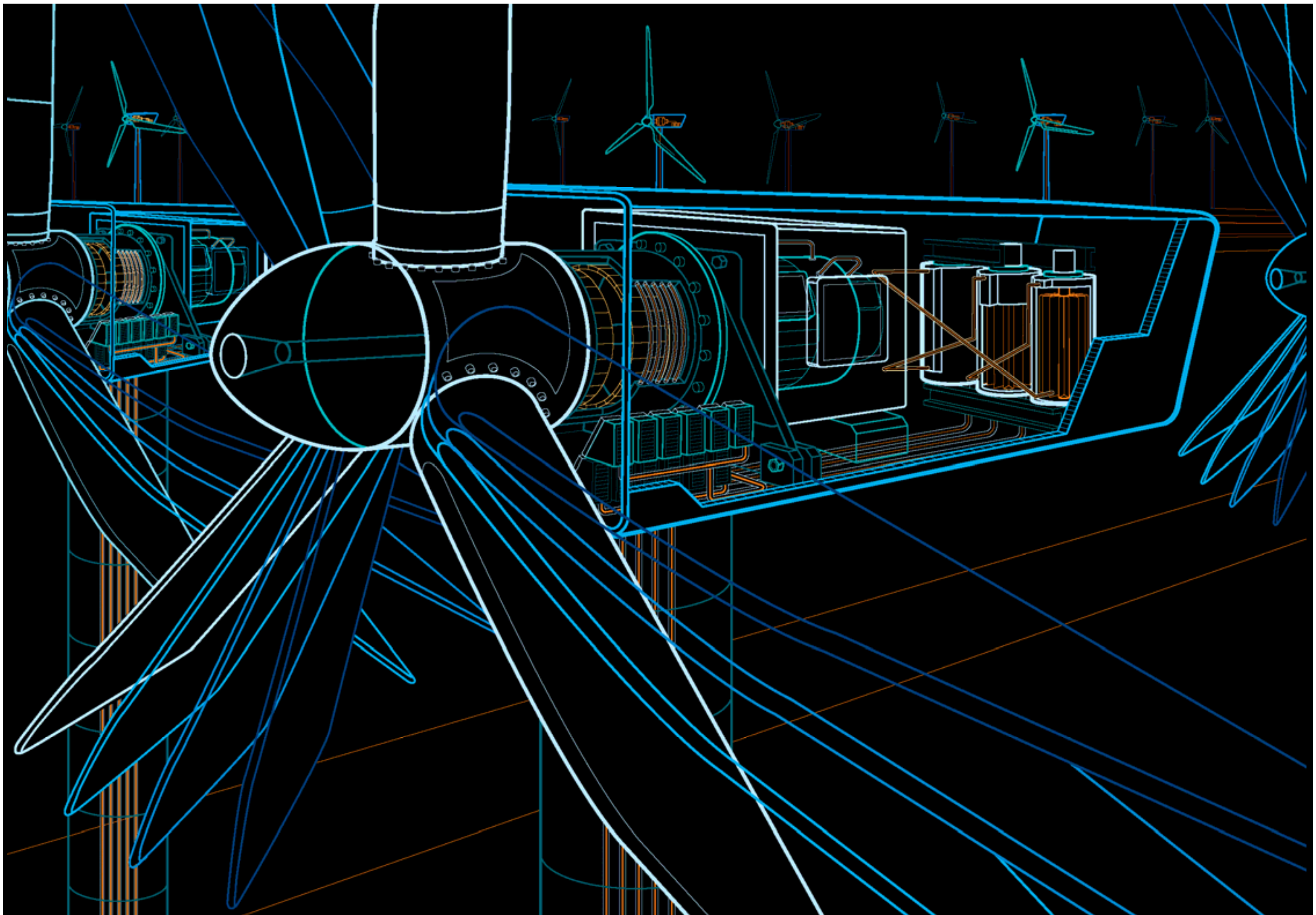

ERCOT

CREZ Reactive Power Compensation Study

E3800-PR-02

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SUMMARY

Background

In 2005, the 79th Texas Legislature (Senate Bill 20) ordered the Public Utility Commission of Texas (PUCT) to designate Competitive Renewable Energy Zones (CREZ) in Texas and to order specific transmission improvements that would be required to connect the CREZ to load centers in the Texas Interconnection. The PUCT designated five zones that cover much of West Texas, from the mesas south of McCamey near the Mexico border to the southern bank of the Canadian River in the northern Texas Panhandle. Distances between these zones and the major load centers in the east (the Dallas/Ft. Worth metroplex, Austin and San Antonio) are as much as 400 miles.

For the CREZ transmission improvements, the PUCT selected from among several options a plan that includes over 2,300 miles of new 345 kV right-of-way and that can accommodate an incremental 11,553 MW of wind generation capacity in West Texas. Two of the CREZ extend outside the traditional boundaries of the Texas Interconnection, so the selected plan includes several long AC circuits that are designed solely to integrate the proposed wind generation with no other connections to traditional thermal generation or load centers. Nine circuits in the plan were designed with approximately 50% series capacitor compensation, but due to the initial study completion deadline, a list of "placeholder" shunt reactive and capacitive devices, modeled as mechanically switched banks, were included in the CREZ Transmission Plan (CTP) along with a recommendation that a more thorough study be conducted to quantify the need for dynamic reactive support.

The PUCT selected several Transmission Service Providers (TSPs) to route and construct the CTP. The Electric Reliability Council of Texas (ERCOT) and the selected TSPs then finalized the proposed scope of the recommended CREZ Reactive Compensation Study and commissioned ABB, Inc. to complete the study scope. The study scope is designed to meet the following objectives:

1. To verify or recommend the continuous current rating and compensation percentage of the proposed series compensation;
2. To identify the recommended size, type and location of additional reactive devices required to control system voltages and maintain dynamic stability;
3. To identify stability-related issues caused by circuit additions, dynamic devices or flow changes related to CREZ projects.

The ultimate goal of the study is to have a comprehensive compensation plan for the CREZ transmission, which requires consideration of various loading levels and worst case contingencies, as well as the need for both static and dynamic compensation to ensure system stability. Further, the study comprises two distinct types of analyses: one that is fundamental frequency in nature, and another focusing on potential interactions between the generation (conventional and wind) and the proposed series and shunt compensation that will occur at subsynchronous frequencies.

These objectives, the types of analyses needed, and the general overall study approach are illustrated in Figure S-1. Several aspects of the study are conducted in parallel but all ultimately influence, to a greater or lesser degree, the final comprehensive compensation plan.

