System Strength Assessment of the Panhandle System
PSCAD Study

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Report Submitted to:
Electric Reliability Council of Texas, Inc.

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1.0 Executive Summary

1.1 Background

Potential challenges related to system strength have been identified in the Panhandle Region when integrating a large amount of wind generation capacity. Electric Reliability Council of Texas (ERCOT) completed the Panhandle Study Report in April 2014[1], which identified system challenges to reliably accommodate large amounts of wind generation in the region. Although the Panhandle study results clearly identified system challenges, including dynamic stability, as well as some potential upgrade options, a more detailed follow up study was desired in order to validate the original study results, and provide further recommendations for ERCOT planners and operators.

Electranix has carried out this analysis using state-of-the-art tools and techniques, never before applied to this extent in power system planning studies. ERCOT planning was involved intimately in the study process, allowing a collaborative approach through the course of analysis and contributing to the understanding of observed outcomes.

1.2 Objectives

The objectives of this study are as follows:

a) Examine the Weighted Short Circuit Ratio (WSCR) based planning and operating thresholds proposed by ERCOT, propose adjustments if necessary, and explore the application of WSCR as a tool for power systems planners studying the Panhandle system.
b) Using very detailed models, validate the effectiveness of ERCOT proposed transmission build out, including installation of synchronous condensers at the Tule Canyon and Alibates 345 kV buses, and a new Alibates-AJ Swope-Windmill-Ogallala-Tule Canyon 345kV circuit, for near-term wind expansion up to 4300 MW capacity.
c) Provide recommendations and information relating to simulation tool adequacy.
d) Provide recommendations on area-wide voltage regulation strategies.
e) Transfer study tools and knowledge to ERCOT engineers.

1.3 Recommendations

The following are summaries of the recommendations in this report. Care should be taken in extrapolating these results and conclusions beyond the scope of work covered in this effort. Further detail may be found in the pertinent sections of the respective chapters.

1.3.1 Weighted Short Circuit Ratio (WSCR)

ERCOT has proposed a WSCR screening level of 1.5 in order to set wind dispatch limits and assist in planning network upgrades in the Panhandle. This analysis has confirmed that level as being appropriate for the Panhandle region for the proposed network topology. The 1.5 level includes margin to account for planning uncertainty and various assumptions used in this study. [2]

[1] Available at http://www.ercot.com/content/news/presentations/2014/Panhandle%20Renewable%20Energy%20Zone%20Study%20Report.pdf

[2] It is important to note that some of the specific issues identified at lower WSCR values could potentially be mitigated through detailed design review and study iterations with manufacturer involvement. However, for planning purposes (and to limit the nearly endless potential study possibilities for the number of wind plants under consideration), it was

Further analysis should be performed to evaluate applicability of the WSCR metric in other regions or transmission networks. As ERCOT gains experience with operating the Panhandle system and other systems, the use of WSCR as a planning tool or operating guideline should be reviewed.

1.3.2 Panhandle Voltage Regulation

ERCOT requires all Generation Resources, including wind plants in the Panhandle, to operate in voltage control mode. There is currently no specific performance requirement for voltage controller tuning (such as response times), and this tuning has been left to plant/equipment experts who commission the plants. ERCOT has observed typical response times of approximately 30 seconds during commissioning tests. Provided sufficient dynamic VARs are available in the Panhandle region to accommodate the post-outage flows during this period, this is acceptable.

However, substantial benefit could be obtained from increased speed of plant voltage controller response (controller providing supporting VARs within 5 seconds or less[3]), provided this is carefully coordinated and provided it does not result in undesired impact to the system and generation entities. Implementing this solution would require additional analysis and timely detailed (Power Systems Computer Aided Design, PSCAD) model submissions for all relevant resources.

ERCOT is considering the use of synchronous condensers to provide general voltage control and improve system short circuit strength. This analysis supports this approach, and it is generally recommended that some proportion of the system dynamic voltage control be provided by dedicated transmission level devices such as synchronous condensers, STATCOMs, or SVCs. This allows flexibility in Wind Power Plant Controller (WPPC) voltage control coordination. As the system is weakened, synchronous condensers provide a special advantage over other voltage control technologies in that they provide inherent stability to the grid through mechanical inertia, however power electronic devices such as Static Var Compensator (SVCs) or Static Synchronous Compensator (STATCOMs) may be adequate to address specific issues.

1.3.3 Simulation Tool Adequacy

Analysis was performed using extremely detailed Electromagnetic Transient (EMT) type simulation models. Test cases were developed to evaluate system performance using three model types:

1. Pure PSCAD (EMT) model of the Panhandle region, using CPU parallelization techniques and a passive network equivalent for the rest of the ERCOT system.
2. Hybrid model, with the Panhandle region represented in PSCAD, and the rest of the ERCOT system in PSS/E dynamics, running in parallel in their respective software suites and connected together using the E-Tran Plus software suite.
3. Entire ERCOT model represented in PSS/E dynamics.

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considered valuable at a planning level to understand the basic performance of the entire region with no special attention paid to individual wind plants.

[3] The amount of "Supporting VARs" which are required within 5 seconds may be dependent on the individual system, and care needs to be taken in specifying and defining "controller response time".

For Panhandle WSCR levels at 1.5 or higher, all three model types performed in a similar manner, with several limitations evident for the pure PSS/E model[4]. As the WSCR drops below 1.5, the need for more detailed EMT type models becomes more critical. It is recommended that periodic studies be done with detailed EMT models to validate PSS/E studies and further develop WSCR planning guidelines.

For studies undertaken well outside of the Panhandle region, it is not necessary to model the Panhandle in PSCAD, although caution is recommended if dynamic issues in the Panhandle are impacting the bulk ERCOT system in these studies.

1.3.4 Additional Recommended Analysis

The following additional analysis is recommended, based on the results of this effort:

1. Further understanding of the capabilities of wind plant level voltage controllers should be obtained through consultation with manufacturers and other stakeholders.
2. If fast plant level voltage control alternatives are considered to lower the WSCR guidelines, certain of these studies should be repeated once detailed models are available.
3. A check should be performed on existing ERCOT PSS/E models to ensure dynamics and powerflow simulations correctly represent short term VAR limits of each wind plant. Unrealistic plant tripping in PSS/E simulations should also be examined and corrected if possible.
4. If significant changes are made to the existing ERCOT transmission expansion plan for the Panhandle region, additional study is recommended to further understand application of the WSCR metric.
5. Periodic PSCAD studies are recommended for all relatively weak networks with high renewable penetration to validate conventional transient stability models and improve understanding of system behaviour.

1.4 Further Observations

Additional results and observations stemming from this study can be summarized as follows:

1. The proposed Panhandle system upgrades for the near term (including installation of synchronous condensers at the Tule Canyon and Alibates 345 kV buses, and a new Alibates-AJ Swope-Windmill-Ogallala-Tule Canyon 345kV circuit) are adequate to solve the voltage stability and weak system issues identified for the wind dispatch scenarios considered.
2. The direct replacement of the proposed synchronous condensers with either STATCOMs or SVCs indicate wind plant control challenges under weakened system conditions, and these technologies are not recommended as direct replacements for synchronous condensers selected to strengthen very weak systems, although they may provide significant benefits with regard to voltage control, and may be beneficial as part of coherent expansion plans.
3. This analysis was done with wind generation capacity at the pre-defined planning level of 4300 MW. If significant additional capacity is required to be connected (even assuming a constant reduced power dispatch) without corresponding network upgrades, more analysis should be done, as increased inverter capacity may degrade performance without corresponding increase in system strength.

[4] For example, PSS/E studies indicate wind plant tripping which was determined by the more detailed analysis to be unrealistic. These and other issues should be corrected before PSS/E is relied upon for planning studies in the Panhandle.

1.5 Acknowledgements

Electranix gratefully acknowledges Shun-Hsien (Fred) Huang and John Schmall from Transmission System Planning at ERCOT for their valuable assistance and participation in these studies.

2.0 Assumptions and Methodology

2.1 PSCAD and E-Tran Software

The studies in this report were done using the PSCAD/EMTDC program (V4.5.3). The E-Tran program (V3.2.15) was used to translate PSS/E.raw loadflow cases into PSCAD. E-Tran V3.2.15 has parallel processing and hybrid simulation features.

Detailed models such as transmission lines, fault logic, Wind turbines, Synchronous condensers and SVCs are maintained in PSCAD "substitution libraries" and are automatically imported into the PSCAD case (and initialized) by E-Tran - this process is automated and therefore can be quickly performed for different loadflow cases. Separate substitution libraries were created for each wind turbine manufacturer, Tesla SVCs and Panhandle system to keep the libraries as simple as possible, as there is a large number of wind farms associated with this project. This eases case conversion and data handling.

2.2 PSCAD Parallel and Hybrid System Model

2.2.1 E-Tran Plus PSCAD Parallel Processing

2.2.1.1 Details of E-Tran Plus Parallel Processing capabilities

The use of multiple PSCAD detailed power electronic-based simulation models (such as wind farms) introduces numerous possible problems:

- *Slow simulations:* Power electronic models are inherently slow due to switching of IGBT/diode models. Source-based or interface based models can be used (which avoid the switching) however are less accurate and can be numerically unstable (particularly in weak systems). The simulation time step requirements of some models can also be very small (as low as 1-5 µs as compared to the normal 50 µs time step required for system modeling) which requires the entire simulation to be performed with the minimum required step size.
- *Compiling/linking issues:* Binary .obj/.lib code from many suppliers needs to be linked into one executable .exe – each vendor supplies models compiled with various Fortran or C compilers, and compatibility problems can occur (known affectionately as "Fortran Hell").
- *Confidentiality problems:* Models from the suppliers often are based on actual code from the real hardware (just compiled into PSCAD) – they are extremely sensitive to NDA (non-disclosure agreements) and do not want the code/models to become generally available (for fear of reverse-engineering or probing of the controls to determine capabilities).

To resolve these issues, the modeling approach used in these studies uses parallel processing using a commercially available PSCAD add-on program called "E-Tran Plus for PSCAD" as shown in Figure 1 (see reference paper entitled "Parallel Processing and Hybrid Simulation for HVDC/VSC PSCAD Studies", ACDC conference 2012).

The speed of simulation issues are solved by placing each wind farm onto its own CPU/CORE (either on one computer or on other computers connected to the LAN). Each wind farm is modeled on its own cpu/processor (through a Bergeron line model) – this allows each wind farm PSCAD model to:

- use a different time step (so the entire simulation is not slowed down if one model needs a small time step)
- to be compiled with different Fortran/C compilers (solving compiling/linking/compatibility issues)
- to be generated with different versions of PSCAD (ie older PSCAD V4.2.1 models can be run with PSCAD V4.5.3/newer versions)
- be completely black-boxed to solve confidentiality problems. The total linked executable .exe needs to be pre-generated by PSCAD, but once available, individual .f source code for each page/model, PSCAD models/components/data do not need to be distributed.
- The modeling approach used in these studies is based on a database approach – ie each detailed model is maintained in a PSCAD/E-Tran database, which allows a PSCAD case to be quickly generated for any existing or future loadflow conditions. The simulations are also more accurate, because the complete system and wind farm models are fully initialized by the standard PSS/E loadflow setup.

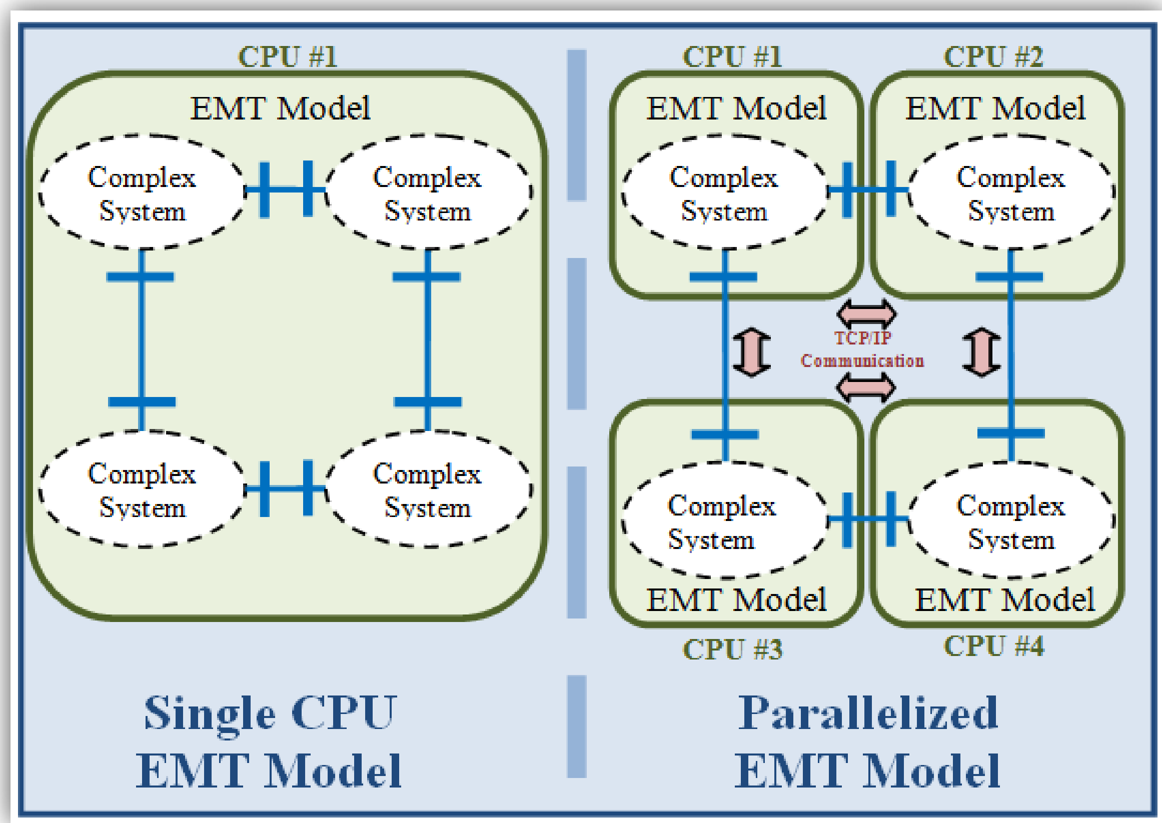

Figure 1 PSCAD single processing Vs. E-Tran Plus Parallel Processing in PSCAD

The "E-Tran Plus for PSCAD" parallel processing method also includes the following features:

- Auto-start component - a single "start" button on one PSCAD case will automatically launch all other cases, including duplication of settings (ie if the main PSCAD case is setup to write output files, then all cases will run output files – if the main case takes a snapshot at 1 second, they all take snapshots at 1 second etc.). This includes starting the PSCAD processes on remote computers, killing processes (which during initial debugging may not have exited cleanly), starting with the process priority and locked to a given cpu core (although the “auto” assignment of processes to cores is recommended) etc.).

