltage below 0.7 pu for 0.25s
- Under-voltage Setting #3: Voltage below 0.6pu for 0.15s

Exhibit 33 depicts the voltage response associated with all the WGRs mentioned above utilizing the specific Type I machines for CTG9 for the original HWHL case. As can be seen from Exhibit 33, the Type I machine associated with WGR L trips on voltage recovery.

It is also interesting to note that the voltages associated with all other WGRs employing that turbine type experience a more pronounced dip during the event as compared to WGR L. This is because all the other WGRs are electrically closer to the fault location when compared to the connection for WGR L. However, the voltage recovery associated with WGR L is much weaker resulting in the WGR trip. This can be attributed to the relative transmission system strength in the vicinity of WGR L when compared to WGRs F through K.

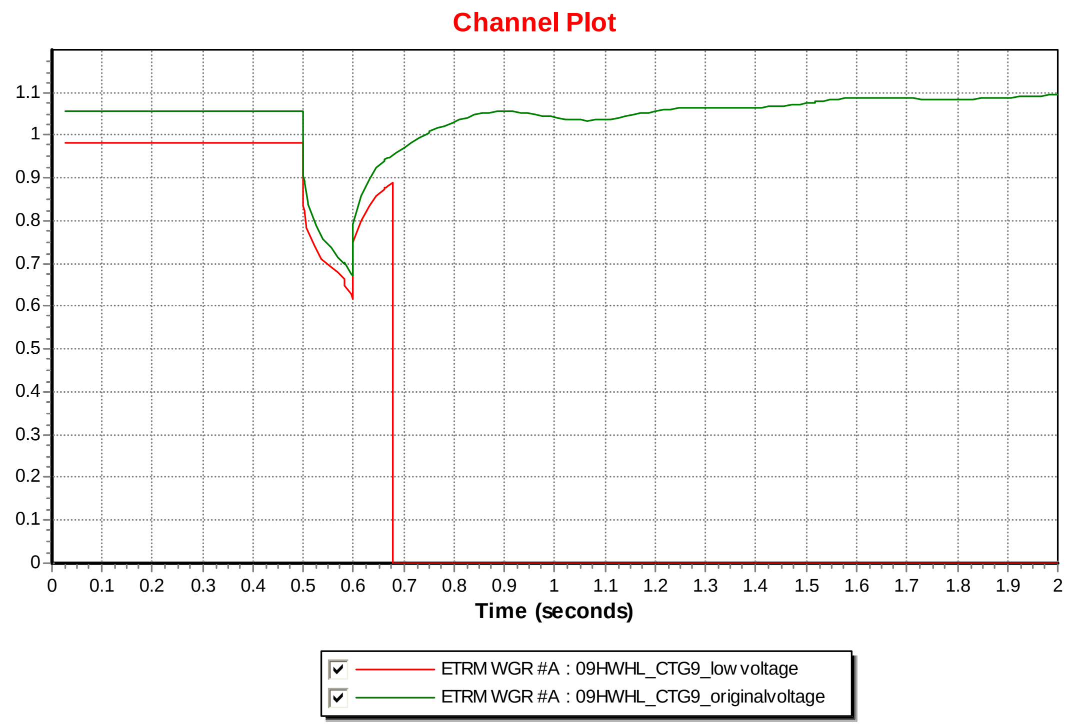

Exhibit 31-a: Terminal Voltage response for WGR A with original and lower pre-fault voltage – CTG9, HWHL Case

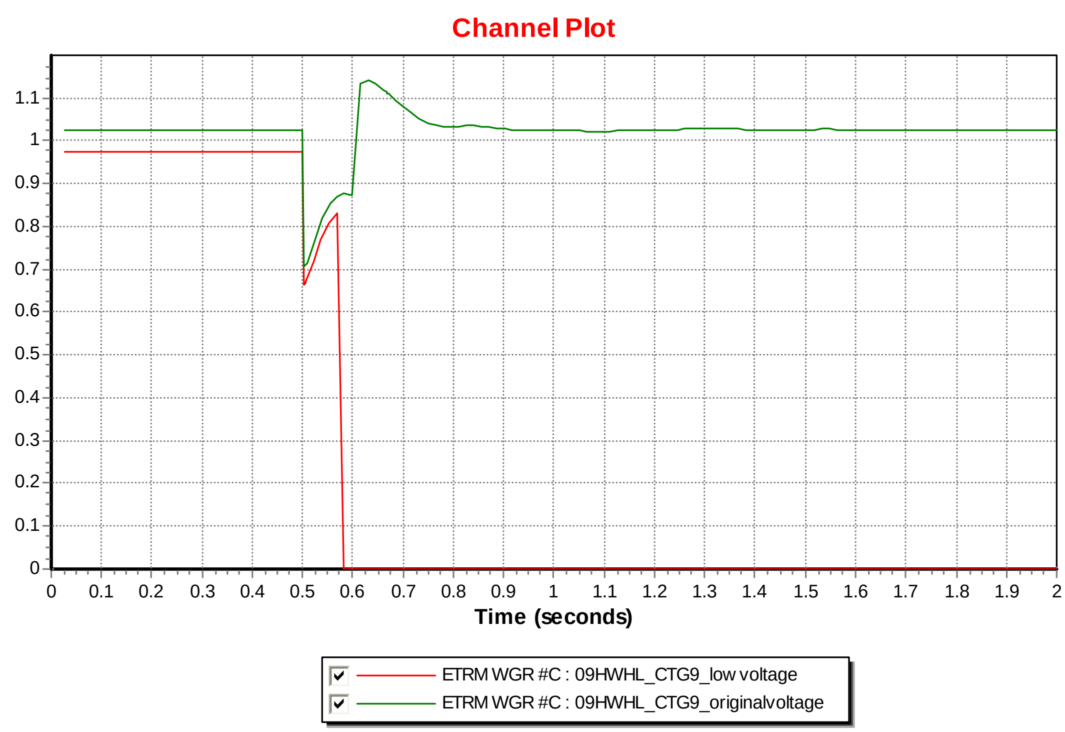

Exhibit 31-b: Terminal Voltage response for WGR C with original and lower pre-fault voltage – CTG9, HWHL Case

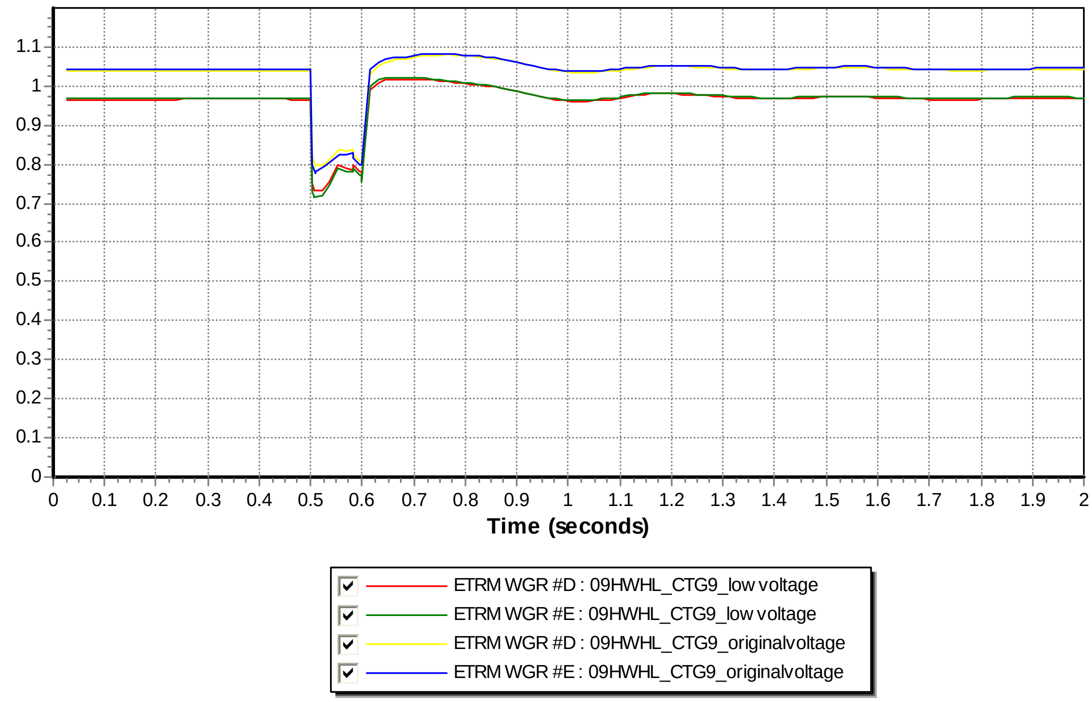

Exhibit 32: Terminal Voltage response for WGR D & WGR E with original and lower pre-fault voltage – CTG9, HWHL Case

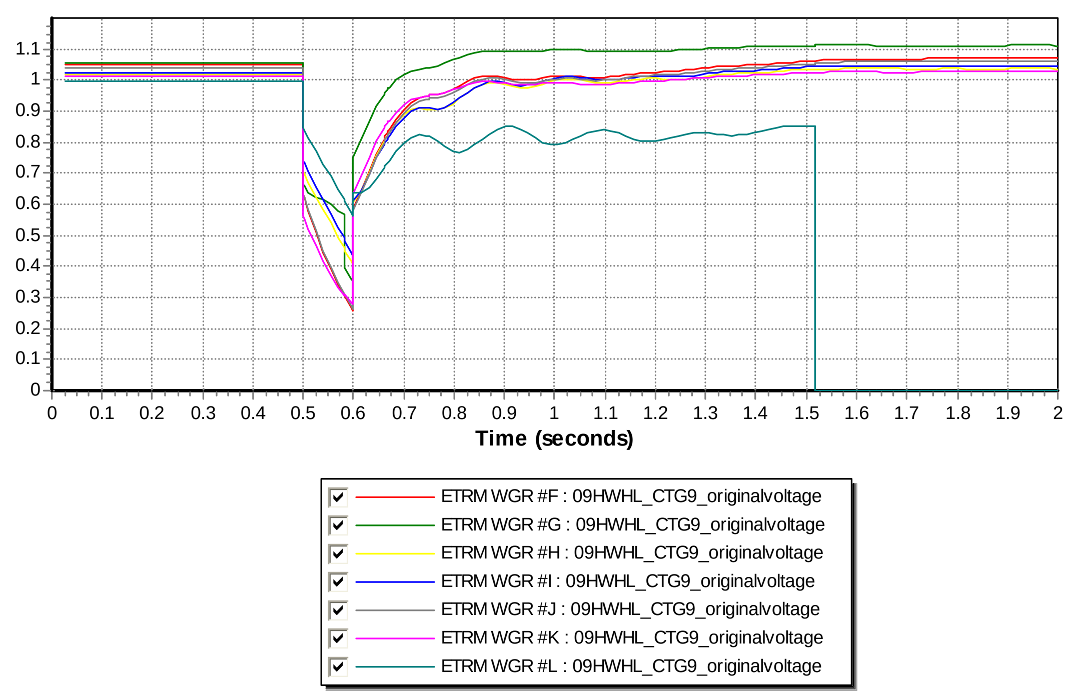

Exhibit 33: Terminal Voltage response for Wind Farms utilizing certain Type I turbines with original voltage – CTG9, HWHL Case

9.1.2 Change Case 1

CTG5 was chosen as the test event for performing sensitivity analysis associated with low pre-fault WGR terminal voltage for Change Case 1. CTG5 was observed to be the most severe event for Change Case 1 but certain WGRs with no VRT capability were observed to have not tripped. As explained in the previous sub-section, the pre-fault voltage at the WGR terminals was adjusted to a lower value without adjusting the transmission bus voltage. In some cases, in the absence of Load Tap Changer at the sub-station transformer associated with WGR, the transmission bus voltage was reduced in order to reduce the terminal voltage for the WGR while still maintaining the transmission bus voltage within acceptable limits. CTG5 was simulated for Change Case 1 with lowered pre-fault terminal voltages for WGRs as depicted in Exhibit 34-a. Exhibit 34-b depicts the amount of WGR trips associated with CTG5 for Change Case 1 with the original and lowered pre-fault terminal voltages. The lower pre-fault terminal voltage results in 413 MW of incremental WGR trips in terms of Change Case 1 WGR dispatch and 642 MW of incremental WGR capacity tripped for CTG5.