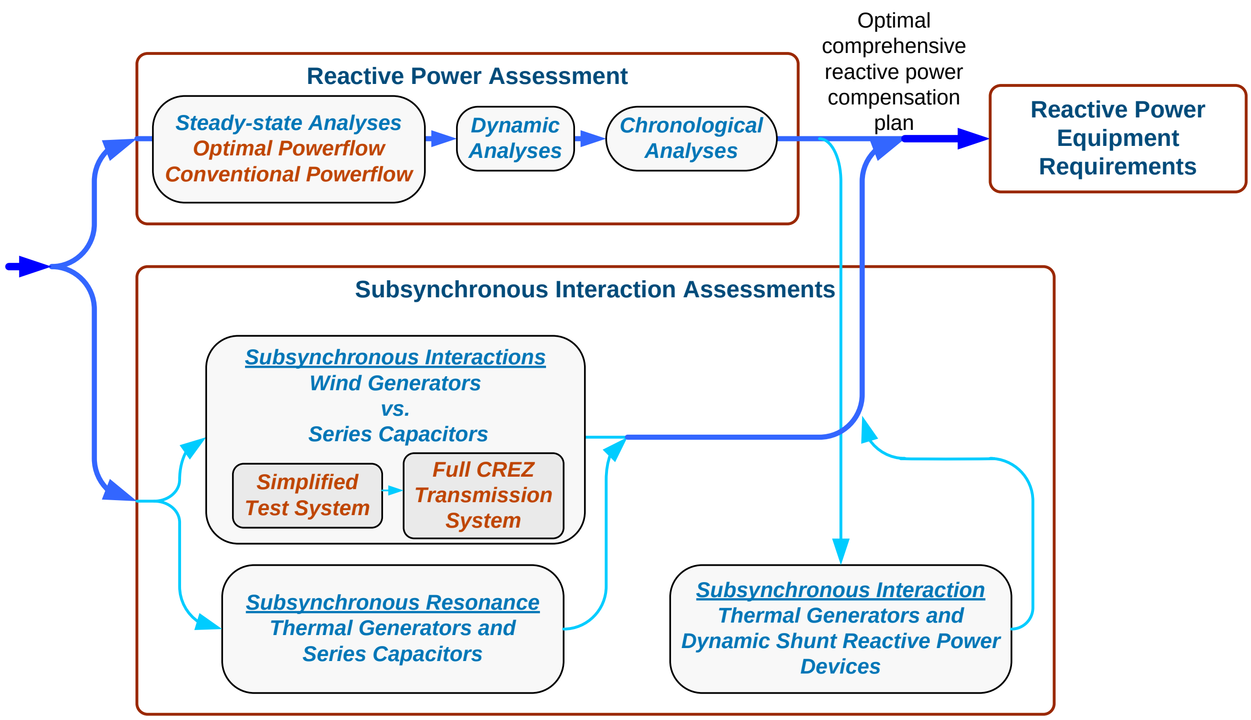

Figure S-1: General study approach

Each of the analyses and assessments involved in the study are discussed in the body of the report. It is noted, however, that this report describes in general terms the overall study and conclusions. Much of the work and information resulting from this study is considered critical infrastructure information and is confidential and has not been included here in order to maintain the required confidentiality. However, more complete details have been provided to ERCOT through several other reports.

CREZ Transmission System Plan

In the CREZ transmission plan originally selected by PUCT there are nine 345kV circuits (i.e. one single circuit and four double-circuits) which were identified for series capacitor compensation. The PUCT docket authorizing the CTP provided that ERCOT could make certain changes if required to develop a secure and reliable system. During the course of the study, it was determined that the following adjustments to the CREZ transmission topology could lead to significant reduction in the reactive compensation requirements:

1) A common bus at the Clear Crossing station to which all of the series compensated circuits into that station would connect. With this change, the series compensation on the Clear-Crossing to West Shackelford line was eliminated. (Note that two older 345kV lines that pass near the location of the new Clear Crossing station will not be tied into the Clear Crossing bus);
2) A common bus at the Tesla station connecting all four circuits at this location;
3) Series compensation added to the second circuit between Silverton and Tesla.

In addition, due to line voltage profile criteria, the locations along each circuit of the various series capacitor segments were adjusted.

Taken together, these changes resulted in the final CREZ transmission system used for the development of the comprehensive reactive compensation plan. The final series compensated lines as modeled in the study are:

- The Tesla-Silverton double-circuit each with a single-segment, mid-line series capacitor;
- The Edith Clarke-Clear Crossing double-circuit, each with a single-segment, mid-line series capacitor;
- The Willow Creek-Clear Crossing double-circuit, each with a single-segment, series capacitor at Clear Crossing;
- The Dermott-Clear Crossing double-circuit, each with a single-segment, mid-line series capacitor;
- The West Shackelford-Sam Switch and West Shackelford-Navarro circuits, each with single series capacitor segments at Romney and Kopperl;
- The Big Hill-Kendall double-circuit, each with two series capacitors segments – one at Edison and the other midway between Big Hill and Edison.

The final CREZ plan can be seen in Figure 2.1-2 in Section 2.1 of the report.