- Communication/plotting between PSCAD cases (an array of any size can be assigned to transfer variables from one case to another – this is useful if real/physical communication is required (say a line relay at one side communicates with the other via fibre) or simply for plotting (so the main simulation can plot quantities from the entire set of simulations).
- Compatibility with the multiple run features of PSCAD.

The communication method used between processes is based on standard TCP/IP networking protocols, using custom code (included in E-Tran Plus products) written with low-level (ie no overhead) interfaces and absolute minimum latency requirements (ie a standard LAN gigabit switch is sufficient).

2.2.1.2 Application of E-Tran Plus Parallel Processing to the Panhandle System

The Panhandle system with 4300 MW wind capacity consists of 20 wind plants representing 35 feeders, as well as two SVCs at Tesla 345 kV substation and two synchronous condensers at Alibates and Tule Canyon 345 kV substations. Simulation of the Panhandle system in a single PSCAD case is not possible due to computational restrictions. Instead, E-Tran Plus for PSCAD was used to create sixteen parallel PSCAD cases with acceptable simulation speeds. Sixteen PSCAD cases are created as shown in Table 1 by carefully analyzing the location and complexity of the wind farms and the system.

Table 1 E-Tran Plus Computer Processor allocation

Code	Name	ETRAN Plus Processor
System	Panhandle Network	1
	Tesla SVC	
	Alibates SYNC.	
	Tule Canyon SYNC.	
WK	Wake	2
SP	South Plains 1	3
	South Plains 2	
	South Plains 3	
CP	CottonPlains1	4
	Old Settler	
BR	Briscoe	5
LH	Longhorn	6
SW	Swisher	7
HF	Hereford	8
	Hereford	
	Jumbo Rd	
SS	SpinningSpur2	9
	SpinningSpur3	
CW	Conway1	10
	Conway2	
R6	Route66	11
PH1	Panhandle1	12
PH2	Panhandle2	13
MM	Miami1a	14
SF	Salt Fork	15
BS	Blue Summit	16

The Physical arrangement of the E-Tran plus parallel PSCAD cases are shown in Figure 2. There are two types of PSCAD cases:

1. Panhandle System PSCAD case (Master Case)

The system PSCAD case consists of all the line models, Tesla SVCs, Synchronous condensers and equivalent boundary buses in the Panhandle system. This is the Master PSCAD case and it is electrically connected to the other Slave PSCAD cases (primarily wind farms). Data from the Slave PSCAD cases such as active power (P), reactive power (Q), voltage (V) and trip/status signals are transferred to the Master PSCAD case. All the controls (such as contingency settings) can be carried out at the Master PSCAD case level.

2. Wind Farm PSCAD cases (Slave Cases)

All the wind farms were modeled as slave PSCAD cases and electrically connected thorough E-Tran plus components to the Master PSCAD case. Wind farms were modeled using custom wind turbines provided by their respective manufacturers. Dispatch and voltage levels were set according to the PSS/E dispatch levels.

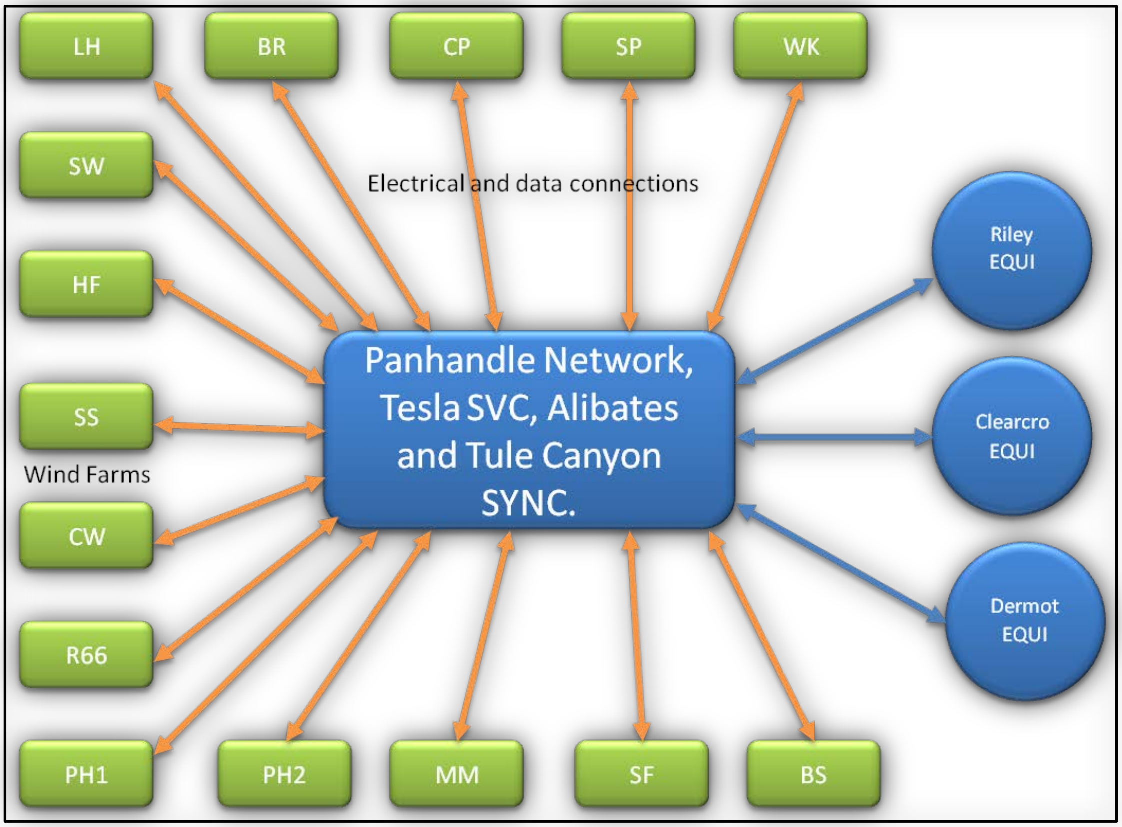

Figure 2 Representation of Panhandle Parallel PSCAD system

2.2.2 E-Tran Plus PSCAD-PSS/E Hybrid Interface

2.2.2.1 Details of E-Tran Plus PSCAD-PSS/E Hybrid Processing capabilities

Normally PSCAD studies are performed with passive network equivalents – these are fixed frequency/fixed source "E Behind Z" equivalents (the E-Tran program has always automated the computation of the passive network equivalents through a multi-port LDU reduction which reproduces the full PSS/E Y/admittance matrix, zeroes out the portion of the network modeled in PSCAD, then does an LDU reduction down to an NxN matrix connected at the boundary busses). This process reproduces the system strength (i.e. the short circuit currents) precisely, as well as the steady state initial conditions.

This type of equivalent (i.e. fixed "E behind Z") ignores the dynamics of the system being equivalenced – this may be acceptable in some studies (for example in radial systems or when the system is very strong) but in general is an approximation.

To further improve accuracy and study capability, this study uses the concept of hybrid simulation through the "E-Tran Plus for PSS/E" product. Essentially the process starts the same as for a normal PSCAD study (i.e. the computation of an NxN network equivalent and starting of the PSCAD case to reach steady state) but with the difference that the PSS/E system is now run in parallel with the PSCAD study, and a communication link is setup so they communicate/update each other as shown in Figure 3. In other words, the PSS/E transient stability model is run on another cpu/core/computer, and everything that happens on the PSS/E side is used to update the network equivalent on the PSCAD side. Similarly, the PSCAD side activity is communicated back to the PSS/E side, where a dynamic load/generator model is updated (and used in the iterative PSS/E solution).

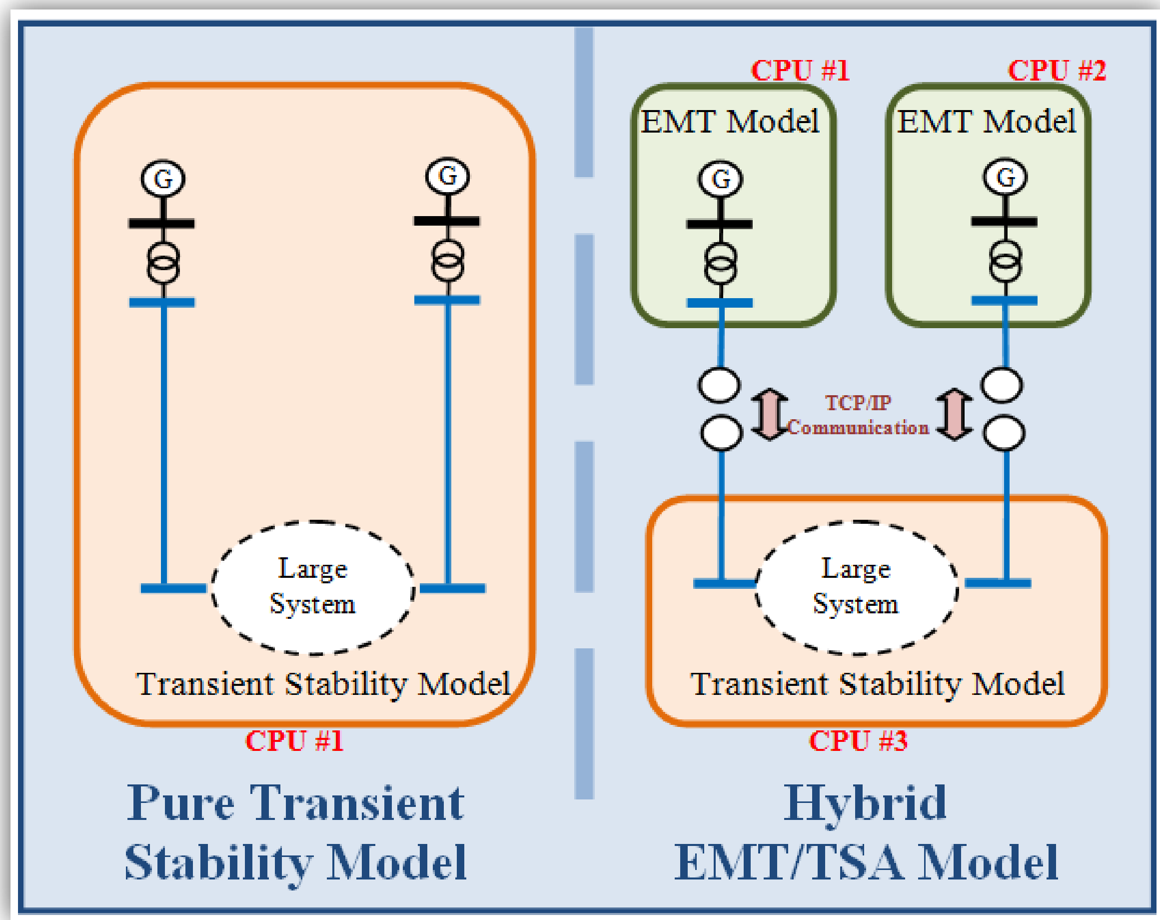

Figure 3 PSS/E Transient Stability Vs. E-Tran Plus PSCAD-PSS/E Hybrid

Details of the process are as follows:

- Communication between PSCAD and PSS/E is performed at every PSS/E time step.
- Terminal conditions at each boundary bus are transferred from PSS/E to PSCAD, where they are used to update the "E" in the "E behind Z" network equivalent. Note the multi-port network equivalent impedance is fixed throughout the run (this is an approximation if a device is switched on the PSS/E side

– if required it is therefore better to put faults/tripping into the PSCAD network by slightly extending the size of the PSCAD model).

- PSCAD network equivalents (E-Tran models) get the updated terminal conditions and updates sources, then runs (at the smaller PSCAD time step) until the next communication instant.
- The PSCAD side uses a DFT (discrete Fourier Transform) to extract the positive sequence, fundamental frequency voltages and currents at the interface boundaries, which are then communicated to PSS/E.
- A custom model (provided) in PSS/E then receives the updated terminal conditions, which it then implements as part of its solution for this step (including iterations and dual time step calculations).

Essentially the above process can be seen as a perfect dynamic network equivalent (i.e. PSCAD equivalents are updated every large step) or as the ability to imbed detailed PSCAD models into PSS/E dynamics studies (instead of trying to develop a custom PSS/E model of a device, which is a complex process).