Change Case 1 is indicative of being more sensitive than the HWHL case to lower pre-fault terminal voltages as far as incremental WGR trips are concerned. This is due to the lack of voltage support from conventional generation in West Texas. However, the total WGR trips associated with lower pre-fault voltages for CTG5 for Change Case 1 do not exceed the ERCOT RRS requirement of 2300 MW in terms of Change Case 1 dispatch and/or WGR capacity lost.

Wind Farm	VRT Capability	ORIGINAL PRE-FAULT VOLTAGE (p.u)	LOWER PRE-FAULT VOLTAGE (p.u)
WGR A	No LVRT	1.043	0.969
WGR B	No LVRT	1.046	0.969
WGR C	No LVRT	1.039	0.968
WGR D	No LVRT	1.036	0.965
WGR E	No LVRT	1.045	0.970
WGR F	No LVRT	1.016	0.961
WGR G	No LVRT	1.020	0.966
WGR H	No LVRT	1.028	0.957
WGR I	No LVRT	1.041	0.959
WGR J	No LVRT	1.036	0.976
WGR K	No LVRT	1.004	0.944
WGR L	No LVRT	1.013	0.952
WGR M	No LVRT	1.042	0.973
WGR N	No LVRT	1.040	0.963
WGR O	No LVRT	1.048	0.959
WGR P	No LVRT	1.035	0.957
WGR Q	No LVRT	1.048	0.970
WGR R	No LVRT	1.032	0.968
WGR S	No LVRT	1.045	0.982
WGR T	No LVRT	1.003	0.952
WGR U	No LVRT	1.007	0.957
WGR V	No LVRT	1.006	0.956
WGR W	No LVRT	0.999	0.949
WGR X	No LVRT	0.992	0.999
WGR Y	No LVRT	1.037	0.971

Exhibit 34-a: WGRs selected for low pre-fault terminal voltage sensitivity, Change Case 1

Wind Farm	Machine Type	Trip Reason	Change Case 1 MW Dispatch	MW Capacity Lost
Total WGR Trips with original pre-fault voltage			**734.60**	**977.90**
Incremental WGR Trips due to lowered pre-fault voltage				
WGR T	Type II	VTGDCA		
WGR U	Type II	VTGDCA		
WGR V	Type II	VTGDCA		
WGR W	Type II	VTGDCA		
WGR K	Type I	VTGDCN		
WGR L	Type I	VTGDCN		
WGR E	Type III	VTGDCA		
WGR H	Type I	VTGTRP		
WGR Z	Type I	VTGTRP		
Total WGR Trips with lowered pre-fault voltage			**1147.60**	**1620.10**

Exhibit 34-b: WGR Trips for CTG5 with original lowered pre-fault terminal voltages - Change Case 1

9.1.3 Change Case 2

Similar to the HWHL case, CTG9 is utilized to perform the sensitivity study associated with lower pre-fault terminal voltages for WGRs not possessing VRT capabilities for Change Case 2. The pre-fault terminal voltage for selected WGRs, as depicted in Exhibit 35-a, was altered to a lower value while maintaining the transmission bus voltage at the original value as modeled in Change Case 2. The objective of performing this exercise on Change Case 2 was to assess the impact of lower pre-fault terminal voltages for the HWHL case with the inclusion of the dynamic load models in West Texas.

Wind Farm	VRT Capability	ORIGINAL PRE-FAULT VOLTAGE (p.u)	LOWER PRE-FAULT VOLTAGE (p.u)
WGR A	No LVRT	1.013	0.989
WGR B	No LVRT	1.026	0.976
WGR C	No LVRT	1.040	0.967
WGR D	No LVRT	1.043	0.969
WGR E	No LVRT	1.053	0.979
WGR F	No LVRT	1.015	0.956
WGR G	No LVRT	1.024	0.964
WGR H	No LVRT	1.048	0.976
WGR I	No LVRT	1.039	0.980
WGR J	No LVRT	1.013	0.984

Exhibit 35-a: WGRs selected for low pre-fault terminal voltage sensitivity, Change Case 2

Exhibit 35-b depicts the amount of WGR trips associated with CTG9 for Change Case 2 with the original and lowered pre-fault terminal voltages for WGRs listed in Exhibit 35-a. The lower pre-fault terminal voltage results in 37.5 MW of incremental WGR trips in terms of Change Case 2 WGR dispatch and 220.5 MW of incremental WGR capacity tripped for CTG5.

Lower pre-fault terminal voltage does result in a small increase in the amount of WGR trips for Change Case 2. However, the total WGR trips associated with lower pre-fault voltages for CTG9 for Change Case 2 do not exceed the ERCOT RRS requirement of 2300 MW in terms of Change Case 2 dispatch and/or WGR capacity lost.

Wind Farm	Machine Type	Trip Reason	Change Case 2 MW Dispatch	MW Capacity Lost
Total WGR Trips with original pre-fault voltage			**1137.29**	**1628.20**
Incremental WGR Trips due to lowered pre-fault voltage				
WGR B	Type III	VTGDCA		
Total WGR Trips with lowered pre-fault voltage			**1174.77**	**1848.70**

Exhibit 35-b: WGR Trips for CTG9 with original and lowered pre-fault terminal voltages – Change Case 2

9.1.4 Change Case 3

CTG9 was observed to be the most severe event for Change Case 3 (apart from CTG5 which is investigated in Change Case 5) and was chosen as the test event for performing sensitivity analysis associated with low pre-fault WGR terminal voltage for Change Case 3. CTG9 was simulated for Change Case 3 with lowered pre-fault terminal voltages for certain WGRs as depicted in Exhibit 34-a. Exhibit 35-c depicts the amount of WGR trips associated with CTG9 for Change Case 3 with the original and lowered pre-fault terminal voltages for WGRs listed in Exhibit 34-a. The lower pre-fault terminal voltage results in 337 MW of incremental WGR trips in terms of Change Case 3 WGR dispatch and 540 MW of incremental WGR capacity tripped for CTG9.

Wind Farm	Machine Type	Trip Reason	Change Case 3 MW Dispatch	MW Capacity Lost
Total WGR Trips with original pre-fault voltage			**685.00**	**988.50**
Incremental WGR Trips due to lowered pre-fault voltage				
WGR B	Type I	VTGTRP		
WGR R	Type II	VTGDCA		
WGR S	Type II	VTGDCA		
WGR E	Type III	VTGDCA		
WGR F	Type III	VTGDCA		
WGR I	Type I	VTGDCN		
Total WGR Trips with lowered pre-fault voltage			**1022.50**	**1528.68**

Exhibit 35-c: WGR Trips for CTG9 with original and lowered pre-fault terminal voltages – Change Case 3

Change Case 3 with no conventional voltage support is observed to be more sensitive to lower pre-fault terminal voltages with incremental WGR trips being higher than HWHL and/or Change Case 2. However, the total WGR trips for CTG9 in terms of Change Case 3 dispatch and/or WGR capacity lost do not exceed the ERCOT RRS requirement of 2300 MW.

9.1.5 Observations

Based on the results of the investigations documented in the previous sub-sections of this chapter, the following observations can be made:

- The total amount of WGR trips for the most severe events associated with the HWHL case and Change Cases 1, 2 and 3 do not pose reliability risks from a VRT standpoint when considering lower pre-fault WGR terminal voltages.
- Lower pre-fault WGR terminal voltage seems to impact WGRs that are on the margin in terms of the voltage dips due to a certain event when compared to the VRT capability. The incremental WGR trips associated with lower pre-fault WGR terminal voltages seem to be more pronounced for Change Cases 1 and 3. This is primarily due to the lack of conventional voltage support in these two cases.
- The results presented in this section are based on the turbine model under-voltage relay settings as provided to PB by WGRs as part of the data submittal. This comment is especially true for specific Type I machines which are demonstrated to ride through pronounced voltage dips based on the under-voltage relay settings. Study results and conclusions would be impacted if the under-voltage relay settings associated with this or other turbine types are found to be different than the settings provided and utilized for sensitivity study.

10 Simulation Results – Change Case 5

Change Case 5 was designed to perform detailed investigation into events that were identified to pose reliability risks to the ERCOT system as a whole spanning all the simulations performed for HWHL/HWLL cases and Change Cases 1 through 4. As evident from the results and discussion presented in the previous chapters, the lone event indicative of potential reliability risks to the ERCOT system as a whole is CTG5 for Change Case 3.

The above mentioned event was identified to result in WGR trips indicative of potential reliability risks in terms of the case dispatch and the WGR capacity lost for Change Case 3. The following aspects were investigated for the event identified above:

- Differentiation between real system phenomenon versus modeling and/or simulation issues
- Role of lack of WGR VRT capability in the reliability risks identified for the event
- Potential mitigation options if the issue identified is representative of real system phenomenon posing credible reliability risk to the ERCOT system as a whole due to lack of WGR VRT capability

The ensuing sub-sections provide elaborate discussion on the investigation associated with the event identified above.

10.1 Change Case 3, CTG5 Investigation

As identified in Chapter 8, CTG5 resulted in 3965 MW of WGR trips in terms of Change Case 3 dispatch and approximately 6214 MW in terms of WGR capacity lost. A majority of the WGR trips were by virtue of over-frequency resulting from drastic frequency variations in West Texas following the outage of the transmission circuits characterizing CTG5. Change Case 3 is representative of high wind light load conditions with no conventional generation in West Texas and the inclusion of the dynamic load models for West Texas. This sub-section provides discussion associated with the following investigation aspects covered for CTG5 for Change Case 3:

- Impact of “token” conventional generation unit in West Texas to serve as frequency reference – Investigation #1
- Impact of West-North voltage stability limit based on the West-North transfers modeled in Change Case 3 in the absence of conventional units in West Texas – Investigation #2

- Role of lack of WGR VRT capability on reliability risks identified for CTG5 for Change Case 3 – Investigation #3

The behavior and impact of the dynamic load model is also observed and commented upon as part of each of the 3 investigations mentioned above.

10.1.1 Investigation #1 Results

One of the primary causes for the large amount of WGR trips being observed for CTG5 in Change Case 3 was the drastic over-frequency swing being observed in West Texas following the outages of the transmission circuits characterizing CTG5. The possibility of low short circuit capacity leading to unstable behavior of GEWTE1 model was ruled out by determining the short circuit capacity associated with all the WGR locations utilizing the aforementioned model. However, discussion with PTI revealed that the GEWTE1 model assumed the presence of an "external synchronous source" within a certain impedance range.

The GEWTE1 model is designed for operation with an external synchronous source. There is an existing concern with a frequency problem when the model operates in a weak network with large impedance separating the WTGs from any synchronous source which is the case in Change Cases 1 and 3. The frequency is reasonable when the network is closely interconnected with other synchronous machines. However, when the fault and or subsequent outages isolate the WTGs from the rest of the system and large impedance separates the WTGs from a synchronous source during and after the clearing of the fault, the GEWTG model tends to have difficulty tracking the voltage angle and thus exhibits strange angle and frequency behavior. This is so because the converter model utilizes the voltage angle to decide the levels of active and reactive power injection into the grid. In this situation, the WTG voltage loses track of the system angle and drifts until it finally "clicks in" again with the system frequency. The duration of this phenomenon is a few cycles, and it tends to manifest itself in the form of a frequency spike in PSS/E purely because of how PSS/E calculates the voltage frequency.

For this precise reason, it is important to ascertain if the lack of a synchronous source within a certain impedance range of the WGRs utilizing the GEWTG model results in the over-frequency phenomenon observed for CTG5. The GEWTG model is focused upon since a majority of the over-frequency trips are associated with WGRs utilizing the GEWTG model.

The first test performed as part of this investigation involved turning on a "token conventional unit" to serve as frequency reference in West Texas following the outages associated with CTG5. The conventional generation unit was chosen in a manner such that it is electrically distant from the fault location thereby not providing any substantial voltage support during the voltage dip associated with the event. Exhibit 36 depicts the active power, reactive power and terminal voltage response associated with the conventional unit turned on for CTG5 for Change Case 3. Exhibit 37 depicts the system frequency response for CTG5 for Change Case 3 with the conventional unit turned on in West Texas. As can be seen from Exhibits 36 and 37, the presence of the conventional unit in West Texas does not seem to alleviate the frequency deviation observed for CTG5 for Change Case 3. In fact, the sharp frequency rise results in drastic increase of the rotor angle for the conventional unit indicative of the machine "running away" and settling at a different equilibrium after the system phenomenon has settled. As expected no change in the WGR trips by virtue of over-frequency is observed.