Note that the actual locations of the series capacitor sections along their respective lines will be established by the TSPs and will not impact the reactive power requirements determined in the study.

CREZ Transmission Loading Scenarios

In order to ensure that the CREZ reactive compensation plan is robust and adequate for a broad range of system conditions, multiple system loading scenarios must be considered. The scenarios provided by ERCOT for use in the study are:

- ***Initial Build*** – this case considers the high wind generation levels anticipated to be on line shortly after the CREZ transmission lines are completed. It represents 12,036 MW of wind generation in the CREZ system.
- ***Minimum Export*** – this case considers low transfer levels of the wind energy and represents conditions where high voltages are probable and adequate regulation is

necessary to maintain appropriate voltages. It represents 1,979 MW of wind generation in the CREZ system.

- ***Maximum Export*** – this case considers the high wind generation levels anticipated in the long term, with a northern bias to the flows in order to stress the Panhandle and northern CREZ lines. 14,662 MW of wind generation is represented.
- ***Maximum Edison*** – this case considers the high wind generation levels anticipated in the long term, with a southern bias to the flows to stress the southern CREZ lines. 15,029 MW of wind generation is represented.

The breakdown of the wind generation modeled in these scenarios is provided below in Table S-1. The breakdown is between wind already on line (existing) and wind anticipated following the build out of the CREZ system. It is further subdivided by the different CREZ areas.

This table also shows both the on-line capacity and the actual amount of wind generation assumed. The on-line capacity is the sum of the rated output of the wind turbines connected to the system, which would only be reached if the wind speeds were sufficiently high at all of the wind turbines and they were all controlled to produce maximum output. In reality, the wind speeds vary from location to location so not all wind turbines will be supplied by enough wind energy to operate at full output. Also, some wind turbines may be off line for maintenance or other reasons.

Table S-1: Breakdown of wind generation in various study scenarios

	Initial Build		Minimum Export		Maximum Export		Maximum Edison	
Zone	On-Line Capacity	Wind Gen	On-Line Capacity	Wind Gen	On-Line Capacity	Wind Gen	On-Line Capacity	Wind Gen
Existing wind generation in CREZ								
Central	4723	3796	1047	490	4723	3796	4950	4941
McCamey	1091	858	181	72	1091	855	1126	591
Panhandle A	60	41	190	25	60	41	230	184
West	550	296	452	146	550	296	550	549
Existing CREZ Sub-total	***6423***	***4991***	***1870***	***733***	***6423***	***4988***	***6855***	***6265***
New wind generation in CREZ (study assumptions)								
Central	2447	2285	42	36	3047	2838	3047	2915
McCamey	1200	793	0	0	200	188	1858	1396
Panhandle A	1400	1316	479	473	2991	2761	3191	2671
Panhandle B	1000	951	594	592	2393	2258	2393	719
West	1063	1020	120	117	1063	949	1063	719
FPL Wind	859	680	141	28	859	680	859	344
New CREZ Sub-total	***7969***	***7045***	***1376***	***1246***	***10553***	***9674***	***12411***	***8764***
Total CREZ (new+existing)	***14392***	***12036***	***3246***	***1979***	***16976***	***14662***	***19266***	***15029***
Wind outside CREZ	1727	915	1667	583	1727	915	1110	538
TOTAL WIND	**16119**	**12951**	**4913**	**2562**	**18703**	**15577**	**20375**	**15567**

Study Results

The study documented in this report is the first of its kind on the ERCOT system concerning the CREZ transmission and has resulted in several key findings that are summarized below.

- **Reactive compensation requirements**

  Series compensation of approximately 50% is required on six 345 kV double-circuit transmission lines (12 circuits total) as shown in Table S-2. The actual percentage of series compensation will vary slightly depending on the final length of the associated line and TSP implementation as a result of procurement.