Other features (of the "E-Tran Plus for PSS/E" hybrid interface include:

- Autostart capability: PSS/E remote cases can be auto-started from a main PSCAD case, including processor priority, locking to a cpu core, or starting on remote computers on the LAN.
- A CHOUT spy model – this allows the PSCAD main case to define and extract any PSS/E quantity, which is included in the communications at each step. This is an extremely useful feature, as it allows online runtime graphing in PSCAD to be used to plot any PSS/E quantities. A complete list of variables can be defined (such as terminal voltages, angles, P and Q flows, generator quantities, VARs, CONs, STATEs etc.).

In general, the parallel and hybrid software supports all possible combinations of PSCAD and PSS/E versions and compilers. The changes required to the PSS/E system models are automated (through a Python script, generated by E-Tran) – this includes replacing the portion of the network which is modeled in PSCAD, by an equivalent generator in loadflow (and .dyr dynamic records to enable the interface to PSCAD at each boundary bus).

Verifications were performed to ensure the voltage, real and reactive power, angle and frequency matches on the PSCAD and PSS/E side (including during large generation mis-match conditions). Differences during the fault and post-fault are possible (due to DFT averaging effects and the use of positive sequence fundamental/frequency vs instantaneous three phase differential equation solvers) but do not affect the machine/electro-mechanical response from the full PSS/E solution.

2.2.2.2 Application of E-Tran Plus PSCAD-PSS/E Hybrid Processing to the Panhandle System

The passive network equivalents at the boundary buses (Riley, Clear Crossing and Dermot) were converted to the E-Tran Plus dynamic equivalents which connect the master PSCAD case to the PSS/E case with the rest of the ERCOT system. A special PSS/E case was created (both .SAV and .DYR) using an E-Tran plus Python script. The PSS/E case was created by deleting buses which were selected for the PSCAD case and creating dynamic equivalent generators at the boundary buses. The dynamic equivalent generators at the PSCAD and PSS/E boundaries communicate with one another other through the E-Tran Plus hybrid interface. The dynamic equivalent generators at the boundary buses are shown in Figure 4. Special dynamic data records were added to the PSS/E DYR file for hybrid electrical communication and data transfer from PSS/E to PSCAD. The hybrid and parallel simulation of the Panhandle system and rest of the ERCOT system can be represented as shown in Figure 5.

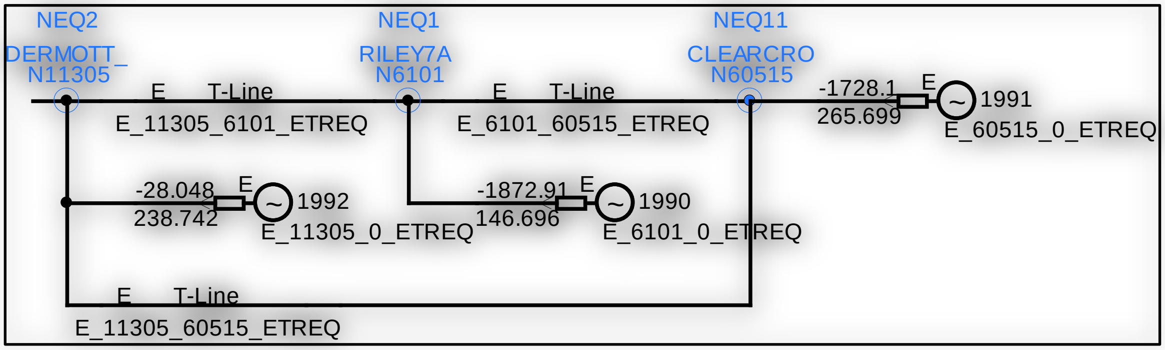

Figure 4 Dynamic equivalent boundary buses of Hybrid case - PSCAD side

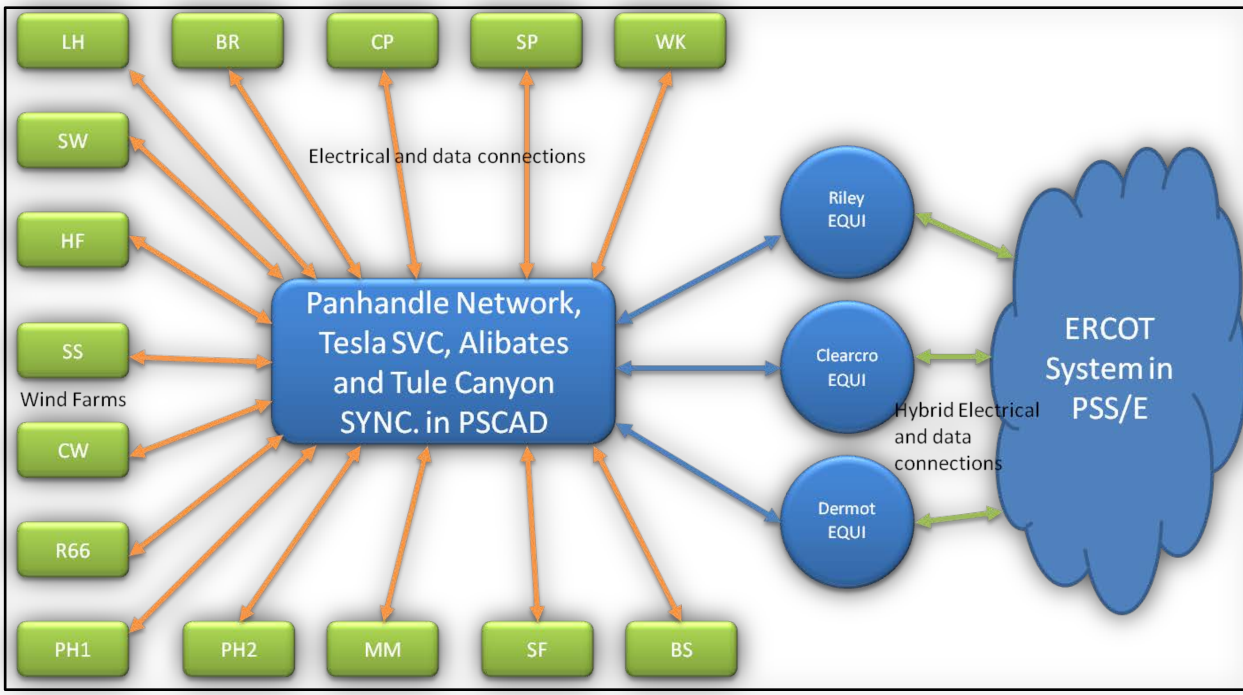

Figure 5 Representation of Panhandle Hybrid PSCAD-PSS/E system

2.3 Wind Farms

There were thirteen detailed PSCAD wind farm models provided from respective manufacturers/project developers, and separate substitution libraries were created for each wind farm for the large Panhandle case creation. Detailed PSCAD models were not available for seven wind farms at the time of this study started, similar wind farm models were used for the simulations as an approximation. Although all possible efforts were made to match the type and the capacity of the wind farms for substitution, it is noted that further refinement of controls and turbine types may cause the behaviour in the Panhandle to differ slightly.

Some wind farms are equipped with DVAR STATCOM devices, and these were modeled in detail in the PSCAD cases. The details of each wind farm in the 3700 MW dispatch case (86% dispatched from total 4300 MW capacity) are shown in Table 2. The Blue Summit wind farm was modeled in the PSCAD case because it is within the defined boundary in the PSCAD case and is electrically close to the Tesla SVC and the Panhandle system. The dispatch of the Blue Summit wind farm was not considered in total dispatch calculations.

Table 2 Details of the Panhandle wind farms in 3700 MW dispatch case

Code	Panhandle Wind	Name	Size (MW/MVAR)	Dispatch (3700 MW) (MW/MVAR)	Location
WK	1	Wake	299.3	257.3	Cottonwood
SP	2	South Plains 1	200	172	White River
	3	South Plains 2	150	130.5	
	4	South Plains 3	150	127.7	
CP	5	CottonPlains1	50.4	43.3	White River
	6	Old Settler	151.2	130	
BR	7	Briscoe	149.9	128.9	Tule Canyon
LH	8	Longhorn	360	309.6	Tule Canyon
SW	9	Swisher	299.5	257.5	Ogallala
HF	10	Hereford	99.9	85.9	Windmill
	10	Hereford	100	86	
	11	Jumbo Road	299.7	257.8	
SS	12	SpinningSpur2	161	138.4	AJ Swope
	13	SpinningSpur3	194	166.8	
CW	14	Conway1	211.22	181.7	Alibates
	15	Conway2	390.22	335.6	
R6	16	Route66	150	129	Alibates
PH1	17	Panhandle1	218.3	187.8	Railhead
PH2	18	Panhandle2	181.7	156.2	
MM	19	Miami1a	288.6	248.2	Gray
SF	20	Salt Fork	200	172	Gray
BS		Blue Summit	135.4 Note1	108.3 Note1	Jim Treece
Total			**4304.8**	**3702.2**	

Note1: Blue Summit wind farm was modeled in the PSCAD case but not considered in dispatch calculations.

As step up transformers are usually modeled inside the manufacturer's wind turbine models, all the components towards the low voltage side from the step up transformer are typically removed and the detailed models are connected.

Detailed DVAR PSCAD models were substituted and switching capacitors and inductors were modeled inside the detailed DVAR models as applicable. Dummy capacitors and inductor models were inserted to replace the shunt capacitors and inductors represented in loadflow. Some of the 345 kV/34.5 kV transformers were replaced by detailed transformers with additional measuring at the Point of Interconnection (POI) for the purpose of DVAR voltage controls as required. The DVAR devices were set to control the POI (345 kV) voltage to pre-contingency voltages. The DVARs were set to operate with a droop and dead bands, and include 300% overload capability for a 2 second period. The DVAR devices switch shunt capacitors or inductors according to VAR requirements, assuming 3 to 5 second time delays. The DVARs were set to keep their dynamic reactive power output at minimum level during normal operation by switching shunt devices to maintain maximum dynamic range during contingency conditions.

The 345 kV transmission line from wind farms to the Panhandle system was replaced by the E-Tran Plus parallel communication component to enable parallel processing in PSCAD. This component consists of a Bergeron line model with parallel communication capability with other PSCAD cases.

With respect to optional controllers such as SSCI damping controllers, plants were modeled as provided by the manufacturer, except for certain wind turbines, which did not function as required with the optional SSCI mitigation turned on. This controller was turned off to allow the study to proceed, since the analysis was focused on weak system analysis.

During the course of this study, it was discovered that some of the provided PSCAD models did not include any plant voltage controller. Other models included plant voltage controllers, but were submitted with default settings that may not reflect actual field tuning. In most cases, these default settings resulted in a very slow response – comparable to disabling the plant voltage controller. Sensitivity analysis was performed to investigate the impact of plant level voltage controller response.

2.4 PSCAD System Model

The PSCAD system model includes following subpages:

2.4.1 Global Initialization Page

Global Initialization is the main control page of the PSCAD simulations as shown in Figure 6.

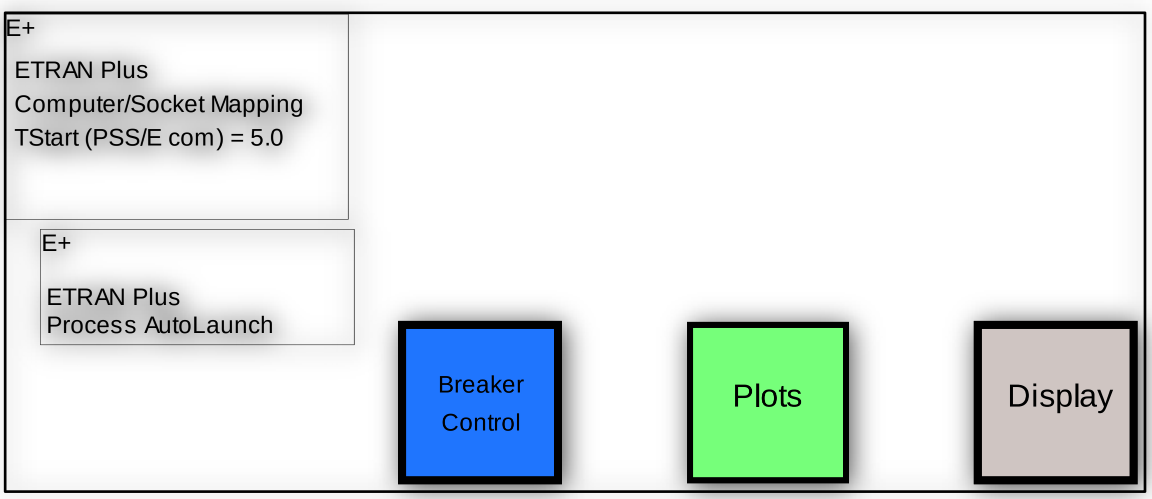

Figure 6 Inside the Global Initialization page

The Global Initialization page has the following sub pages and E-Tran Plus components:

2.4.2 Breaker Control Subpage

The Breaker control page has the following components and operations as shown in Figure 7.