The second test performed as part of this investigation involved turning on two conventional units at a location electrically close to the fault location associated with CTG5. The units were dispatched at their respective minimums. No wind dispatch was scaled down allowing the slack bus to account for the increase in output at the two conventional units. The objective of this test was to assess whether the drastic frequency response associated with West Texas was due to the lack of frequency reference or a manifestation of West-North voltage instability being observed for CTG5 for Change Case 3. Apart from the West Texas frequency, the reactive power output of the two units was observed carefully during the simulation. This was done to assess the reactive deficiency which is often the primary cause of short-term voltage instability similar to that being observed for Change Case 3. Exhibits 38-a, 38-b and 38-c depict the system frequency and voltage response associated with CTG5 for Change Case 3 with the two conventional generation units online while Exhibits 39-a, 39-b and 39-c depict the active power, reactive power and rotor angle response associated with the two units respectively.

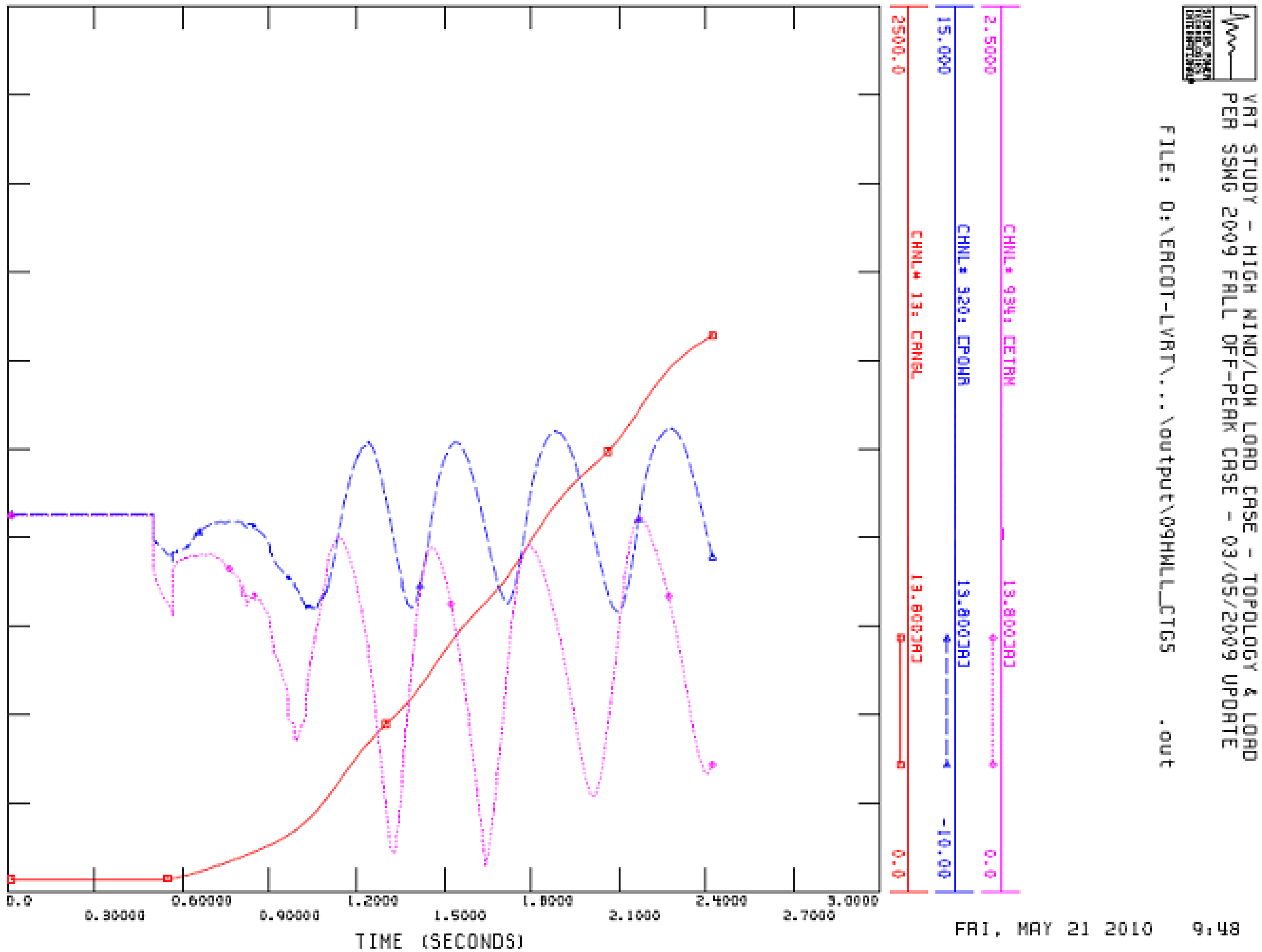

Exhibit 36: Active Power, Terminal Voltage and Rotor Angle Response for "token conventional unit" West Texas – CTG5, Change Case 3

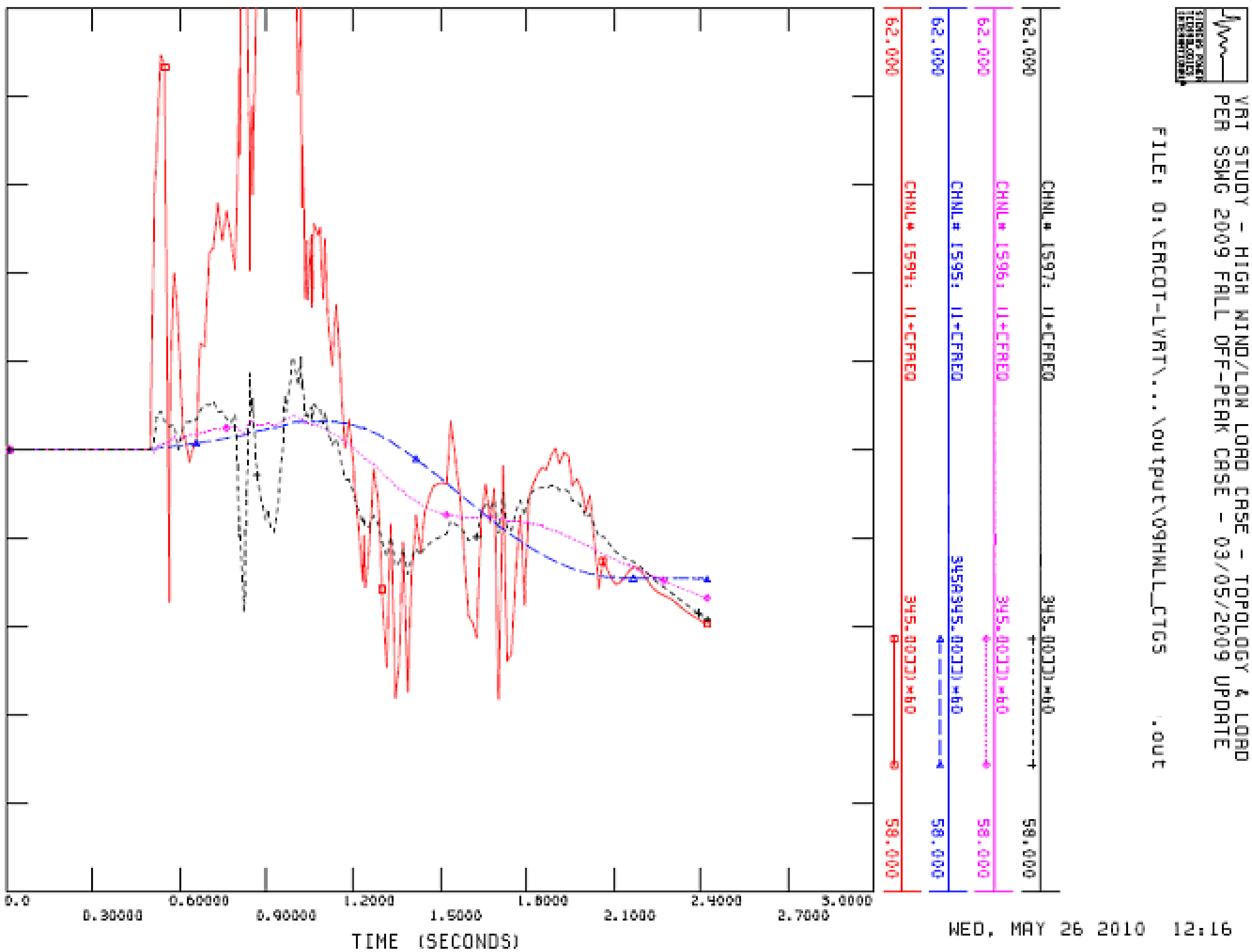

Exhibit 37: System Frequency Response with “token conventional unit” On in West Texas – CTG5, Change Case 3

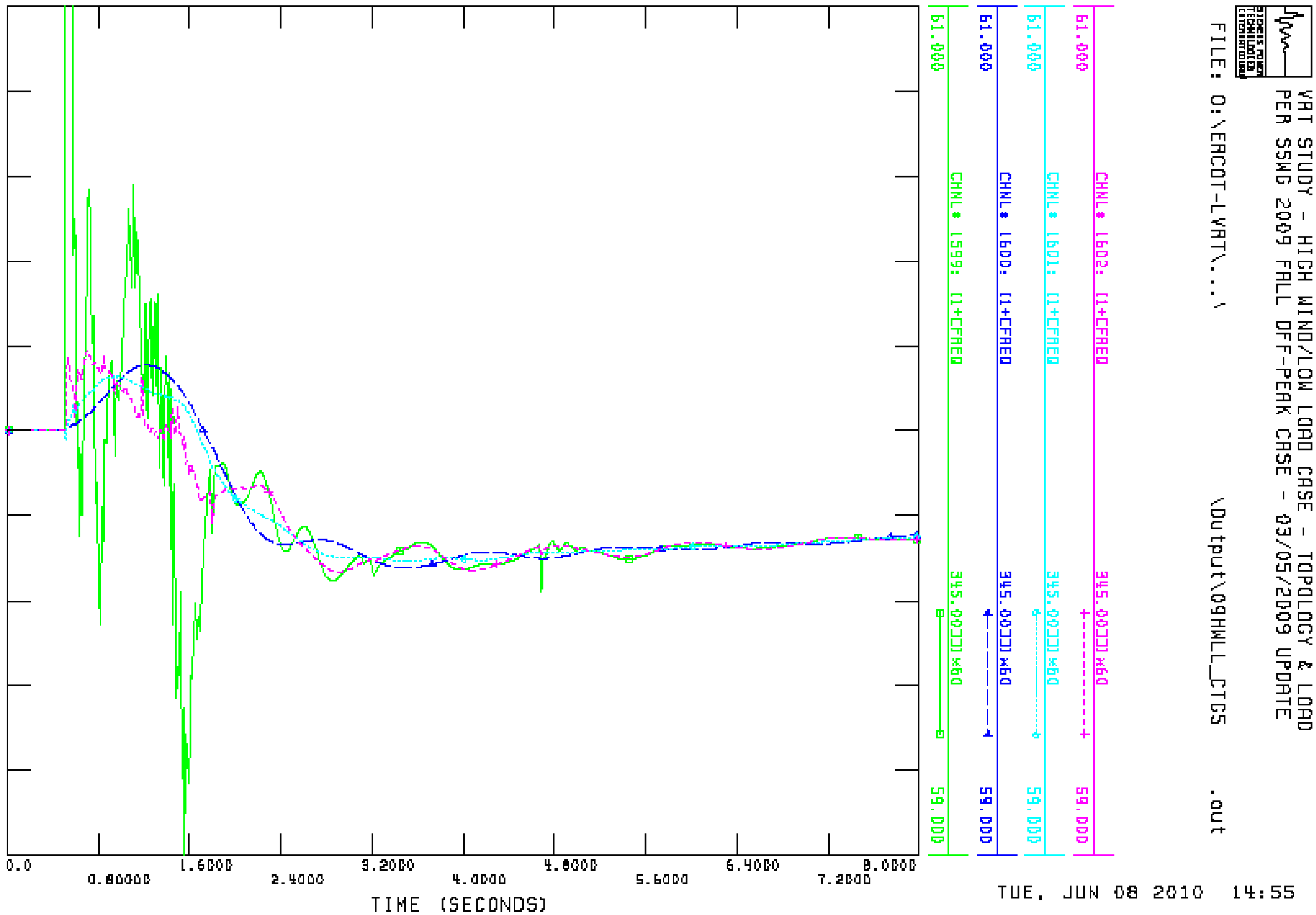

Exhibit 38-a: System Frequency Response with 2 Conventional Units near fault location Online – CTG5, Change Case 3