Table S-2: CREZ Series Capacitor Locations as Studied

TSP	Line	Circuit #	Segment #	Study Series Capacitor Location
CTT	Silverton-Tesla	1	1	Mid-line
		2	1	Mid-line
ETT	Edith Clarke- Clear Crossing North	1	1	Mid-line
		2	1	Mid-line
	Dermott – Clear Crossing West	1	1	Mid-line
		2	1	Mid-line
	Big Hill – Kendall	1	1	Mid-line at Edison
		1	2	Midway between Big Hill and Edison
		2	1	Mid-line at Edison
		2	2	Midway between Big Hill and Edison
ONCOR	Willow Creek- Clear Crossing East	1	1	Clear Crossing East
		2	1	Clear Crossing East
Lone Star	W. Shackelford – Sam Switch	1	1	Romney 1 (~1/3 from W. Shackelford)
		1	2	Kopperl 1 (~1/3 from Sam Switch)
	W. Shackelford – Navarro	2	1	Romney 2
		2	2	Kopperl 2

The locations of the series capacitor segments along the length of these lines as studied were provided by ERCOT and the TSPs. The ultimate locations on the lines will be established by the TSPs based on maintenance needs, line design criteria and similar considerations. The locations on the lines will not influence the reactive compensation requirements.

Shunt compensation is required in a number of different forms. The sizes and locations were determined assuming that the series compensation shown above is in place. The recommended sizes and locations for new and existing switched shunt reactors have been identified as shown in Table S-3. These reactors are required to regulate high bus voltages and maintain voltages at acceptable levels under conditions with low power flow on the CREZ system. The reactors are needed when the transmission lines are energized.

Table S-3: Shunt reactor requirements for the CREZ transmission system

Bus name	Bus voltage [kV]	Reactor size (recommended # steps x step size) [MVAr]	Bus name	Bus voltage [kV]	Reactor size (recommended # steps x step size) [MVAr]
Willow Creek	345	-100 (1 x -100)	Riley	345	-200 (4 x -50)
Brown	345	-200 (2 x -100)	Gillespie	345	-100 (2 x -50)
Oklaunion	345	-30 (1 x -30)	Edison1	345	-100 (2 x -50)
Tonkawas	345	-200 (4 x -50)	Edison2	345	-100 (2 x -50)
Dermott	345	-100 (2 x -50)	Big Hill	345	-100 (2 x -50)
Scurry	345	-100 (2 x -50)	Nazareth	345	-50 (1 x -50)
Sweetwater East	345	-100 (2 x -50)	Hereford	345	-200 (4 x -50)
Tesla	345	-200 (4 x -50)	Cottonwood	345	-100 (2 x -50)
Clear Crossing North	345	-300 (6 x -50)	White Deer	345	-100 (2 x -50)
Romney1 W	345	-100 (2 x -50)	Gray	345	-150 (3 x -50)
Romney2 W	345	-100 (2 x -50)	West Shackelford	345	-200 (2 x -100)
Silverton	345	-150 (3 x -50)	Edith Clarke	345	-200 (4 x -50)
Krum West	345	-100 (1 x -100)	Graham	345	-450 (6 x -75)
Central Bluff	345	-100 (1 x -100)	SA Red Creek	345	-100 (1 x -100)

In addition, the recommended sizes and locations for switched shunt capacitors needed to regulate voltage during periods with large amounts of wind generation, when additional reactive power is needed to support voltage, have been identified for both the initial build of the CREZ system and for the long term build out envisioned in the study assumptions. Those needed for the initial build are shown in Table S-4. For the ultimate build out, shunt capacitors at additional locations will be needed, some of which were approved in the CTP.

Table S-4: Shunt capacitor requirements for the CREZ initial build

Bus Name	Bus voltage [kV]	Total shunt capacitance required for initial build [MVAr]
Riley	345	316.4
Krum West	345	50
Scurry	345	100
Grelton	345	50
Brown	345	200
Killeen	345	100[1]
Big Hill	345	144

[1] A 50 MVAr capacitor would also meet system requirements

The main role for switchable shunts (capacitors and reactors) is to off-load the reactive output from the CREZ wind farms and the proposed dynamic shunt compensation. This allows their respective reactive range to be preserved for when they are most valuable following disturbances.