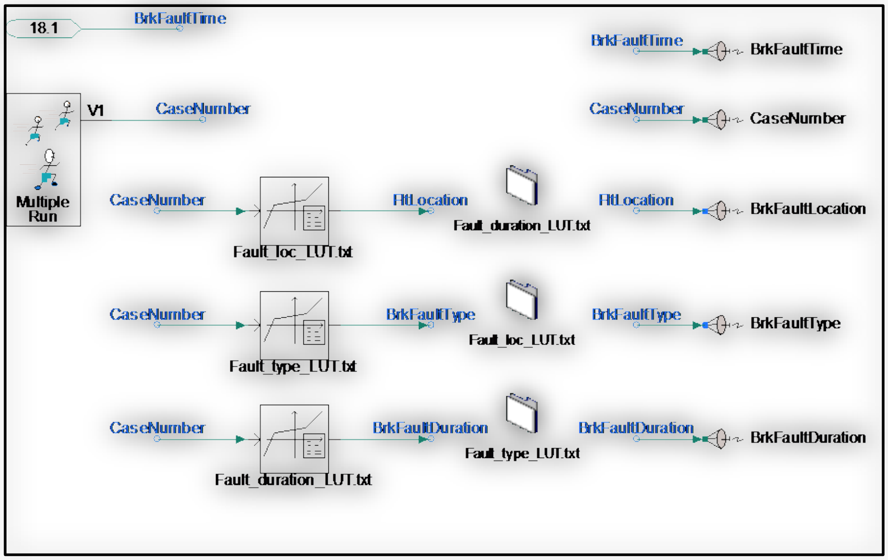

Figure 7 Breaker Control Subpage

2.4.3 Display Subpage

This page displays breaker operations of each line end for all the contingencies listed as shown in Figure 8.

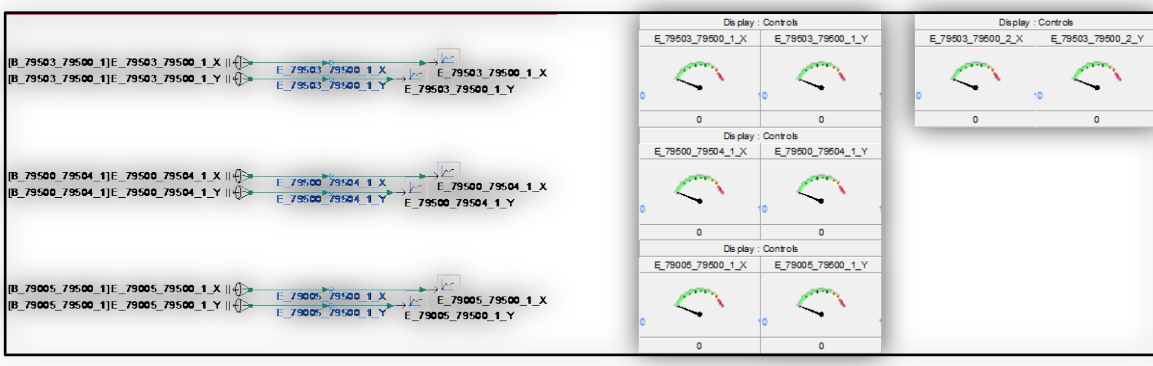

Figure 8 Inside Display subpage

2.4.4 E-Tran Plus components

Two E-Tran Plus components are modeled inside the Global Initialization page to communicate between parallel PSCAD cases as shown in Figure 9 and Figure 10.

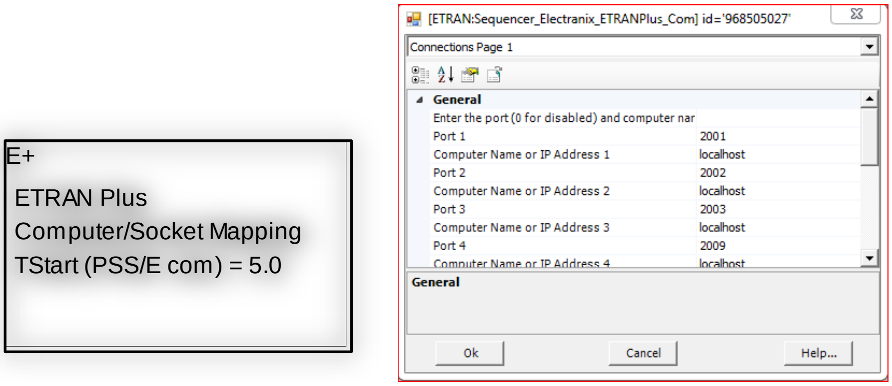

Figure 9 E-Tran Plus Socket Mapping Component

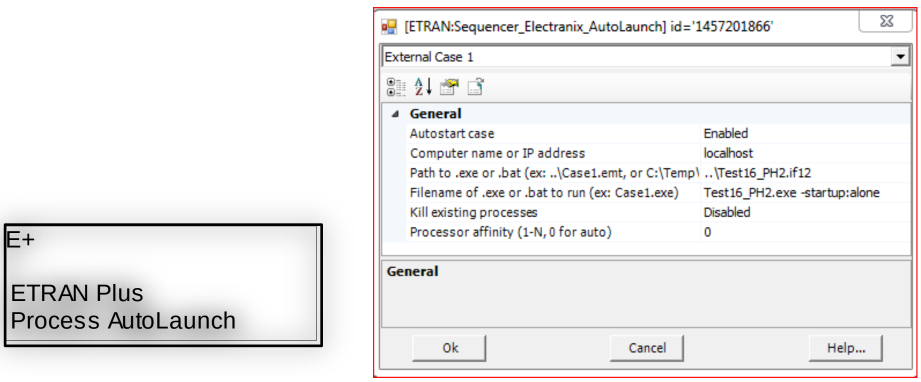

Figure 10 E-Tran Plus AutoLaunch Component

The E-Tran Plus Computer/Socket Mapping component has TCP/IP numbers to communicate with parallel PSCAD cases during the simulation. Elecrical signals and data singanls are transferred between parallel PSCAD cases through TCP/IP sockets.

The E-Tran Plus Autolaunch component launches parallel PSCAD cases from the main PSCAD case.

2.4.5 Transmission Line modeling

All the transmission lines in the Panhandle system were modeled using Bergeron line models as shown in Figure 11. Fault logic, measuring and signal transferring were modeled inside the transmission line model to connect to the outside controller pages.

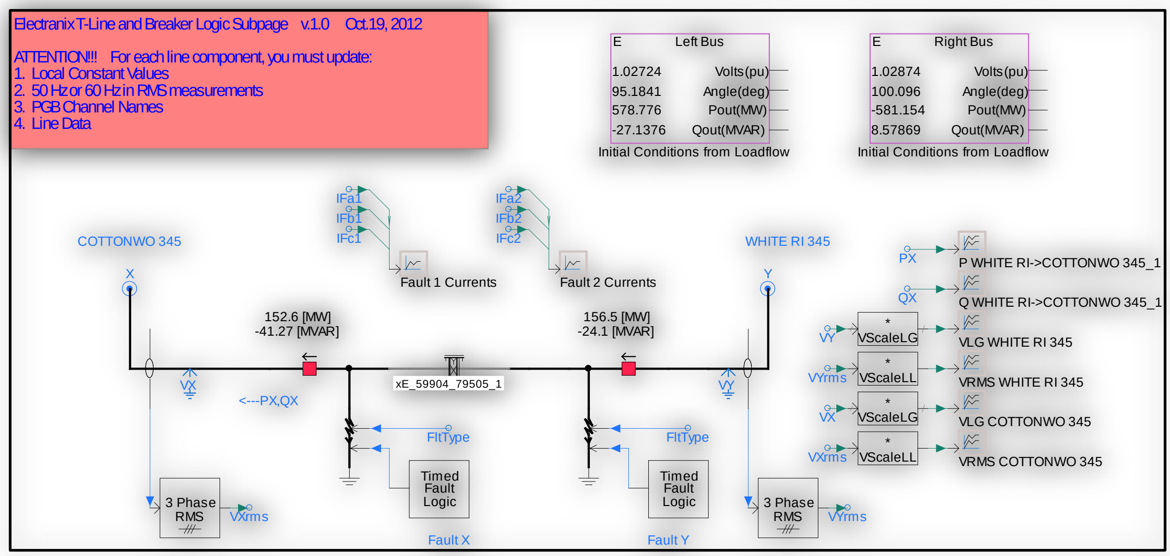

Figure 11 345 kV Transmission Line Model with faults

2.4.6 Tesla SVC model

A detailed SVC model was provided by the Transmission Service Provider (TSP) for the Tesla SVCs. The voltage in the solved powerflow at the 345 kV bus was set as the reference voltage to the SVCs. A substitution library was created for Tesla SVCs and can be used to generate PSCAD cases for different PSS/E base cases.

2.4.7 Alibates and Tule Canyon Synchronous Condenser Models

Alibates and Tule Canyon Synchronous Condensers were represented with generic models according to the PSS/E dynamic data records as shown in Figure 12.

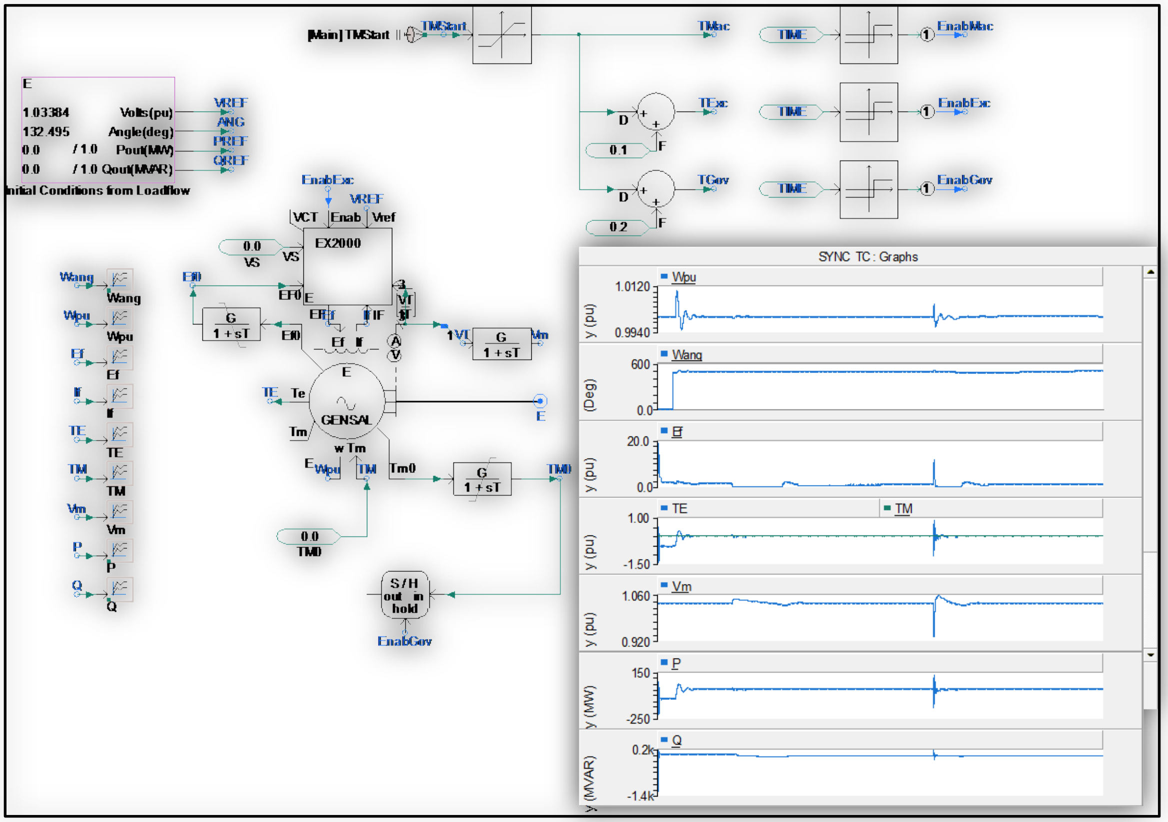

Figure 12   Synchronous Condenser model

2.5 Study Cases and Contingencies

ERCOT provided two study cases with 4300 MW wind capacity and 3700 MW dispatch in the Panhandle system. One case is the existing system without upgrades. The second case includes upgrades, including synchronous condensers at Tule Canyon and Alibates 345 kV buses and a new Alibates-AJ Swope-Windmill-Ogallala-Tule Canyon 345kV circuit. Five study cases were generated from these two base cases as shown in Table 3. A sixth sensitivity case was generated by increasing the generation to 3900 MW in the PSCAD model.

Table 3 Panhandle Study Cases

Study Case	Description	Panhandle Wind Capacity (MW)	Panhandle Wind Dispatch (MW)	Upgrades (Second Circuit + 150MVA x2 Sync.Cond.)	Upgrades (Second Circuit + 150MVA x2 STATCOM)	Upgrades (Second Circuit + 150MVA x2 SVC)	Plant Voltage Controls
1[5]	Base Case	4300	3700	No	No	No	No (*)
2	Sensitivity Case	4300	3700	No	No	No	**Yes (**)**
3[6]	Proposed Upgrades	4300	3700	**Yes**	No	No	No
4	Sensitivity Case	4300	3700	No	**Yes**	No	No
5	Sensitivity Case	4300	3700	No	No	**Yes**	No
6	Sensitivity Case	4300	3900	**Yes**	No	No	No

(*) default Plant Control Voltage setting based on the submitted models
(**) Plant voltage controller tuned to provide some VAR response within approximately 3 seconds. Full reactive response time is dependent on system and definition of "response time".

Based on the dynamic simulation results and the existing system topology condition, eighteen critical contingencies were considered in the PSCAD simulation that included balanced normal clearing and unbalanced breaker failure events, single and double circuit outages. Contingencies 1 to 16 are inside the Panhandle region and contingencies 17 and 18 are outside the Panhandle. The contingencies inside the Panhandle region were applied in the PSCAD model of the simulation with pure PSCAD and with PSCAD-PSS/E hybrid simulations. The contingencies outside the Panhandle region were applied in the PSS/E side of the PSCAD-PSS/E hybrid simulations.