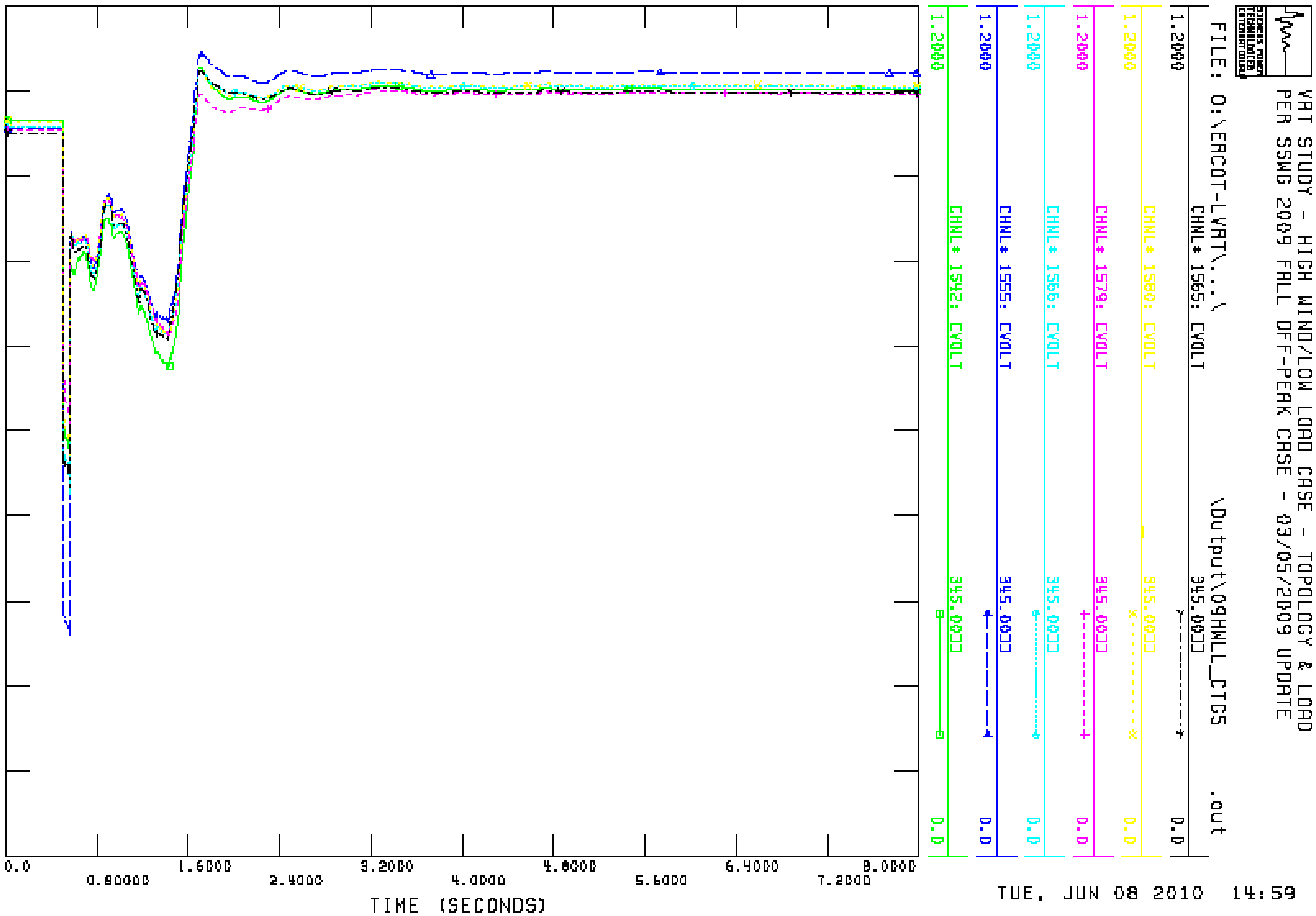

Exhibit 38-b: ERCOT West 345kV Voltage Response with 2 Conventional Units near fault location Online – CTG5, Change Case 3

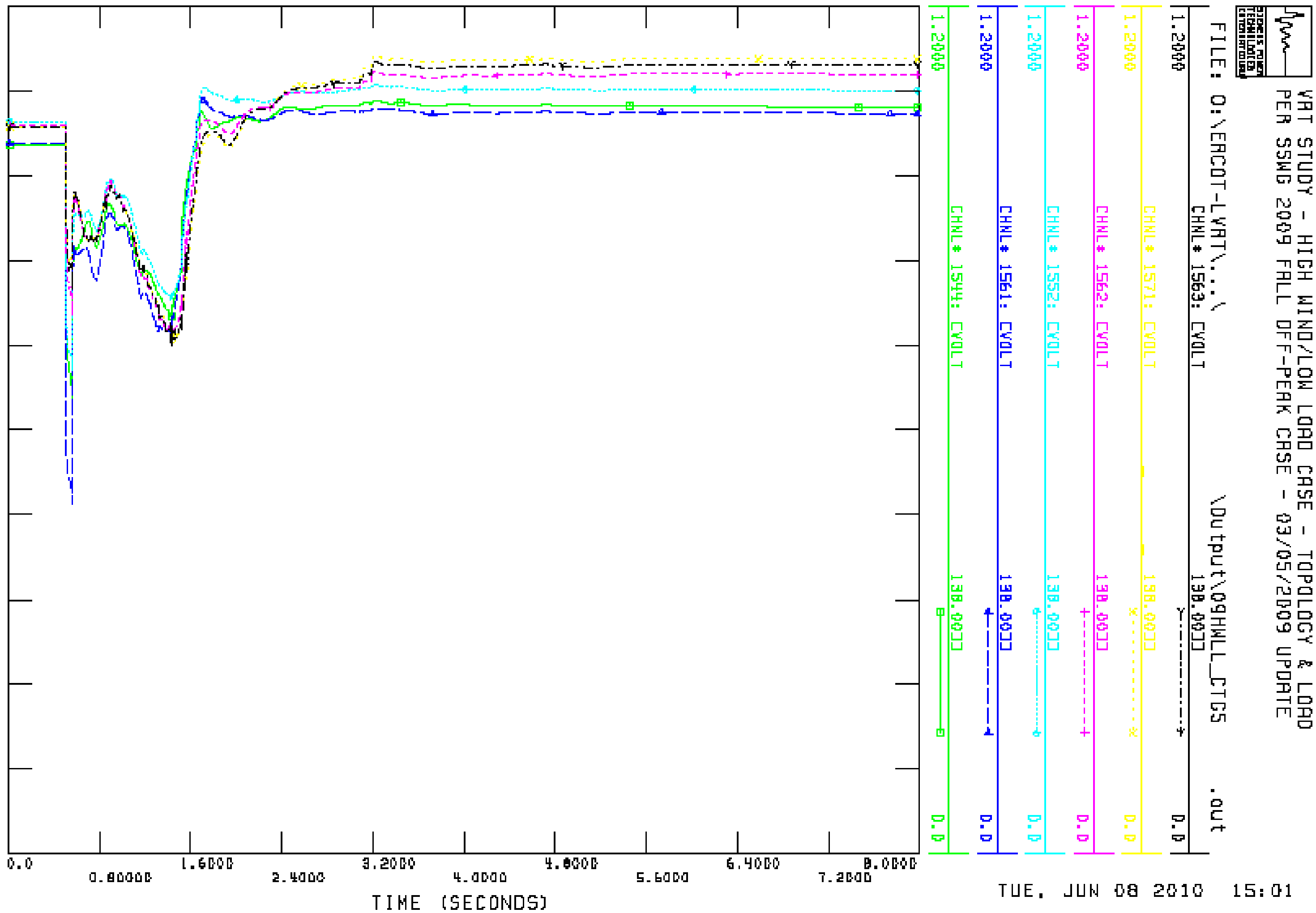

Exhibit 38-c: ERCOT West 138kV Voltage Response with 2 Conventional Units near fault location Online – CTG5, Change Case 3

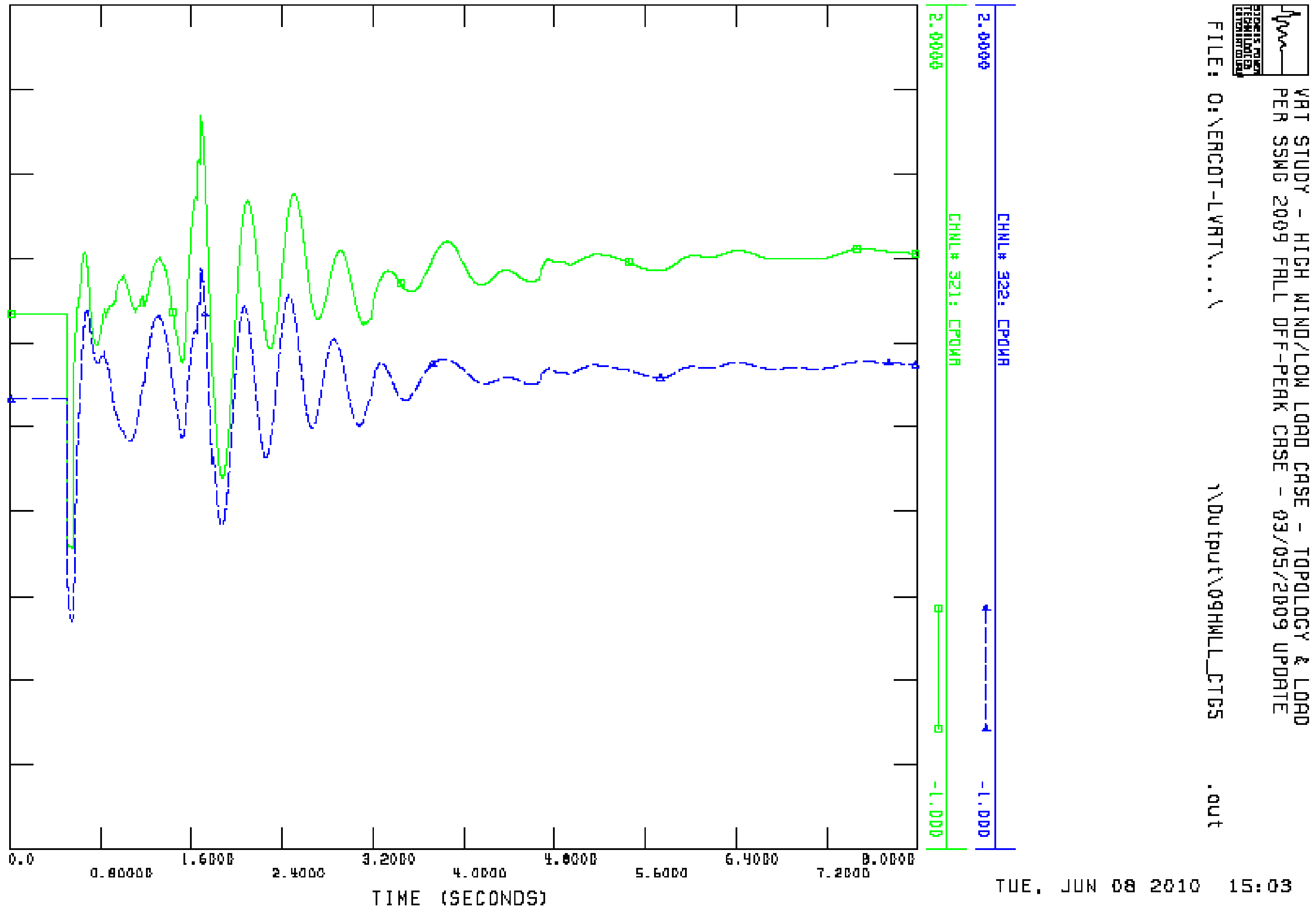

Exhibit 39-a: Active Power Response for 2 Conventional Units near fault location – CTG5, Change Case 3