2.6 AC System Representation

All the buses inside the Panhandle system were modeled in PSCAD. Riley, Clear Crossing and Dermot 345 kV buses were selected as boundary buses and were modeled initially with passive network equivalents in the PSCAD model, and subsequently with a full hybrid PSS/E dynamic interface.

2.7 Performance Criteria

The following general wind plant performance requirements were applied in these studies to evaluate whether performance was acceptable[7].

2.7.1 Capability to ride through disturbances

The WPP should not be tripped in the event of normally cleared system faults. Fault ride through is a requirement where wind generators are required to remain connected to the grid during and after the clearance of a system fault. Following the clearance of the fault, the WPP should be able to provide real and reactive

[5] This case was also run with Hybrid simulation.
[6] This case was also run with Hybrid simulation, as well as pure PSS/E Transient stability
[7] For a more detailed discussion of weak system performance requirements, see DRAFT Technical Brochure – Cigre B4.62 Chapter 3

power to the grid, assisting in maintaining angle and voltage stability of the system.

2.7.2 Post-fault steady state voltages

If the system is too weak and has insufficient voltage support, the system may experience post fault steady state voltage violations before the power plant voltage controller is able come into action (which may take 20 to 30 seconds depending on the responsiveness of these plant level controllers). This may lead to low post fault voltage values, and some wind farms may enter fault ride through modes before plant controller can respond.

2.7.3 Stable coordination of dynamic controllers

Generators are expected to operate in a stable fashion, and to avoid interfering with the controls of neighboring equipment. Modern power electronics based wind generators are equipped with numerous control systems performing numerous control functions. These control functions can interact with nearby power electronic based dynamic devices with comparable control system time constants. This can lead to detrimental dynamic oscillations. The potential of such oscillations is greater when the devices are connected to a weak grid.

Generators are also expected to operate in a stable fashion during varying system conditions, including following outages which may significantly weaken the connection strength.

2.7.4 Sufficient contribution to network voltage support

Generators are expected to contribute to the support of the bulk electric system. This includes reactive power available to regulate voltage (fast and slow support), as well as frequency control in some cases. ERCOT requires all Generation Resources to provide reactive support per ERCOT Protocol 3.15. The reactive support from wind plants in this analysis is based on the provided model and data from Resource Entities, and it is clear from this analysis that the extent to which the generators contribute to this support is critical in overall performance.

2.7.5 Frequency and Power ramp rate

There is currently no specific requirement for active power ramp rates in the ERCOT system. The active power ramp rates of the wind plants are very important for weak system performance. If the ramp rates are too low, the system may experience frequency violations as energy is not supplied during the post fault period. If the ramp rates are too high, the system may experience voltage violations in weak system conditions, and the ability of the plant controllers to remain stable is reduced as the system is weakened.

The wind plants in the Panhandle system have different active power ramp rates, ranging from as low as 0.2 sec to others as high as 2.0 sec. Drastically varying the mix of ramp rates in the Panhandle system may impact the results of this study.

2.8 Additional Assumptions

Following additional assumptions were made for both parallel and hybrid simulations.

1. The PSCAD models for some of the wind farms were not available at the time of studies. Similar wind farm models were used for the simulations. All possible efforts were made to match the type and the capacity of the wind farms for substitution.
2. One wind turbine PSCAD model with an SSR mitigation function had technical issues with starting, as well as during contingencies. Consequently, the SSR mitigation option was disabled for the simulations,

which may impact weak system behaviour. However, the SSR protection option was kept enabled, as this does not impact controls.

3. The PSCAD simulation was run up to 18 seconds simulation time in order to get a steady state flat run. This is due to the presence of many dynamic devices (wind farms, DVARs and SVCs) which ramp up during the first few seconds. Infinite source models were connected during the first five seconds of the simulation to support ramp up of all the wind turbines at the same time.
4. This study was carried out in order to gain understanding of the weak system issues. No Sub-synchronous oscillation issues were specifically studied. The selection of boundary buses makes some series compensated lines (outside the Panhandle system) excluded from the main PSCAD system case.
5. Line arresters and MOVs of the series capacitors were not modeled in this simulation.
6. Transmission lines were modeled as Bergeron line models.
7. The length of certain very short 345 kV transmission lines (less than 3 km) from wind farm POI locations to the main Panhandle buses of a few wind farms (Herford to Windmill and Briscoe to Tule Canyon) were increased to 3 km (minimum length for a travelling wave line model with a simulation time step of 10 us) by changing R, X and B values to model those lines as Bergeron line models. This makes it possible to implement parallel communication between the wind farms and the main system PSCAD case.
8. The north HVDC tie was modeled as a negative load in the PSCAD-PSS/E hybrid simulation due to non-convergence issues with the PSS/E model.
9. The Blue Summit wind farm was modeled in PSCAD studies even though it is outside the Panhandle system due to its closeness to the Tesla SVC and boundary buses.
10. The PSCAD cases were developed with 4300 MW wind capacity and 3700 MW and 3900 MW dispatch conditions. The performance of the system may differ if the wind capacity is increased with same dispatch levels due to reactive power performance of the additional wind turbines added to the system.
11. Some of the wind turbines models do have the built in Wind Power Plant Controller (WPPC) and some do not. Generic WPPC models developed by Electranix were used for wind plants that do not have the built in WPPC in sensitivity cases where voltage controllers are enabled as shown in Table 3. Two wind farms were not equipped with the WPPC because the provided PSCAD models do not support WPPC. The parameters used for any WPPC enabled cases are set to provide some VARs within 3 seconds (Ti = 3 sec), and a 2% droop.
12. All the PSCAD simulations were run with a 10 µs simulation time step to accommodate most wind plant models. The PSCAD snapshot feature was not used in the simulations as some models do not support this feature.
13. Transformer saturation was disabled for many of the cases. Detailed saturation data was not available, however sensitivity analysis done with typical saturation characteristics indicated slightly improved transient damping when considering the effects of transformer saturation.

3.0 Dynamic Performance Studies

3.1 Summary of Dynamic Performance Study Results

Several system scenarios were studied in the Panhandle area, with and without system upgrades, with 4300 MW wind capacity, and with different reactive power devices and varying wind dispatch. Certain of these simulations were repeated using Hybrid PSCAD-PSS/E software tools and pure PSS/E models. A summary of key results for the Panhandle weak system study is shown in Table 4.

Table 4 Summary of Panhandle weak system study results

Case	Description	Panhandle Wind Capacity (MW)	Panhandle Wind Dispatch (MW)	Upgrades (Second Circuit + 150 MVA x2 Sync.Cond.)	Upgrades (Second Circuit + 150 MVA x2 STATCOM)	Upgrades (Second Circuit + 150 MVA x2 SVC)	Plant Voltage Controls	WSCR	Results	Total Wind Tripped (MW)
1	Base Case	4300	3700	No	No	No	No*	1.2	Fail	≈3150
2	Sensitivity Case	4300	3700	No	No	No	**Yes****	1.2	Wind Trips	≈250
3	Proposed Upgrades	4300	3700	**Yes**	No	No	No	1.5	Good	0
4	Sensitivity Case	4300	3700	No	**Yes**	No	No	1.3	Wind Trips	≈375
5	Sensitivity Case	4300	3700	No	No	**Yes**	No	1.3	Wind Trips	≈225
6	Sensitivity Case	4300	3900	**Yes**	No	No	No	1.4	Marginal	0

(*) default Plant Control Voltage setting based on the submitted models
(**)Plant voltage controller tuned to provide some VAR response within approximately 3 seconds. Full reactive response time is dependent on system and definition of "response time".

The high level summary of the study case results can further be described as follows:

1. The non-upgraded case (Case 1, Base Case) with 3700 MW dispatch fails with multiple issues. Many of these issues stem from failure of the wind plants to adequately support the system voltage in the seconds following critical contingencies. Wind plant tripping, voltage violations and unstable behaviour was observed for most contingencies (including 3LG faults followed by single or double circuit outages and 1LG faults with breaker failure).
2. The non-upgraded case (Case 2, Sensitivity Case) with 3700 MW generation (same as Case 1), but with WPPCs enabled (custom and generic with relatively fast control response) shows much improved performance. However, several wind turbines still trip following critical contingencies (including 3LG faults followed by single or double circuit outages) due to inability to maintain terminal voltage control in the post-fault recovery period.
3. The upgraded case (Case 3, Proposed Upgrades) with 3700 MW dispatch and synchronous condensers passes all the performance criteria without voltage violations.
4. The upgraded case (Case 4, Sensitivity Case) with 3700 MW dispatch (same as Case 3), but with generic STATCOMs instead of Sync. Condensers experiences several wind turbines tripping following certain

critical contingencies (including 3LG faults followed by single or double circuit outages), as well as rough or delayed recovery from severe faults.

5. The upgraded case (Case 5, Sensitivity Case) with 3700 MW dispatch with generic SVCs shows no voltage violations. However, similar to Case 4, several wind turbines do trip following certain critical contingencies (including 3LG faults followed by single or double circuit outages), as well as rough or delayed recovery from severe faults.
6. The upgraded case (Case 6, Sensitivity Case) with 3900 MW dispatch with synchronous condensers is a marginal case. It shows undesired voltage responses such as extended 0.95 pu post fault voltage dips, and dynamic reactive power devices such as SVCs and Synchronous condensers remain at their maximum limits for extended periods during some critical contingencies (including 3LG faults followed by double circuit outages and 1LG faults with breaker failure). No wind plant tripping was observed.

3.2 Discussion of Dynamic Issues

3.2.1 Use of STATCOMs and SVCs to replace synchronous condensers

Generic STATCOMs and SVCs were used for study cases 4 and 5, and some wind tripping was observed in these cases. Additional tuning and optimization of control parameters for the STATCOM and SVC may improve the wind plant post-fault performance. Synchronous condensers inherently improve the inertia of the system and short circuit strength, while STATCOM and SVC technologies rely on pure voltage control response to solve weak system issues. Although these power electronic devices may benefit weak systems substantially depending on the specific limitations encountered, it is evident from these results that voltage recovery from faults is smoother with synchronous condensers due to their inherent physical properties, with minimal effort required in control tuning. Significant further analysis could be done to optimize the response of both the power electronic devices and the wind farm controllers themselves.

Additional note:

- FACTS devices such as STATCOMs can be enhanced to supply “synthetic inertia” by incorporating the use of energy storage. It is noted that they are still inverter based however, and will be subject to blocking during faults, and a short recovery period as they regain synchronism with the network.

3.2.2 Use of Hybrid PSSE/PSCAD analysis

The Case 3 (upgraded Panhandle system) scenario was further studied with Hybrid PSCAD-PSS/E simulations. The Panhandle system was modeled in PSCAD and the rest of the ERCOT system was modeled in PSS/E. The results show no major changes compared to the pure PSCAD cases for the faults studied, although hybrid cases do indicate improved damping when compared to pure PSCAD responses.

3.2.3 Planning Margins for WSCR

The 3900 MW dispatch case (with upgraded system) is at the margin of voltage stability, as all the reactive power devices hit limits at the end of the active power ramping. Post-contingency voltages dip as low as 0.95 pu at some wind turbine terminals (2 sec after the fault clearing), but all plants recover with no special attention paid to voltage control coordination. This case is below the WSCR planning threshold of 1.5 used by ERCOT, with WSCR values dipping to less than 1.4.

3.2.4 Post-fault steady state voltages and mode cycling

The non-upgraded case (Case 1 in Table 4) shows post-fault voltage problems. The voltage goes as low as 0.82 pu at some wind plant terminals as shown in Figure 13 when the active power of the wind plant ramps up to the post fault level under post-fault weakened network conditions. As discussed in Chapter 2, the wind power plant voltage controllers are slow (taking 20 to 30 seconds to react) and the system voltage goes very low within a few seconds after the fault prior to the plant voltage controllers response. This leads to post fault voltage violations in the non-upgraded case, and many wind farms experience difficulty in recovery, either tripping, or cycling through LVRT modes (mode cycling) several times before tripping as shown in Figure 13.

The upgraded case (Case 3 in Table 4 with synchronous condensers) shows no voltage violations and no plant tripping (example shown in Figure 14) for all the contingencies studied.

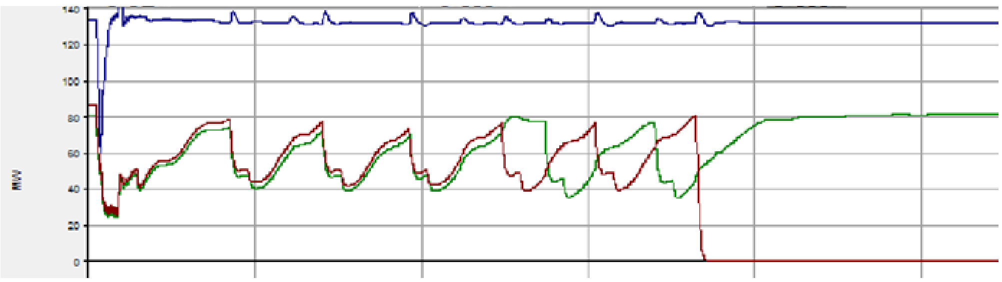

Figure 13 Sample of poor active power recovery for the non-upgraded system

Figure 14 Sample of stable active power recovery for the upgraded system

When the Wind Power Plant Controllers (WPPC) of the plants were enabled with VAR response occurring within 3 seconds, most of the steady state voltage violations were greatly improved in the non-upgraded case (Case 2 in Table 4)as shown in Figure 15, although some wind plants still were observed to trip for severe contingencies. The improvement of the post fault voltage response due to the WPPC resolves most of the wind plant mode cycling and tripping issues.

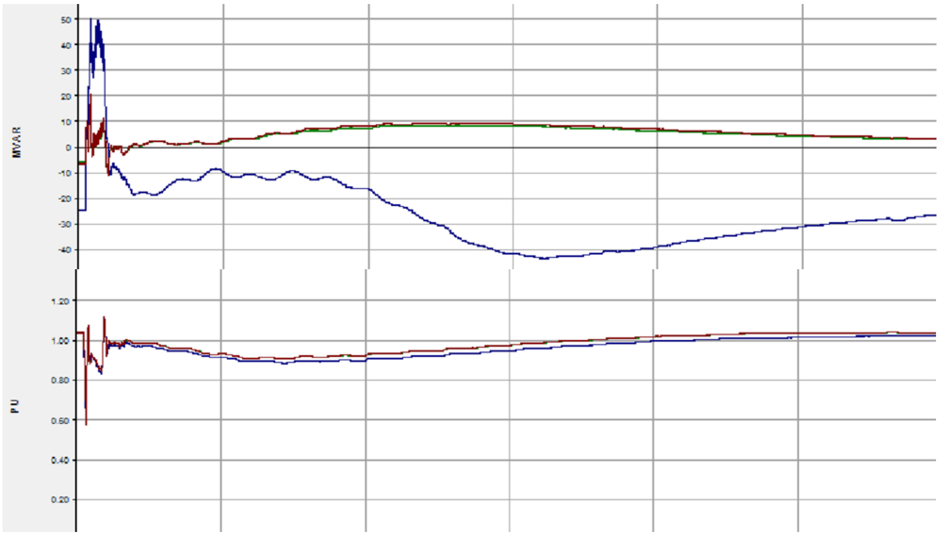

Figure 15 Improved system response with WPPCs enabled (Reactive power from sample plants on top, system voltage below)

The improved performance observed with fast WPPCs is an important result, as it demonstrates the unique characteristics of wind and the importance of dynamic voltage control planning. It is possible for wind plants to support the voltage across a system, but these controllers may not be configured to operate in the fast timeframes required to prevent voltage collapse in the few seconds following a fault, and the controllers may not be available if the wind plants are out of service, or the wind is not blowing. A mix of network based voltage support and wind power plant voltage support is desirable, and special care is required in conventional planning to ensure sufficient VARs are available in the immediate post-fault timeframes as well as the extended simulation timeframes typically examined in powerflow studies.

3.2.5 Unstable and oscillatory cases

Undamped oscillations were identified in the non-upgraded Panhandle system case (Case 1 in Table 4) as shown in Figure 16 due to post-fault weakened system conditions and poor voltage support. This leads to wind plant tripping, uncontrolled oscillations, and system voltage violations.

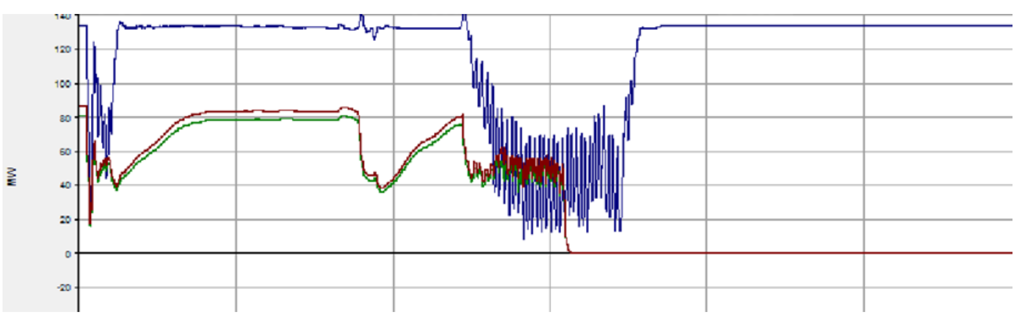

Figure 16 Sample post-fault oscillatory response (active power) for the non-upgraded system

When the system is upgraded with synchronous condensers and additional circuits (study case 3), these unstable and oscillatory conditions were no longer evident. (Figure 17)

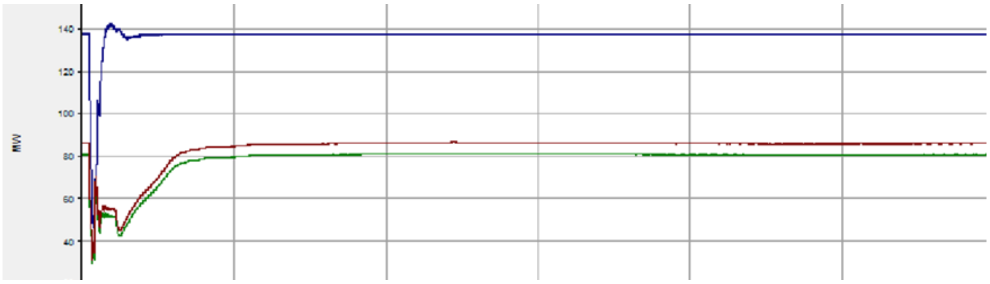

Figure 17 Improved active power recovery of the upgraded system

3.2.6 Instantaneous trip just after the fault

Wind plant tripping was observed for all study cases except Study Cases 3 and 6 (which include new circuits and synchronous condensers). These tripping events are typically due to temporary voltage excursions in the period immediately after the fault cleared. When the power system is weakened, the frequency tracking controllers (Phase Locked Loops, or PLLs) of the power electronics devices such as wind turbines, STATCOMs, SVCs have more difficulty locking on to the system frequency following a fault, and smooth and accurate control of the voltage becomes more difficult. Careful tuning of control parameters on a plant-by-plant basis could be effective in improving voltage controller response and avoiding plant tripping.

When the STATCOMs and SVCs were replaced by synchronous condensers in the upgraded cases all the tripping issues were resolved. In addition to supplying dynamic reactive power, the synchronous condensers inherently stabilize voltages with minimal tuning effort (by virtue of their physical nature).

4.0 Parametric SCR Reduction Analysis

4.1 Summary of SCR Reduction Analysis

A test system was developed to examine the behaviour of the Panhandle system by parametrically reducing the short circuit strength (increasing impedance) of the passive network equivalents at the boundary buses (Riley, Clear Crossing and Dermot 345 kV). The purpose of this analysis development was designed to provide a basic **screening-level understanding** of the stability limits of the Panhandle in a timely fashion as the relative strength of the supporting ERCOT network was reduced.[8] This analysis neither applied the identified dynamic contingencies described in Chapter 3 nor aimed to identify the maximum Panhandle wind dispatch level to obtain the reliable responses. The PSCAD model of the Panhandle system (including detailed wind plants) was used for these tests. Transmission upgrades, including a new Alibates-AJ Swope-Windmill-Ogallala-Tule Canyon 345kV circuit and two synchronous condensers were included in the test system.

4.2 SCR Test System Development

The passive network equivalents of the boundary buses were replaced by the custom generators as shown in Figure 18. A resistor and an inductor were connected in series to the passive network equivalent generators as shown in Figure 19. A custom PSCAD component was developed which increase the series connected R and L which reduces the effective short circuit strength of the boundary buses. This component was also used to maintain the voltage and relative angles at the boundary buses constant by adjusting the source terminal voltages of the equivalent generators.

The short circuit strength of the boundary buses was decreased linearly, and the corresponding WSCR values were calculated using PSS/E. The relationship between the SCR index at the boundary buses and the overall WSCR of the Panhandle system is shown in Table 5.

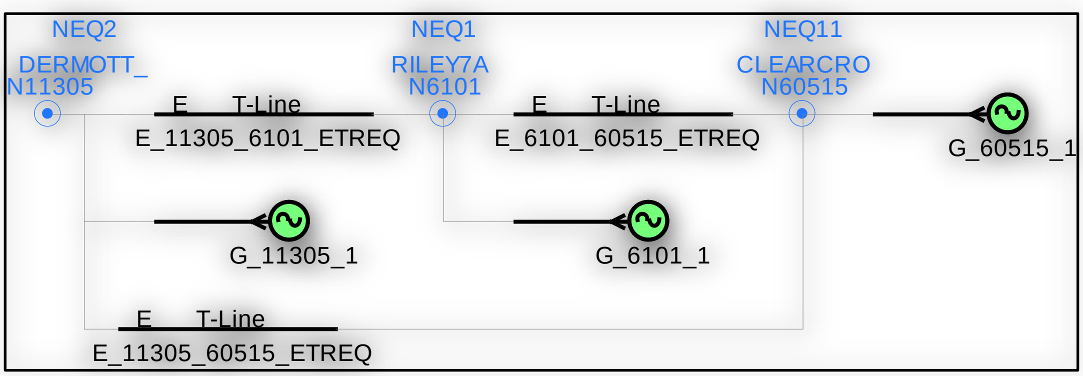

Figure 18 Modified passive network equivalents at the boundary buses

[8] It took approximately 32 hrs to run 16 contingencies on a Core i7, 8 core (16 threads) desktop computer running 16 parallel PSCAD cases with the E-Tran Plus software. The SCR test case provided screening understanding of the limits to stability in a single run taking less than 2 hrs.

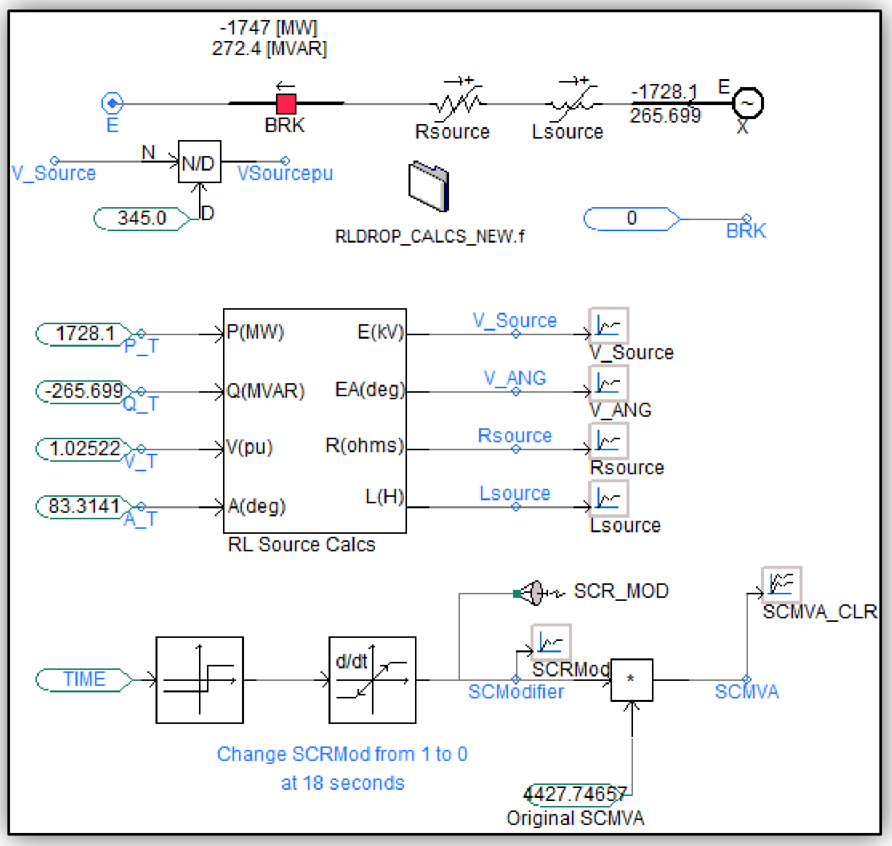

Figure 19 Inside the modified passive network equivalent

Table 5 SCR index mapped to ERCOT WSCR metric

SCR index at boundary buses (pu)	WSCR
1	**1.5**
0.9	1.4
0.8	**1.35**
0.7	1.25
0.6	1.20
0.5	1.1
0.4	1.05
0.3	**1.00**

4.2.1 Large signal stability of the Panhandle system with reducing SCR

Three phase to ground faults were applied at a Panhandle 345 kV bus over four cycles and cleared, without any line outage, every 4 seconds as the SCR was linearly ramped down. The four second duration was chosen to provide enough time for wind plants to recover following the disturbance. The behaviour of all wind farms and reactive power controlling devices was monitored for any abnormal behaviour or tripping.

4.2.2 Small signal stability of the Panhandle system with reducing SCR

The case developed for the large signal stability SCR test was further modified to apply small signal disturbances to the Panhandle system by bypassing and un-bypassing one series compensated 345 kV line from Tule Canyon to Tesla over four cycles at every 2 seconds. The behaviour of all wind farms and reactive power controlling devices was monitored for any abnormal behaviour or tripping.

4.3 Results of Parametric SCR Reduction Analysis

The results of the SCR test are shown in Table 6.

Table 6 SCR Test Results

Scenario	WSCR	Small Signal Stable	Large Signal Stable
1	**1.5**	Yes	Yes
2	1.4	Yes	Yes
3	**1.35**	Yes	Yes
4	1.25	Yes	No
5	1.20	Yes	No
6	1.1	Yes	No
7	1.05	Yes	No
8	**1.00**	Yes	No
9	0.93	No	No
10	**1.3(1)**	Not done	No
11	**1.3(2)**	Not done	No

(1) Based on scenario 1 and replacing synchronous condensers with SVCs.
(2) Based on scenario 1 and replacing synchronous condensers with STATCOMs.