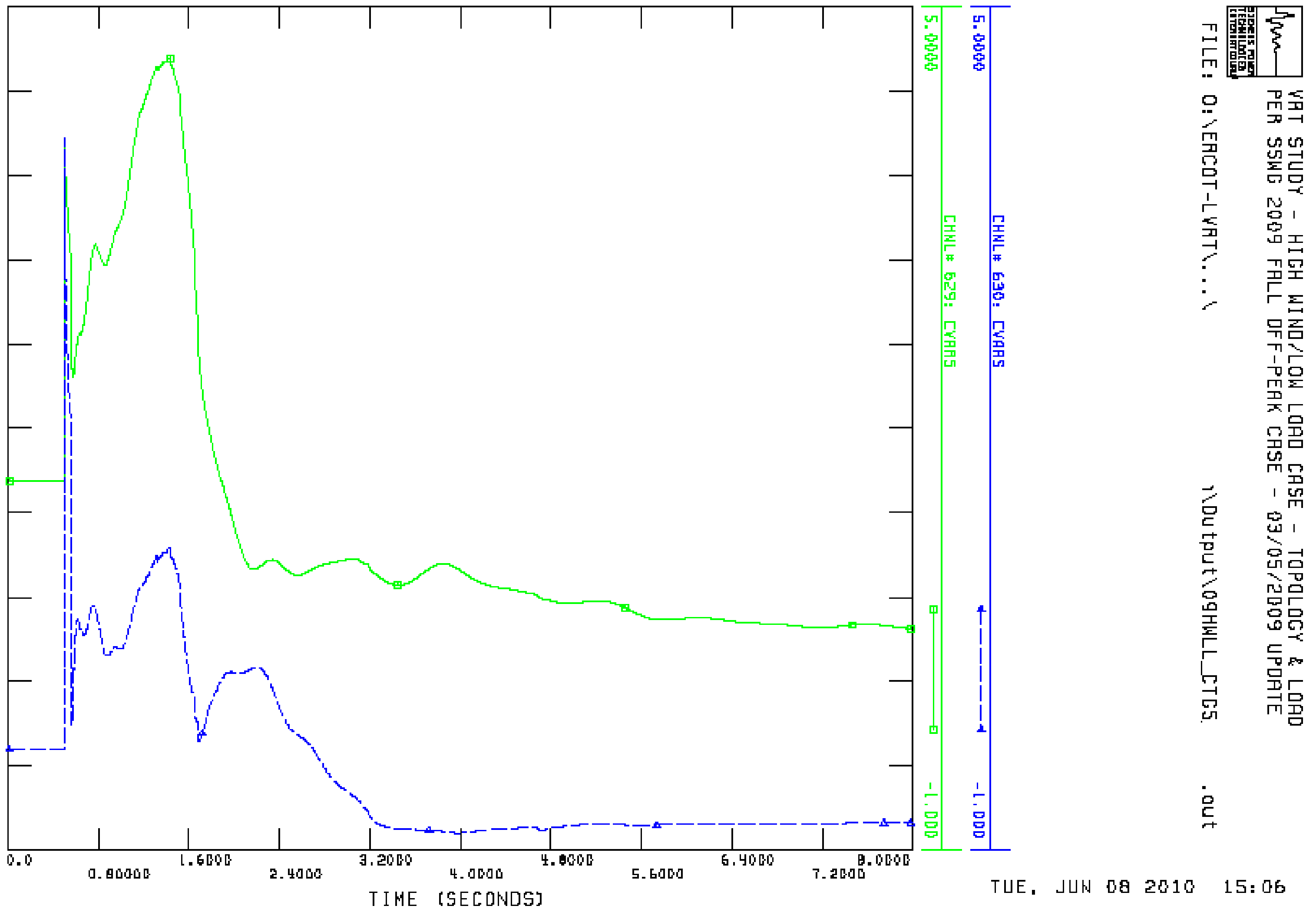

Exhibit 39-b: Reactive Power Response for 2 Conventional Units near fault location – CTG5, Change Case 3

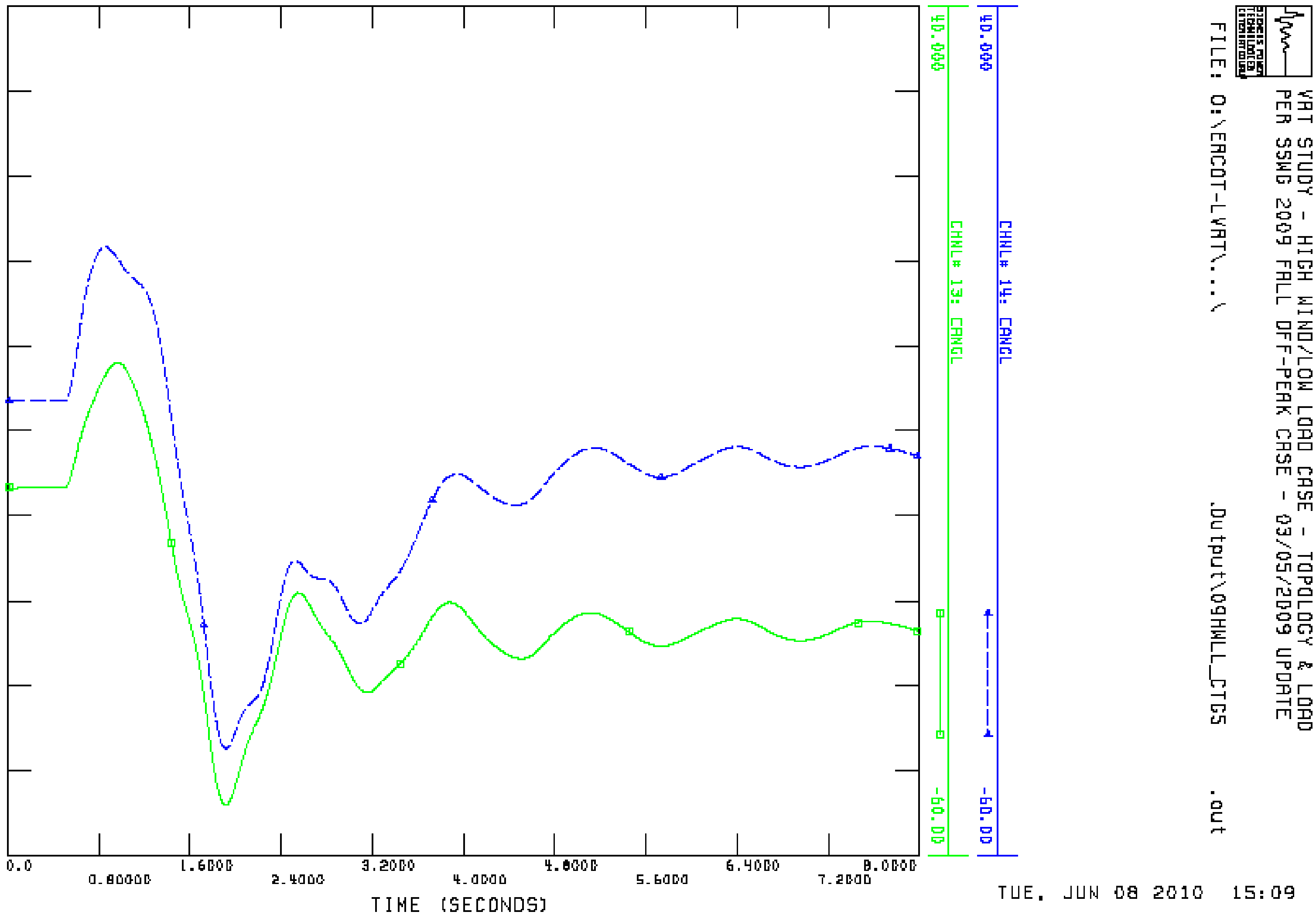

Exhibit 39-c: Rotor Angle Response for 2 Conventional Units near fault location – CTG5, Change Case 3

As evident from Exhibits 36 and 37, the presence of “token conventional” unit in West Texas does not alleviate the over-frequency spike observed for CTG5 for Change Case 3. A combination of this observation and observing the duration of the over-frequency spike indicates that the issue does not seem to stem from the lack of an adequate frequency reference for the GEWTG model.

As is evident from Exhibits 38 and 39, the presence of two conventional units electrically closer to the fault location does assist in alleviating the WGR trips. The total WGR trips associated with CTG5 for Change Case 3 with the two conventional units closer to fault location online amount to 1558 MW in terms of Change Case 3 dispatch and 2268 MW in terms of the WGR capacity lost. As observed from the reactive power response of the two units depicted in Exhibit 39-b, the system clearly exhibits a reactive power deficiency at or near the fault location of CTG5 for the West-North transfer level modeled in Change Case 3 under conditions simulated for CTG5. Despite the reactive support provided by the two conventional units turned on, the 138kV and 345kV systems experience a second albeit less pronounced voltage dip following the clearing of the fault resulting in numerous under-voltage WGR trips. Unlike previous instances, all the WGR trips now correspond to under-voltage which is expected from a system phenomenon standpoint. The system frequency response depicted in Exhibit 38-a does not exhibit the exaggerated over-frequency swing previously witnessed for CTG5 for Change Case 3. This seems to explain the frequency swing to be a manifestation of the West-North voltage instability for CTG5 for Change Case 3.

The amount of WGR trips are below the ERCOT RRS requirement of 2300 MW in terms of both Change Case 3 dispatch and WGR capacity lost when the two conventional units are on line. That said, the WGR capacity lost for CTG5 for Change Case 3 with the two units online is marginal being just below the ERCOT RRS requirement.

Assuming that the dynamic load models accurately and adequately represent the behavior of the motor load in West Texas, PB deems that the West-North transfer modeled in Change Case 3 does pose a reliability risk from a short-term voltage stability standpoint. The results of this investigation indicate that reactive compensation near the fault location helps to maintain system stability in Change Case 3 for CTG5. The presence of reactive support in the form of conventional units online does alleviate the magnitude of the second voltage dip although still resulting in numerous WGRs by virtue of under-voltage trips. The WGR trips associated with CTG5 for Change Case 3 are marginal when compared to the ERCOT RRS requirement even after turning on the two conventional units.

10.1.2 Investigation #2 Results

The second aspect investigated for CTG5 for Change Case 3 is the impact of the West-North transfer modeled in Change Case 3 with respect to the West-North stability limit in the absence of conventional generation in West Texas. In order to isolate the investigation to focus on the West-North transfer modeled in Change Case 3 and the impact of the same on the West-North voltage stability limit, Change Case 3 was simulated for CTG5 with all the WGR models in West Texas G_{netted}. This was done in order to retain the West-North transfer levels while eliminating any WGR model behavioral issues from this investigation. Exhibit 40-a depicts the voltage response associated with 345kV stations in West Texas for CTG5 for Change Case 3 with all WGR models G_{netted}. As can be observed from Exhibit 40-a, the West-North transfer modeled in Change Case 5 results in voltage instability and subsequent voltage collapse for CTG5 which is manifested in the form of non-convergence and inability of the voltages to recover to pre-fault levels at 345kV stations in West Texas. The result is as expected since similar voltage collapse and non-convergence issues were observed with CTG5 for Change Case 1 for 6 cycle fault duration. However, the problem was alleviated for Change Case 1 upon the reduction of the fault duration to the TSP fault clearing time of 4 cycles suggesting that the transfer level modeled in Change Cases 1 and 3 is near the voltage stability limit. The results further re-iterate the fact that WGR trips resulting in reduced West-North transfer does play a significant role in avoiding voltage collapse. Additionally, the results corroborate the observation made in the previous sub-section wherein the reactive power response of the two conventional units close to the fault location was observed to improve voltage stability for Change Case 3 under CTG5 conditions.

Exhibit 40-b depicts the behavior of a sample large induction motor model utilizing the CIMWOW model in the ONCOR territory of West Texas. As evident from Exhibit 40-b, the active power consumption of the motor model drops with a drop in applied/terminal voltage with no change in frequency. While the voltage drop typically also results in an increase in slip, the reduction in voltage results in a lower torque-slip curve coming into play thereby resulting in an over-all reduction in active power consumption. The drop in terminal voltage during the fault is followed by a temporary and small voltage recovery during which time the active and reactive power consumed by the motor model are observed to be a function of the terminal voltage. However, after the fault is cleared and subsequent outages associated with the event, the voltage collapse by virtue of the West-North transfer is manifested in a second voltage dip thereby resulting in non-convergence of the dynamic dataset.

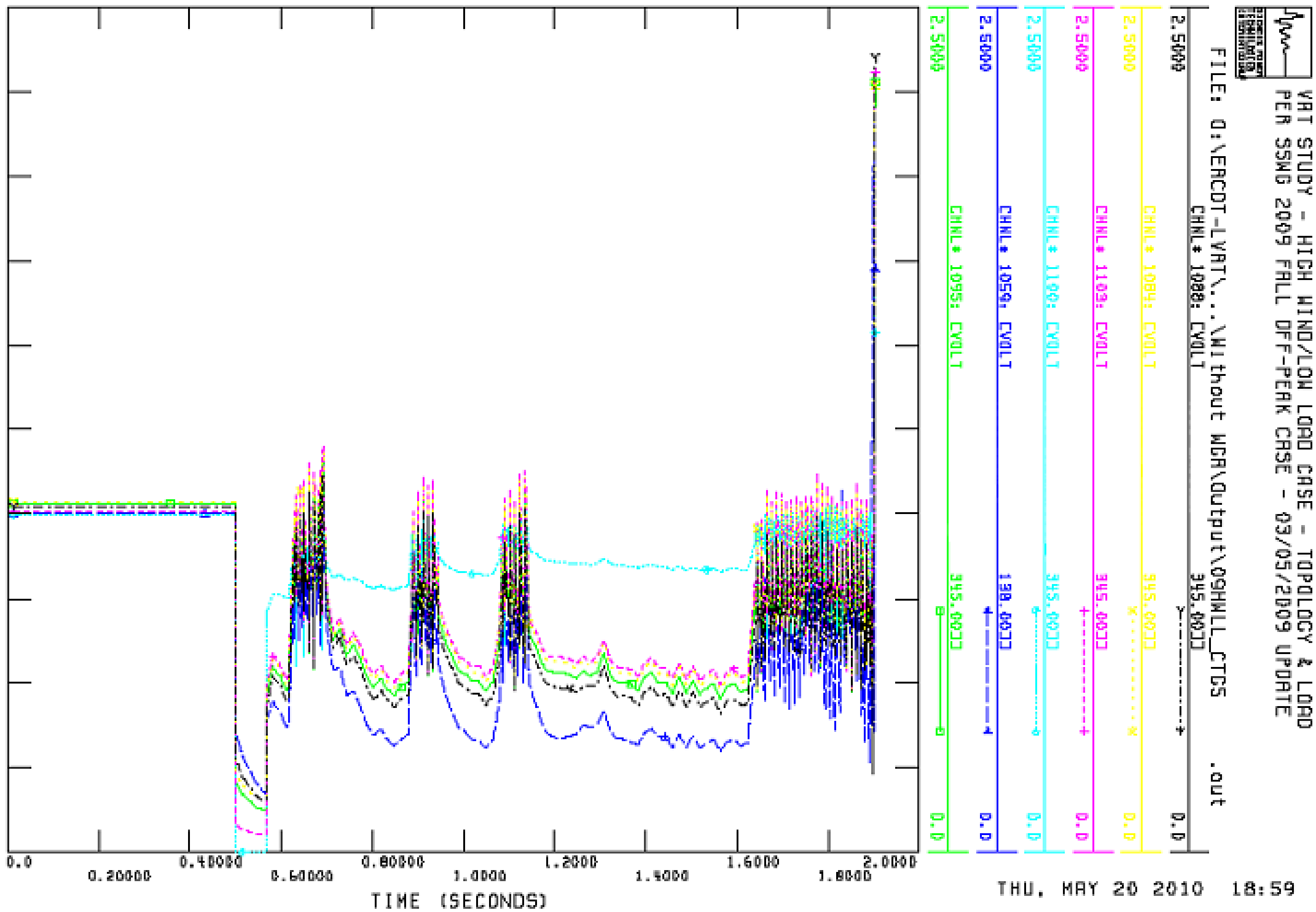

Exhibit 40-a: Voltage Response for 345kV ERCOT West stations – CTG5, Change Case 3 with WGR models Gnetted

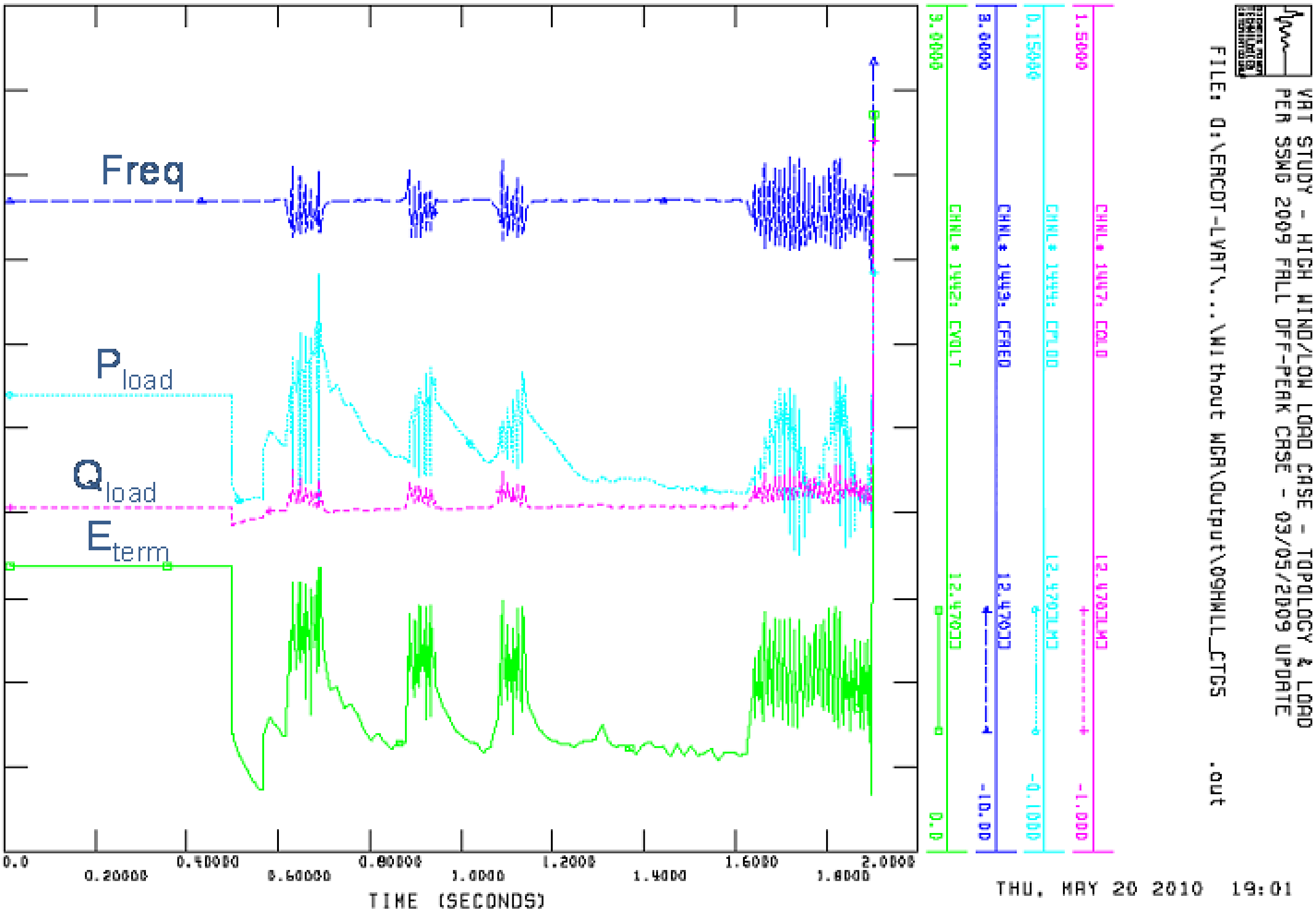

Exhibit 40-b: Sample Large IM model (CIMWOW) Response– CTG5, Change Case 3 with WGR models Gnetted

The induction motor model behavior is observed since the lone incremental change from Change Case 1 to Change Case 3 is the inclusion of the dynamic load models in West Texas. As mentioned above, CTG5 exhibited similar voltage instability and potential voltage collapse for the West-North transfer modeled in Change Case 1 for 6 cycle fault duration. However the inclusion of the dynamic load models results in a similar phenomenon at 4 cycle fault duration.

The results of this investigation seem to indicate a condition of short-term voltage instability and subsequent voltage collapse by virtue of the West-North transfer modeled in Change Case 3. The voltage collapse and subsequent non-convergence of Change Case 3 for CTG5 in the absence of any WGR models seems to corroborate the observation.

10.1.3 Investigation #3 Results

The investigation discussed in this sub-section focuses on the role of the lack of WGR VRT capability on the reliability risks being observed for CTG5 for Change Case 3. The previous investigation identified the presence of a voltage collapse condition by virtue of the West-North transfer modeled in Change Case 3 in the absence of the WGR models. In this investigation, the system behavior for CTG5 for Change Case 3 is observed with the WGRs in West Texas represented with their respective aggregated collection systems and turbine models.

Exhibit 41 depicts the voltage response associated with 345kV stations in West Texas for CTG5 for Change Case 3 with all West Texas WGR models included. As can be seen from Exhibit 41, unlike the previous investigation the presence of the WGR models and associated WGR trips prevent the impending voltage collapse following the fault and outages associated with CTG5. The voltage recovery in essence is assisted on 2 counts namely:

- WGR trips by virtue of over-frequency and under-voltage conditions which results in reducing the overall West-North transfer thereby preventing a voltage collapse
- The reactive power support provided by the non-tripped WGR models during the voltage dip which was absent in the previous case when the WGRs were represented as negative loads or G_{net}

Exhibit 42 depicts the reactive power response for sample WGRs to confirm the reactive support provided by the un-tripped WGR models during and after the event.

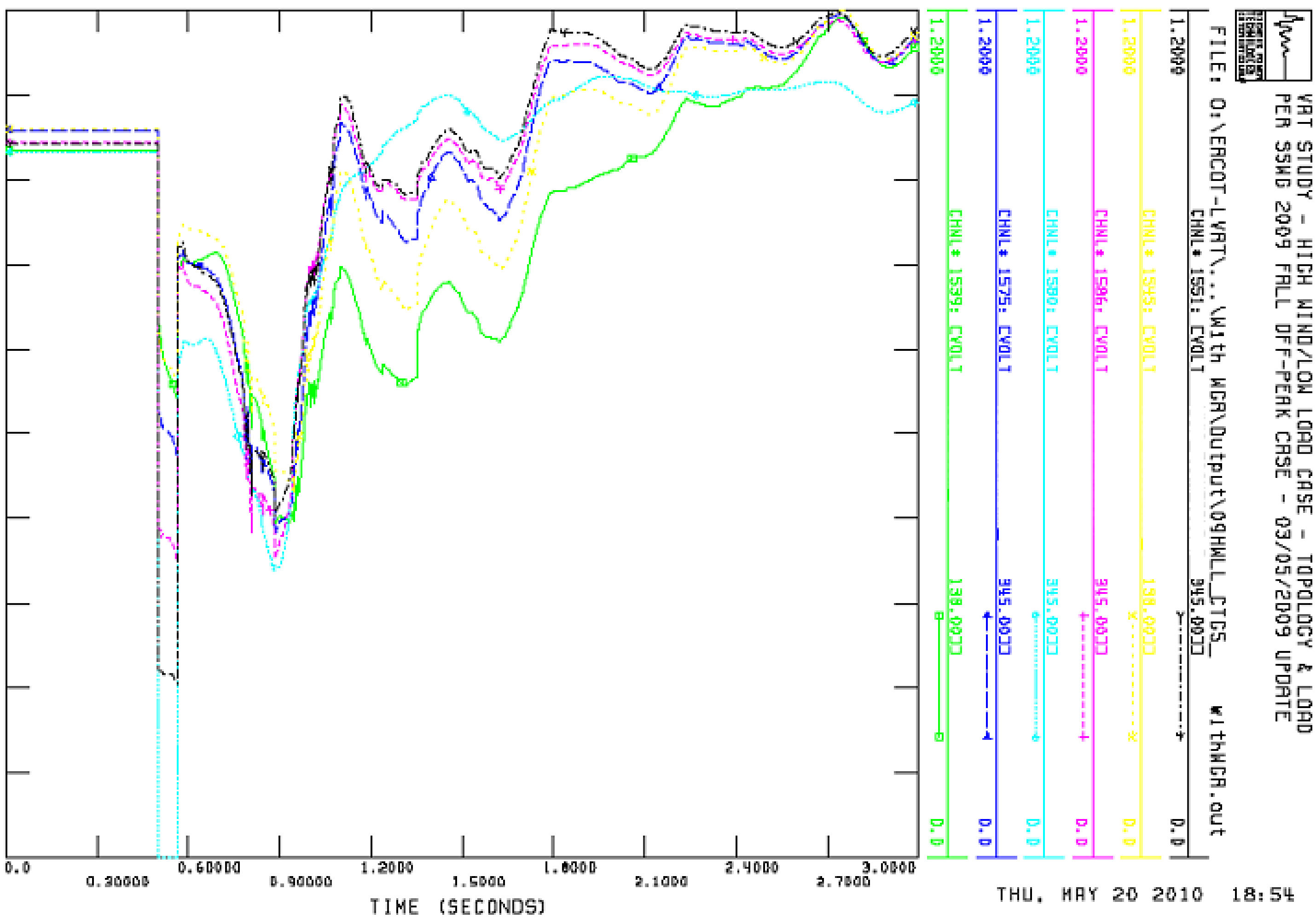

Exhibit 41: Voltage Response for 345kV ERCOT West stations – CTG5, Change Case 3 with WGR models included