4.3.1 Large signal stability

The application of a three phase fault in the Panhandle for four cycles makes all the wind farms go to fault ride through mode as shown in Figure 20. When the fault was applied at an SCR index of 0.7 (WSCR = 1.25), one of the wind plants failed to ride through, and this level was considered to be "Large Signal Unstable". The 0.8 pu SCR index is equivalent to WSCR of 1.35. It should be noted that this level is still "system intact" in the Panhandle, so this corresponds well with the post-fault levels studied in the dynamic performance analysis. (i.e. WSCR = 1.5 prior to the fault corresponds to a reduced (but stable) WSCR after the fault).

A similar large-signal stability sensitivity study was carried out with STATCOMs/SVCs (Scenario 10 and 11) connected to the system at Alibates and Tule Canyon instead of Synchronous condensers. Wind plant tripping was observed in these scenarios. It can be concluded that STATCOMs/SVCs do not provide equivalent system strength advantages compared to the synchronous condensers. (As previously noted, these devices were generic and not purposely tuned to optimize stability.)

4.3.2 Small Signal Stability

Using this test setup, it is possible to evaluate the small-signal stability of the system, which would normally be encountered with no significant event (possibly as wind was ramping up in a system normal condition). Without significant disturbances, the linear reduction of short circuit strength causes large oscillations to develop and the overall system to collapse at a WSCR index of approximately 0.86. However, it can be observed that minor undamped oscillations are already evident at a WSCR index of 0.93. Therefore, it can be concluded that a WSCR index of 1.0 passes the small signal stability SCR test. The small signal stability test was not carried out with STATCOMs/SVCs.

4.3.3 Conclusions of SCR Ramp Tests

The results of these SCR tests are in good alignment with the detailed time domain simulations described above, as follows:

- The SCR ramp test indicates that the system is stable with a WSCR of 1.35 for N-0 conditions. The detailed contingency tests indicated that the system is stable with WSCR of 1.5 prior to sixteen selected contingencies (N-1 and N-2). Based on detailed tests, the system is marginally stable (pre-fault) with a WSCR of 1.4.
- Further testing with STATCOM/SVC indicates that these devices may not provide comparable system strength enhancement compared to synchronous condensers, and these results are also in alignment with the detailed time domain simulations with 16 selected contingencies.
- The small signal stability tests indicate that there is a final limit beyond which controls will not be able to operate. Approaching this limit will yield diminishing returns and increased cost and difficulty in mitigation.

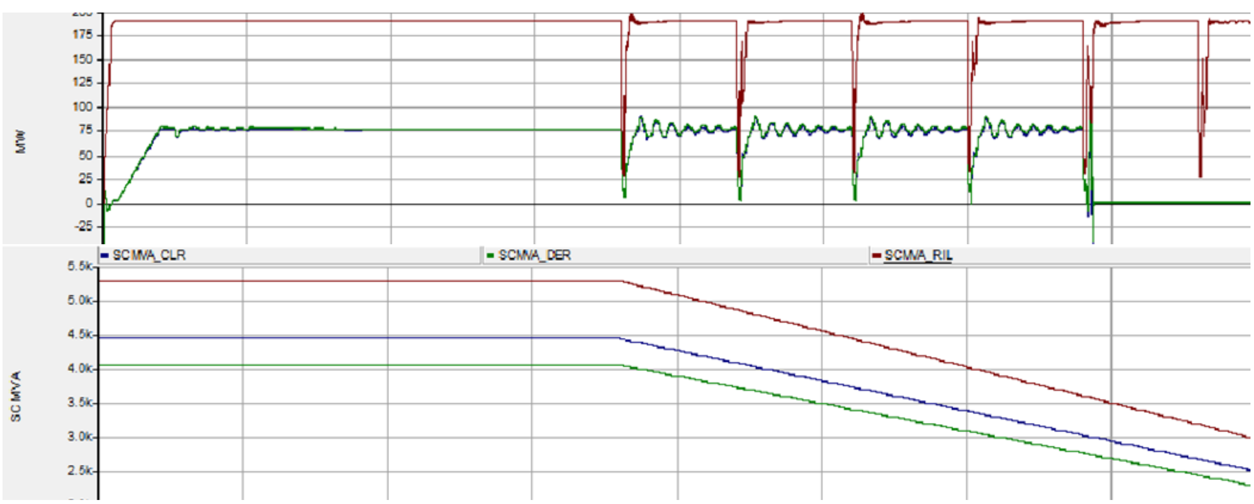

Figure 20 Large signal stability behaviour of a Panhandle wind farm as SCR is linearly reduced (top trace shows sample active powers, with tripping finally occurring)

5.0 Area Wide Voltage Coordination

5.1 Wind Farm Voltage Control Behaviour

The system voltage of the Panhandle system should be kept within acceptable limits during four major timeframes with contingencies as follows:

1. During the fault: 4 to 6 cycles (67 to 100 ms).
2. Just after the fault: 6 to 12 cycles (100 to 200 ms).
3. Just after the wind plants ramp up: 0.2 sec to 3 sec.
4. Post fault steady state voltage: 3 sec to 40 sec.

Fault Period

Most of the wind plants enter fault ride-through modes during the fault, injecting reactive power to the system as dictated by their control settings. The amount of the reactive power which is available during the fault period is mainly dependent on the capacity (MVA) of the wind farm connected to the system (which reflects inverter sizes), rather than the active power dispatch level. All other fast reactive power devices such as STATCOMs, DVARs and synchronous condensers will supply reactive power to the system if not blocked by the control system. The blocking/unblocking of these devices mainly depends on the terminal voltage lying within an acceptable band (e.g. 0.3 pu to 1.2 pu).

Fault Recovery Period

During a fault period and immediately after fault clearing, wind farms actively control their terminal voltages using fast voltage control loops. During this period, in some cases power electronic controllers may be unable to maintain synchronism if the system voltage is not sinusoidal or the voltage is too low. Without synchronism, accurate reactive power injection for voltage control becomes difficult, and any improper VAR injection to the system makes recovery for other devices more difficult. Accurate control of voltage becomes more difficult the weaker the system gets, as the wind farms become large relative to the supporting system strength. The Panhandle system study was carried out with 4300 MW wind capacity connected to the system, dispatched at a 3700 MW active power level. The upgraded system with synchronous condensers didn’t show any tripping issues with 4300 MW capacity and 3700 MW dispatch. However, TOV tripping issues were observed when the wind capacity was increased drastically above 4300 MW, even though the 3700 MW dispatch was maintained. A thorough quantitative assessment of this phenomenon was not studied here.

Post-Fault Short Term Period

As real power ramps up following the fault, system reactive power demand ramps up quickly to support the additional flows on network lines. Wind farms continue to quickly try to maintain voltage control at their terminals. The ramp period settings for the wind farms in the Panhandle range between 0.2 seconds and 2.0 seconds depending on the manufacturer and individual plant settings. When the wind plants reach their pre-fault power levels, they exit their fault ride-through modes, and control of the voltage is transferred from a fast terminal controller to various plant level voltage controllers (WPPC). As described above, WPPCs in the ERCOT Panhandle are currently set to be relatively slow, which may leave the majority of system voltage control during this period to dedicated devices such as synchronous condensers and SVCs. The post fault conditions are generally weakened due to line outages, making accurate voltage control more challenging.

The results of the non-upgraded Panhandle system show that voltage collapse can occur during this period due to lack of fast voltage support and causes serious system issues. If WPPC settings remain slow, fast system-level voltage support devices such as synchronous condensers, STATCOMs, or SVCs are required to overcome this problem.

Although at 3700 MW active power dispatch the system performed well, marginal voltage issues were observed during this period when the active power level was increased to 3900 MW. Voltages as low as 0.95 pu were observed at some wind plant terminals for severe contingencies, with the Tesla SVC and both synchronous condensers at Alibates and Tule Canyon all hitting maximum output levels.

Post-Fault Steady State Period

For timeframes longer than 1 minute, the output of dynamic reactive power devices such as synchronous condensers, STATCOMs, and SVCs should be returned to minimum levels to be available for next contingency events. When the system becomes stable, other slow dynamic voltage devices such as shunt capacitors, transformer tap changers, and WPPC should come into operation.

The non-upgraded Panhandle system case was analyzed with a relatively fast WPPC implemented in most wind farms across the Panhandle (time constants in the 3 second range, with a 2% controller droop) as a potential alternative to improve the system response in Panhandle that may reduce the need of the proposed upgrades as presented in Chapters 2 and 3. Post-fault system voltages improve drastically with the fast WPPC action as the WPP dynamic VARs are available to meet the system wide VAR deficit caused by line outages. However, practically achieving such a fast response from all the wind farms, while ensuring proper co-ordination of all the voltage controllers to avoid interactions between devices would require care and analysis.

While fast WPPC action does address post-fault VAR deficit issues, it does not solve weak system issues nor fault recovery issues, as is evident from wind plants tripping observed in the WPPC study cases. A balance is required between central VAR controllers, sufficiently strong networks, and WPPC action.

5.2 Observations and Recommendations for Voltage Coordination

The following recommendations can be made from the results of the analysis for the proposed upgrades:

1. The current ERCOT plan to install synchronous condensers to strengthen the system and provide dynamic VAR support allows a suitable compromise between central dedicated VAR controllers and distributed control provided by wind plants.
2. If the wind capacity is extended far beyond the 4300 MW with the current proposed upgrades, further analysis should be done. In this case, detailed wind plant control tuning or additional general system strength improvement upgrades (such as additional transmission lines or synchronous condensers) will likely be required.
3. With the proposed ERCOT upgrades, Panhandle wind dispatch (with locations and topologies approximately as described in this report) should be limited to 3700 MW. Additional fast dynamic reactive power sources (SYNC, STATCOM or SVC) will be required to keep the voltage within limits with dispatch higher than 3700 MW, or the consideration for fast dynamic WPPC should be reviewed.
4. This analysis shows improvement of the system performance under weak grid conditions with WPPC providing VAR response in the post-fault period and voltage control droops set to approximately 2%. Follow up can be considered to check with turbine vendors on the feasibility of such wind plant control and additional study may be required to ensure no adverse impact on the system performance.

6.0 Simulation Tool and Model Adequacy

6.1 Simulation Tool Background

The nature of transient stability (phasor based) models for wind generators is such that they may not represent the power electronic controls in sufficient detail (and in some important cases such as the PLL may not be represented at all) to reflect the behavior under weak grid conditions. This can result in either over or underestimation of control stability (leading to planners making inaccurate or uninformed decisions based on system impact study results), numerical instability in the transient stability simulation results, or protection models operating inappropriately (or failing to operate). Conventional transient stability models alone are not suitable to perform wind integration studies under weak system configurations. In very weak networks, transient stability studies usually need to be supplemented with electromagnetic transient (EMT) simulations.

EMT simulation tools such as PSCAD have in common a key distinction from phasor-based tools. Phasor based tools iteratively solve a system of equations to satisfy a set of constraints in the phase domain (given a nominal frequency such as 50 or 60 Hz). EMT tools solve the system of differential equations which describe the three-phase electrical network in the time domain. This allows them to represent the power system behavior at all frequencies, limited only by the period of time between solutions (simulation time-step). Real code from equipment firmware can be embedded into the models, and the approximations in control modeling required in phasor tools can be avoided if desired. In addition, every individual instantaneous phase quantity is represented, allowing unbalanced faults, harmonics, fast transients and other effects to be modeled (See Figure 21).

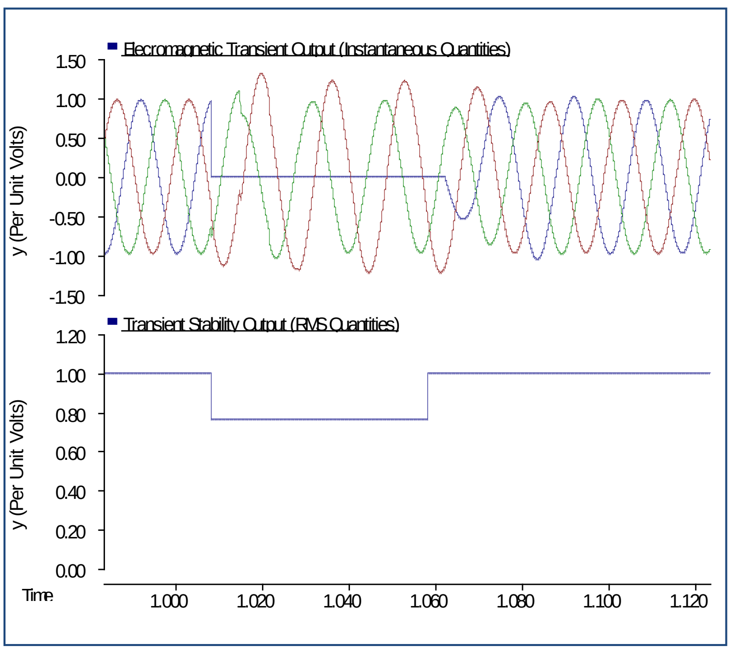

Figure 21 Comparison between an EMT type simulation of a single-line-to-ground fault, and the expected output from a transient stability type simulator for the same fault

EMT simulations are normally limited by simulation speed, forcing studies to limit their scope to small electrical regions. As discussed in Chapter 2, a hybrid of these two simulation types has been explored in this analysis to overcome the limitations of each type.