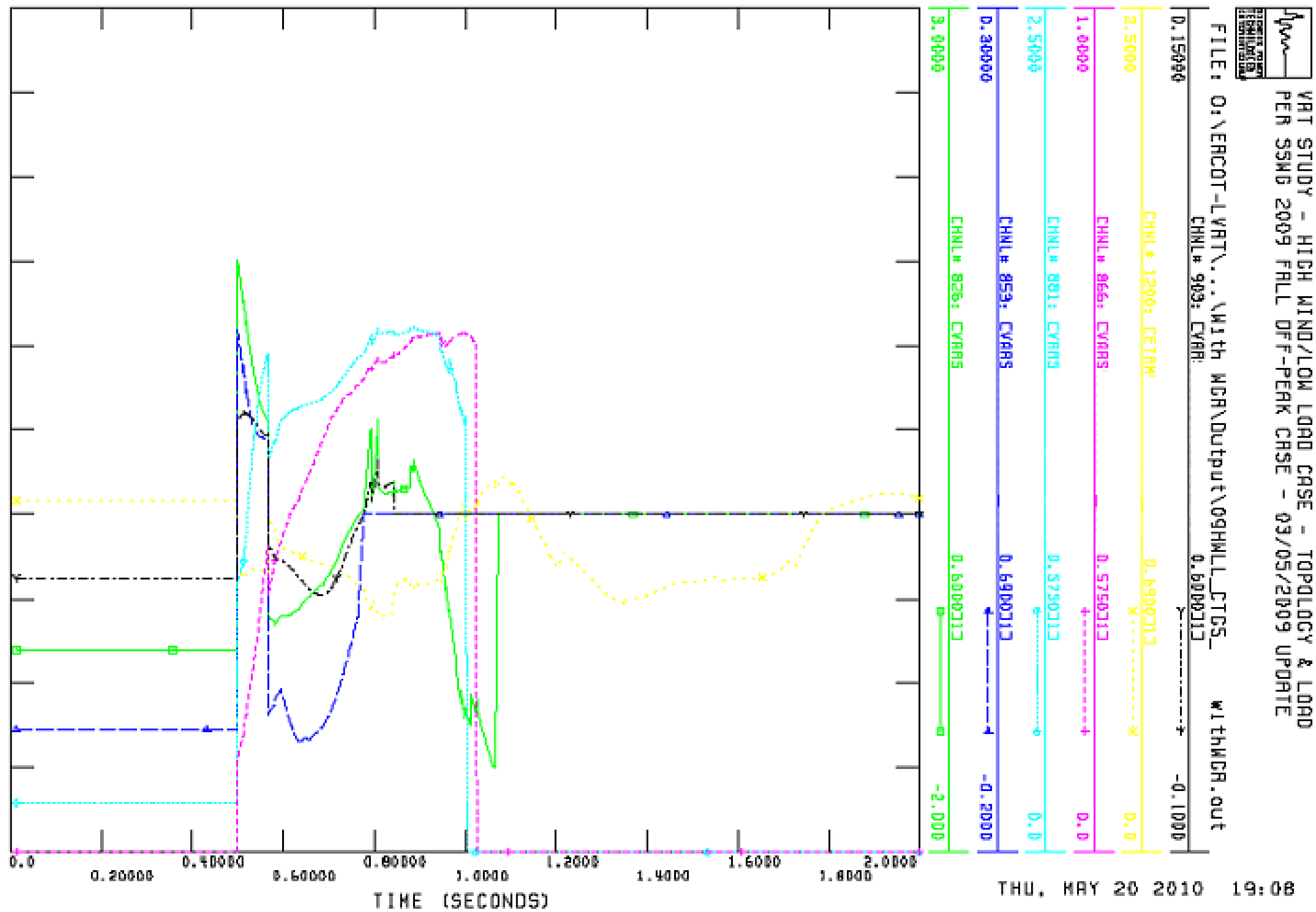

Exhibit 42: VAR Response for sample WGRs – CTG5, Change Case 3 with WGR models included

Exhibit 43 depicts the response of the sample large IM model utilizing CIMWOW model in ONCOR region in West Texas for the case with WGR models included.

As can be seen from Exhibit 43, the fault and subsequent outage associated with CTG5 for Change Case 3 results in partial voltage recovery but drastic frequency variations. The frequency spikes result in a large enough slip to cause the motor models to "pull-out" thereby causing drastic reduction in the active power consumption and an increase in the reactive power consumption due to reduced power factor. The impact of the increased reactive power consumption exacerbates the second voltage dip originally due to the West-North transfer levels modeled in Change Case 3. Following the WGR trips, the overall West-North transfer is reduced and the generation in West Texas is also reduced thereby resulting in frequency and voltage to gradually recover to nominal range.

As evident from the results presented in this investigation, the inclusion of the WGR models does not exacerbate the existing voltage instability and potential voltage collapse condition by virtue of the West-North transfer modeled in Change Case 3. The voltage collapse condition is avoided to a certain extent following the inclusion of WGR models since the over-frequency relay in the WGR models results in numerous WGR trips thereby reducing the overall West-North transfer. The voltage collapse condition is also avoided to a lesser extent due to the voltage support provided by the non-tripped WGRs during the voltage recovery process. The inclusion of dynamic motor load models in West Texas appears to impact the critical fault clearing time for CTG5 with respect to voltage stability under the conditions modeled in Change Cases 1 and 3. Detailed investigation into the parameters associated with the motor load models is beyond the scope of the VRT study as outlined in the Scope of Work agreed upon by ERCOT and PB.

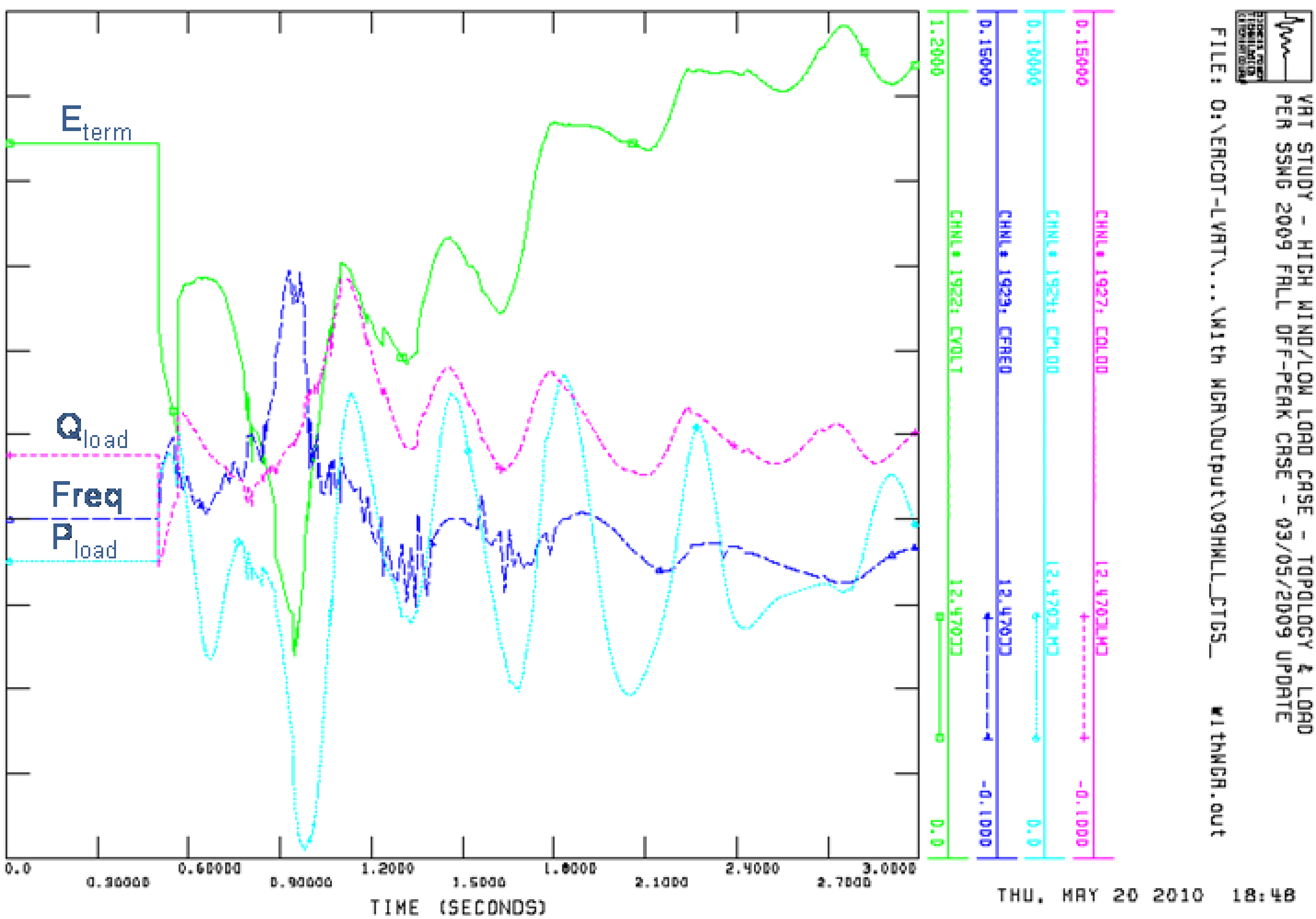

Exhibit 43: Sample Large IM model (CIMWOW) Response– CTG5, Change Case 3 with WGR models included

10.2 Observations

Based on the detailed investigations performed as part of Change Case 5, the following observations can be drawn relative to normal clearing and breaker failure events posing potential reliability risks to the ERCOT system:

- **CTG5 - Change Case 3**
  - CTG5 is indicative of a voltage instability situation based on conditions modeled in Change Case 3
  - Detailed investigations performed as part of Change Case 5 indicate that the voltage instability and potential voltage collapse is primarily due to the level of West-North transfer modeled and the inclusion of dynamic motor load models in Change Case 3.
  - The lack of a frequency reference for GEWTG model is not the cause for the over-frequency deviations experienced during the event. The simulation of CTG5 for Change Case 3 with a "token conventional unit" online in West Texas underlines the above observation. Moreover, the issue associated with the lack of an adequate voltage angle reference for the GEWTG model is not expected to manifest itself in a frequency spike of the duration experienced in CTG5. PB deems that the drastic over-frequency deviations are a manifestation of the unstable behavior of the system due to the West-North transfer level and load models used for Change Case 3
  - The observation made above is further corroborated by performing simulation of CTG5 for Change Case 3 with two conventional units near the fault location turned online. The large amount of reactive power drawn from the units in transient conditions during and immediately after the event are indicative of the reactive support requirements to maintain voltage stability for CTG5 for Change Case 3.
  - The fact that the exaggerated over-frequency deviations are not observed when the two conventional units are turned online indicates the over-frequency variations to be a manifestation of the unstable system behavior.
  - With the two conventional units near the fault location online, CTG5 results in 1558 MW of WGR trips in terms of Change Case 3 dispatch and approximately 2268 MW of WGR capacity lost.

- o However, the lack of WGR VRT capability cannot be attributed as the cause for the phenomenon observed for CTG5 for Change Case 3.
- o The existing transmission system capability needs to be examined to handle the West-North transfer modeled in Change Case 3 under the conditions modeled in Change Case 3 for CTG5. These include the behavior and/or models for the dynamic loads in West Texas (including the impact of the load models on the fault clearing time associated with CTG5 in terms of voltage stability) and the conditions pertaining to the absence of any conventional generation units vis-à-vis the WGR dispatch and West Texas load levels.

11 Conclusions

Based on the analysis presented in the preceding chapters of this report, conclusions associated with the reliability risks associated with WGRs that may not comply with the ERCOT VRT requirements (as defined in Operating Guide 3.1.4.6.1) when assessed vis-à-vis the reliability metrics defined in Phase I and agreed upon by ERCOT are discussed in this chapter. Exhibit 44 depicts a summarized version of the reliability risks identified for all the cases assessed as part of the ERCOT VRT study.

Study Case	Normal Clearing	Breaker Failure
HWHL	No Risk	No Risk
HWLL	No Risk	No Risk
Change Case 1	No Risk	No Risk
Change Case 2	No Risk	No Risk
Change Case 3	Voltage Stability	No Risk

Exhibit 44: Summary of reliability risks identified as part of the ERCOT VRT study

11.1 HWHL & HWLL Cases

- The HWHL & HWLL cases were updated with models developed as part of Phase II of the ERCOT VRT study. Updated information associated with the collector system, turbine reactive capability and VRT capability for various WGR campuses was accurately and adequately represented in the updated HWHL and HWLL cases
- All 65 normal clearing events were simulated for the HWHL and HWLL conditions with 6 cycle fault duration (keeping a 1-2 cycle clearing margin for 138/345kV system faults). No reliability concerns were observed for any normal clearing event simulated for the HWHL and/or HWLL case with 6 cycle fault duration.
- The most severe normal clearing event associated with HWHL & HWLL cases was identified to be CTG9. The WGR trips associated with CTG9 for HWHL and HWLL cases are listed below:
  - HWHL Case
    - 1140 MW of WGR trips in terms of HWHL case dispatch
    - 1706 MW of WGR trips in terms of capacity lost
  - HWLL Case

    - 761 MW of WGR trips in terms of HWLL case dispatch
    - 1274 MW of WGR trips in terms of capacity lost

- As obvious from the WGR trips corresponding to most severe normal clearing events for HWHL and HWLL, the WGR trips do not exceed the ERCOT RRS requirement of 2300 MW. The WGR trips are also not indicative of an unacceptable frequency deviation. It should be noted that the amount of WGR trips would be expected to be lower if the margin was eliminated from the simulated fault duration.
- All 31 breaker failure events were simulated for HWHL and HWLL conditions. No reliability concerns were observed for any breaker failure event simulated for the HWHL and/or HWLL case.
- The most severe breaker failure event associated with HWHL & HWLL cases was identified to be BF#8. The WGR trips associated with BF#8 for HWHL and HWLL cases are listed below:
  - HWHL Case
    - 514 MW of WGR trips in terms of HWHL case dispatch
    - 831 MW of WGR trips in terms of capacity lost
  - HWLL Case
    - 277 MW of WGR trips in terms of HWLL case dispatch
    - 672 MW of WGR trips in terms of capacity lost
- As obvious from the WGR trips corresponding to most severe breaker failure events for HWHL and HWLL, the WGR trips do not exceed the ERCOT RRS requirement of 2300 MW. The WGR trips are also not indicative of an unacceptable frequency deviation.

11.2 Change Case 1

- Change Case 1 was representative of high wind light load conditions with no conventional generation units in West Texas online. All the 65 normal clearing and 31 breaker failure events were assessed for Change Case 1.
- CTG5 resulted in 2959 MW of WGR trips in terms of Change Case 1 dispatch and approximately 4989 MW in terms of WGR capacity lost when simulated for 6 cycle fault duration for Change Case 1. However, a majority of these trips were over-frequency trips possibly attributable to system behavior stemming from West-North voltage instability. The results and plots associated with CTG5 are

indicative of voltage instability and potential voltage collapse due to the West-North voltage stability limit for 6 cycle fault duration.

- The first mitigating solution that was assessed was the utilization of expected normal TSP fault clearing times.
- Following the utilization of expected normal TSP fault clearing times, no normal clearing event resulted in WGR trips indicative of reliability risks by virtue of lack of WGR VRT capability. The most severe normal clearing event associated with Change Case 1 (TSP fault clearing time) was identified to be CTG5. The WGR trips associated with CTG5 for Change Case 1 are listed below
    - 734 MW in terms of Change Case 1 Dispatch
    - 978 MW in terms of WGR capacity lost
- The reduction in the fault duration is found to have an alleviating impact on voltage stability for the West-North transfer modeled in Change Case 1 for conditions associated with CTG5. Utilizing expected normal TSP fault duration, no reliability risks associated with the lack of WGR VRT capability are observed for Change Case 1 as far as the simulated normal clearing events are concerned.
- In terms of breaker failure events, BF#17 was identified as the most severe event resulting in the following WGR trips for Change Case 1:
    - 835 MW in terms of Change Case 1 Dispatch
    - 1307 MW in terms of WGR capacity lost
- No simulated breaker failure events result in WGR trips indicative of reliability risks associated with the lack of WGR VRT capability
- The potential limitations associated with the utilization of PSS/E for assessing unbalanced events within a purely positive sequence environment are discussed. ERCOT is advised to work closely with the machine manufacturers to understand the reference of the under-voltage relay settings provided in the PSS/e model vis-à-vis actual field conditions.

11.3 Change Case 2

- Change Case 2 was representative of high wind high load conditions with the incremental addition of dynamic load model to represent the motor loads in West Texas. All the 65 normal clearing and 31 breaker failure events were assessed for Change Case 2.

- The most severe normal clearing event (6 cycle fault duration) associated with Change Case 2 was identified to be CTG9. The WGR trips associated with CTG9 for Change Case 2 are listed below:
    - 1190 MW of WGR trips in terms of Change Case 2 dispatch
    - 1788 MW of WGR trips in terms of capacity lost
- The results associated with CTG9 for Change Case 2 are on expected lines since the same event was identified to be the most severe event for HWHL case and Change Case 2 is derived from HWHL case
- No simulated normal clearing events result in WGR trips indicative of reliability risks associated with the lack of WGR VRT capability. It should be noted that the amount of WGR trips would be expected to be lower if the margin was eliminated from the simulated fault duration.
- In terms of breaker failure events, BF#20 was identified to be the most severe event resulting in the following WGR trips for Change Case 2:
    - 824 MW of WGR trips in terms of Change Case 2 dispatch
    - 1189 MW of WGR trips in terms of capacity lost
- No simulated breaker failure events result in WGR trips indicative of reliability risks associated with lack of WGR VRT capability
- The above comments and/or observations assume that the dynamic load model representation provided to PB accurately and adequately represents the motor load behavior, concentration and characteristics in West Texas

11.4 Change Case 3

- Change Case 3 was representative of high wind light load conditions with no conventional generation units in West Texas online and the incremental addition of the dynamic load models for West Texas. All the 65 normal clearing and 31 breaker failure events were assessed for Change Case 3.
- Based on the results associated with 6 cycle fault duration for normal clearing events for Change Case 1, all normal clearing event simulations for Change Case 3 were performed utilizing the expected normal TSP fault clearing times.
- CTG5 resulted in the following WGR trips for Change Case 3:
    - 3965 MW of WGR trips in terms of Change Case 3 dispatch
    - 6214 MW of WGR trips in terms of capacity lost

- As in the case of CTG5 (6 cycle fault duration) for Change Case 1, a majority of the WGR trips were by virtue of over-frequency. Detailed investigations associated with the potential cause for the phenomenon and associated reliability risks were performed as part of Change Case 5:
  - Impact of lack of frequency reference on behavior of GEWTG model
  - Impact of West-North transfer modeled in Change Case 3 on voltage stability limit
  - Role of lack of WGR VRT capability on the phenomenon and associated reliability risks
- The following observations were made based on the investigations performed as part of Change Case 5:
  - The drastic over-frequency variations cannot be attributed to the lack of frequency reference for GEWTG model due to the following reasons:
    - The lack of adequate frequency and/or voltage angle reference associated with GEWTG model manifests itself in the form of a momentary spike which is not the case for CTG5. The duration of the over-frequency spike is much longer in the case of CTG5 for Change Case 3
    - Change Case 3 was simulated for CTG5 with a conventional generation unit serving as "token" conventional unit in West Texas to provide frequency reference. However, no alleviation in the over-frequency deviations was observed
  - The impact of the West-North transfer modeled in the case in conjunction with the dynamic load models results in voltage instability and subsequent voltage collapse for CTG5 for Change Case 3 in the absence of conventional generation in West Texas. This was confirmed by performing the simulation for Change Case 3 under CTG5 with all the WGR models G_{netted} to maintain the transfer modeled in the case.
  - Furthermore, additional tests were performed by turning on two conventional units close to the fault location of CTG5 which alleviated the over-frequency deviations being observed. This confirmed the fact that the over-frequency deviations were a manifestation of the unstable system conditions for Change Case 3 under CTG5. The two conventional units were observed to supply large amounts of reactive power during and immediately after the event clearly indicating reactive deficiency near the fault location for CTG5 for Change Case 3. The system performance was observed to be significantly improved with the two conventional units providing reactive support for CTG5.

  - No WGR trips by virtue of over-frequency were observed for CTG5 for Change Case 3 with the two conventional units online.
  - Assuming that the dynamic load models utilized in Change Case 3 adequately and accurately reflect the system load conditions and behavior in West Texas, the existing transmission system cannot handle the West-North transfer modeled in Change Case 3 without additional reactive support for CTG5.
  - The reliability risks stemming from CTG5 for Change Case 3 cannot be attributed to the lack of WGR VRT capability since the primary cause of concern stems from the high West-North transfer and the existing West-North stability limit in the absence of conventional generation in West Texas. The primary mitigation options may comprise of one of the following:
    - Dynamic VAR support at fault location of CTG5 and/or other locations
    - Reduction of West-North transfer to ensure West-North voltage stability
  - Either of these mitigation options are bound to have an alleviating impact on the WGR trips by virtue of lack of VRT capability
- The role of dynamic load model parameters and/or behavior on the critical fault clearing time for CTG5 for Change Case 3 should also be evaluated by ERCOT. To that effect, benchmarking the load model to adequately represent actual system conditions in West Texas may be required.
- No other simulated normal clearing events result in WGR trips indicative of reliability risks associated with lack of WGR VRT capability
- In terms of breaker failure events, BF#16 was observed to be the most severe event in terms of WGR trips resulting in the following trips:
  - 1193 MW of WGR trips in terms of Change Case 3 dispatch
  - 1903 MW of WGR trips in terms of capacity lost
- No simulated breaker failure events result in WGR trips indicative of reliability risks associated with lack of WGR VRT capability
- All observations made for Change Case 3, especially for CTG5, are based on the dynamic load model representation for West Texas as provided to PB by ERCOT. Any deviations in actual system load behavior in comparison to the dynamic load models utilized for Change Case 3 are bound to impact the results documented herein.

11.5 Change Case 4

- Change Case 4 was designed to perform investigations associated with the impact of low pre-fault WGR terminal voltage on the WGR trips for various cases. WGRs with no VRT capability were identified and the pre-fault terminal voltage for these WGRs was reduced without altering the transmission bus voltage.
- Selected events were utilized to assess the impact of low pre-fault WGR terminal voltage on the WGRs with no VRT capability.
- The low pre-fault WGR terminal voltage is found to impact WGRs that are marginal in terms of the magnitude of the voltage dip when compared to the under-voltage relay settings. WGRs that experienced voltage dips that were marginally less than the voltage relay settings were found to trip when the pre-fault WGR terminal voltage was set to a lower value. However, no simulated event resulted in WGR trips that posed reliability concerns from a VRT standpoint even after lowering the pre-fault terminal voltages.
- The impact was observed to be more pronounced on Change Cases 1 and 3 since no conventional voltage support was present for these cases, but no simulated event resulted in WGR trips indicative of reliability risks from a VRT standpoint for Change Cases 1 and 3.
- The results presented as part of the Change Case 4 investigation are based on the turbine model under-voltage relay settings as provided to PB by WGRs as part of the data submittal. This comment is especially true for specific Type I machines which are demonstrated to ride through pronounced voltage dips based on the under-voltage relay settings. Study results and conclusions would be impacted if the under-voltage relay settings associated with this or other turbine types are found to be different than the settings provided.

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