Three model types have been used in this analysis, including:

1. Pure PSCAD (EMT) model of the Panhandle region, using CPU parallelization techniques and a passive network equivalent for the rest of the ERCOT system.
2. Hybrid model, with the Panhandle region represented in PSCAD, and the rest of the ERCOT system in PSS/E dynamics.
3. Entire ERCOT model represented in PSS/E dynamics.

It remains an important question for ERCOT as to which tools are appropriate for planners going forward. In general, these tools have the following inherent advantages and disadvantages (among others):

Pure PSCAD Model

Advantages:

- Very accurate within study region
- Correctly represents control and protection of power electronics (assuming accurate models are used)
- Correctly represents unbalanced conditions (eg. SLG faults)
- Accounts for phenomena at sub-synchronous and super-synchronous frequencies

Challenges:

- Computationally intensive, requiring care in selecting study area and study cases. This may be mitigated to some extent using parallelization software (E-Tran Plus for PSCAD).
- Requires advanced training for correct end-use
- Requires very detailed models which require specialists to produce, and may contain proprietary data
- Requires approximations at the edge of study area (difficult to represent very large systems)

Hybrid PSCAD/PSSE Model

Advantages:

- Most accurate model, removing approximations at the edge of the study area, and allowing very large system models to be used and wide-area dynamics to be represented.
- All the advantages of the pure PSCAD model.

Challenges:

- Requires special software and additional training for engineers.
- Requires detailed models.
- Computationally intensive.

Pure PSS/E Model

Advantages:

- Widely understood and embedded in industry understanding
- Runs quickly, allowing many cases to be automated and run
- Represents wide-area dynamics

Challenges:

- Unable to represent detailed control and protection behaviour in weak systems
- Approximates control functionality, giving rise to some uncertainty in model behaviour
- Unable to represent unbalanced conditions, are any phenomena other than 60 Hz phenomena.

6.2 Comparison of PSS/E and PSCAD results

The Results of the PSCAD-PSS/E hybrid simulations and the pure PSS/E simulations were compared to check the adequacy of the system studies carried out with PSS/E. These comparisons were undertaken for the 3700 MW upgraded study case (Study case 3).

6.2.1 Contingencies inside the Panhandle system

A fault was applied inside the Panhandle system including a post-fault line outage following fault clearing. The PSS/E results show multiple wind plants tripping for most of the contingencies due to over voltage just after the fault, while the PSCAD-PSS/E hybrid results do not show any wind plant tripping. The PSCAD-PSS/E hybrid and PSS/E results comparison of two wind farms' active power, reactive power, and voltage for a tested contingency are shown in Figure 22 (Note: comparison measurements were done at the 345 kV level in PSS/E and at the 34.5 kV level in PSCAD and consequently there may be some magnitude differences. The shape of the plots is generally consistent between these two voltage levels). The green curves are PSS/E results. The main observations are as follows:

Active Power

The behaviour of the active power of the wind farm (shown in right side in Figure 28) shows good comparisons between the tools, except that the PSCAD-PSS/E Hybrid simulation has a ramped power reduction compared to the abrupt reduction seen in PSS/E. The power ramping on recovery between the tools is slightly different, but track fairly well together.

Some differences are evident. For example, as shown in the left side in Figure 28, the wind farm's active power goes to zero in PSS/E while the PSCAD-PSS/E Hybrid model does not dip beyond approximately half power (~60MW). The PSS/E model comes out from zero active power to 60 MW output instantaneously. Again, the recovery ramp rates and general recovery trends are approximately the same.

Terminal Voltage

The terminal voltage comparisons are usually different between the tools, reflecting rms measurement delays. PSS/E typically drops to its fault voltage instantly, while the Hybrid case voltage measurement drops over time. The PSS/E voltages also tend to ramp up quickly to medium high levels (eg. 1.16 pu) and remain for some time (approximately 70 ms) above the 1.10 pu voltage. The PSCAD-PSS/E hybrid case ramps more slowly to 1.14 pu and stays above 1.10 pu voltage for only 20 ms. This is generally true in many of the comparisons, and the very fast (likely unrealistic) voltage response is the source of wind turbine tripping observed in many of the PSSE studies done thus far, as the over-voltage levels and durations can trigger the protection system models for the wind generators.

Reactive Power

The differences in active power and voltage can cause significant differences in voltage controller and reactive power response. The sudden drop of active power and voltage during the faults induce a fast increase in reactive power in PSS/E, resulting in higher sustained values than those in the PSCAD-PSS/E hybrid model. In some cases, it is possible to see stark differences in voltage controller responses from the tools, particularly in the ramping period post-fault. The detailed representation of controllers in PSCAD are critical in these responses, and the impact of PLL synchronization is a critical element which is neglected in PSS/E simulations.

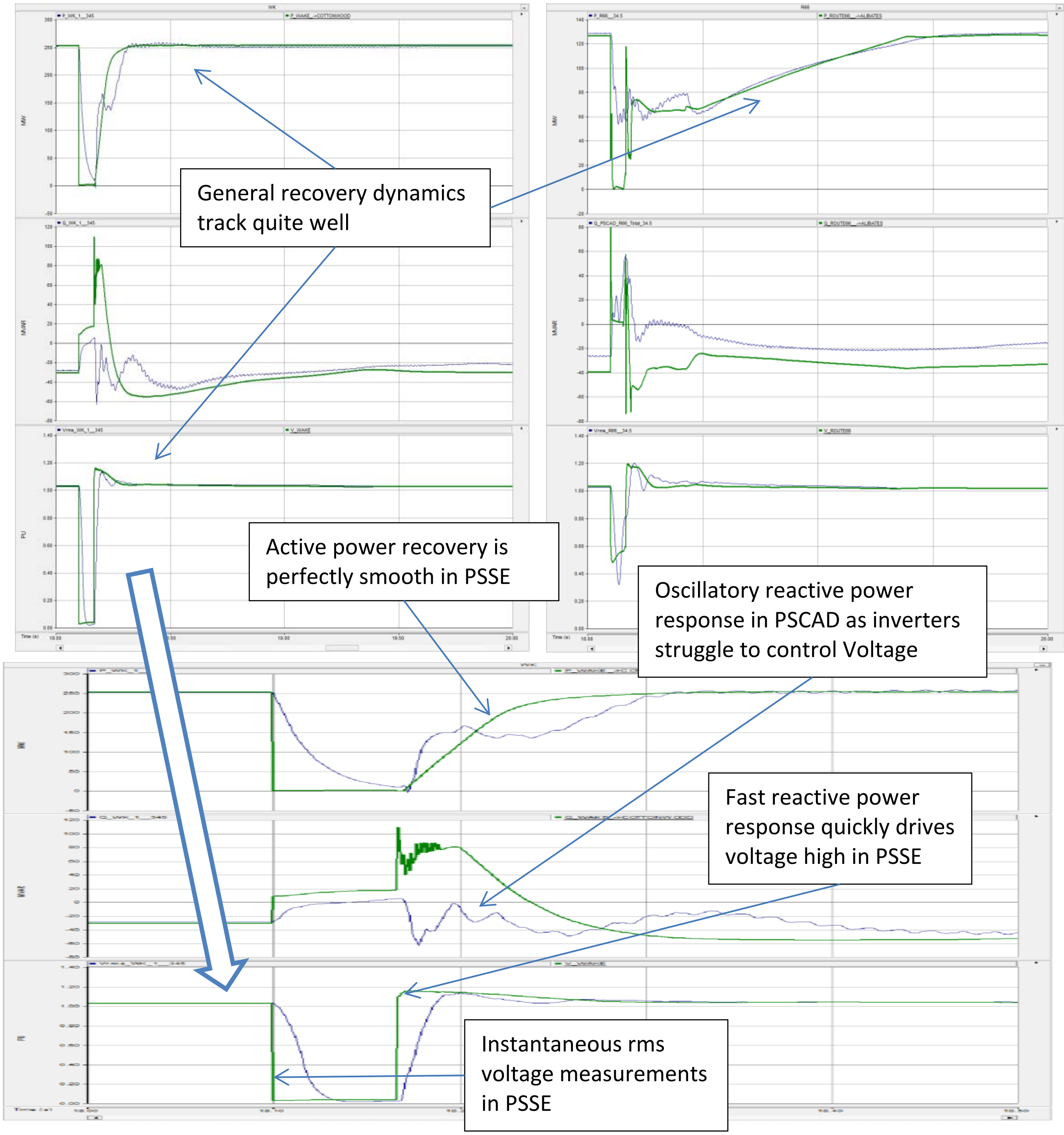

Figure 22 Comparison of PSCAD-PSS/E Hybrid and PSS/E results for fault inside the Panhandle

6.2.2 Contingencies outside the Panhandle system

To test the adequacy of PSS/E models for studies undertaken outside the panhandle region, the following comparisons were done:

Two remote faults were simulated with both PSS/E and PSCAD-PSS/E Hybrid simulations outside the Panhandle system and cleared with line outages. No wind plant tripping inside the Panhandle system was observed in either simulation. The PSCAD-PSS/E hybrid and PSS/E results comparison of the two wind farms for contingency 17 are shown in Figure 23. The green curves are PSS/E results.

There are differences in PSS/E and PSCAD-PSS/E Hybrid performance. However, the differences are minor compared to the faults inside the Panhandle system. The behaviour of the voltage and reactive power of the Wake wind farm is almost same with some differences in active power just after the fault.

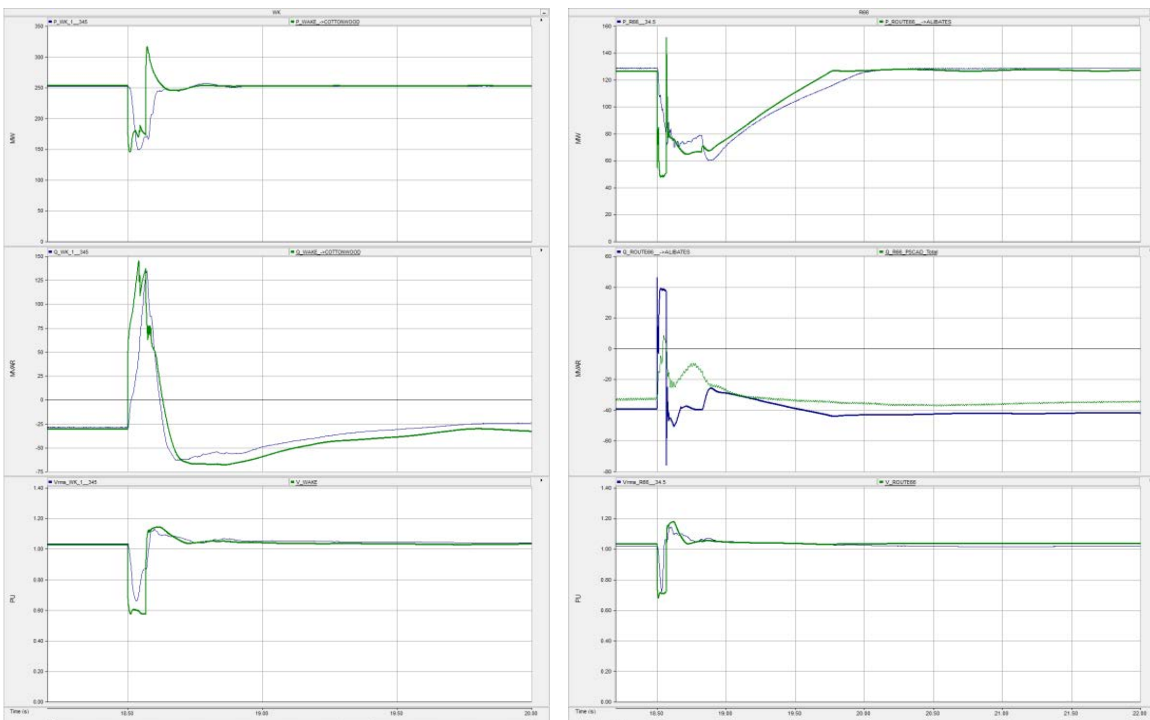

Figure 23 Comparison of PSCAD-PSS/E Hybrid and PSS/E results for fault outside the Panhandle

6.3 Applicability of Tools

For study case 3 (3700 MW of wind output with system upgrades), the overall steady state system behaviour of both simulations is very similar for faults inside and outside the Panhandle. However, significant differences can occur in the post-fault recovery period due to the level of detail in the models representing fast acting controllers and protections in the wind farms. During this period, specific behaviors of the controllers will impact the ability of the plants to ride through faults, and control voltage transients.

For example, it was observed that PSS/E models of the Panhandle tended to predict overvoltage tripping, while the more detailed PSCAD models predicted ride-through. For comparisons between the tools to be completely valid, the overvoltage tripping in the PSS/E (determined to be incorrect) should be corrected prior to drawing conclusions based on this behaviour. It is noted also that once wind farms disconnect due to inappropriate tripping, the system strength relative to the remaining wind plants is increased, possibly improving the subsequent overall behaviour of the region. If the tripping is not accurate, this improved behaviour may also not be accurate, masking other system issues which could arise if the wind plants do not trip (as seen in PSCAD). Until these issues are resolved, study outcomes based solely on PSS/E results should be used with caution.

As the short circuit strength drops, these differences are expected to become more pronounced. For general studies in the Panhandle, assuming sufficient system strength (e.g. WSCR of at least 1.5 in this case), PSS/E analysis is still useful and quite accurate, although periodic checks are recommended in PSCAD to validate models and ensure key negative behaviors are caught and understood.

For these short circuit levels, analysis of faults outside the Panhandle region was mainly the same, whether the Panhandle was modeled in PSCAD or not.