Finally, the size and locations for dynamic reactive compensation have been identified for the initial CREZ build, as shown in Table S-5. The dynamic reactive devices must be able to provide continuous voltage control and respond in less than 50ms, which is well within the capability of devices such as Static Var Compensators (SVCs) and Static Compensators (STATCOMs).

Table S-5: Dynamic shunt requirements for the CREZ initial build

Bus Name[1]	Bus voltage [kV]	Dynamic shunt range required for initial build	
		Capacitive [MVAr]	Inductive [MVAr]
Tesla	345	300	-100
Brown	345	600	-200
Parker	345	300	-100
Hamilton	138	200	-50

[1] Final locations may change due to practical considerations. Such changes may influence the required range.

The dynamic reactive compensation requirements have also been identified for the long term plan based on the stated input assumptions. Due to higher transfer levels and their effect on reactive losses and system stability the dynamic reactive compensation requirements could be much higher – in the order of 6000 MVAr – but are dependent on the assumptions made for the study of the long term build out.

Specific assumptions were made regarding the reactive capability and performance of the CREZ wind farms. Simulation results confirm that the success of the proposed compensation strategy relies on the availability of reactive support from wind generation as modeled. This, in turn requires operation of the system with such availability in mind. Specifically, the support from the wind farms must be available when needed, in the required quantity and with the required speed suggested by the simulation models. Further, the system must be operated to allow the wind farms to provide as close to zero reactive output as possible (thereby preserving their reactive range for disturbances), while maintaining overall high voltages. Extensive testing and monitoring of wind farms is recommended to ensure that such performance is provided.

The potential for subsynchronous torsional interactions (SSTI) between the dynamic reactive compensation devices and nearby thermal generators has been explored for the thermal generators closest to the recommended locations of the initial CREZ build out. Typical SVC controls were used in the study. The results indicate that there is little concern for detrimental SSTI between dynamic shunt devices and nearby thermal generators. Experience in other studies has shown that if concerns for SSTI were to exist, control enhancements on the dynamic shunt device can effectively remove such concerns.

- **Potential concerns for operation near series capacitors**

  There are several issues of which generation developers should be cognizant when operating generation near series compensated lines.

  SSI with wind turbines: The first issue relates to wind farms and has been identified in the report as subsynchronous interactions (SSI). Type 1 and Type 2 wind turbine generators (standard induction generators and wound rotor induction generators with externally connected variable resistor) can experience self-excitation with the series capacitors that may result in the turbines being damaged or being tripped off line under protective action. Type 3 (DFIG) machines are more sensitive to SSI, apparently due to the influence of the controls responding to the subsynchronous series resonance. Type 4 (full converter) machines have not shown any sensitivity to SSI in this study.

  The locations on the CREZ system at which wind turbine generators are most likely to be affected by SSI have been identified as indicated in Table S-6. This table also indicates the system contingencies evaluated to determine the sensitivity to SSI. Two Type 3 wind turbine generator models were available for evaluation. In order to fully understand the appropriateness of any transmission system mitigation at the series capacitors, a more complete set of models is needed.

Table S-6: Conditions found to be conducive to SSI with Type 3 WTGs on CREZ system

#	Wind turbine generator location	Size of represented wind farm [MW]	System contingency conditions	Case description	Model 1 SSI	Model 2 SSI
1	West Shackelford	743	N-0	Normal system conditions	**Y**	N
2	West Shackelford	743	N-1	Outage of one circuit of the double circuit line between Scurry and West Shackelford	*not tested*	**Y**
3	West Shackelford	743	N-2	Outage of double circuit line between Scurry and West Shackelford	*not tested*	**Y**
4	West Shackelford	743	N-2	Outage of double circuit line between West Shackelford and Romney	**Y**	*not tested*
5	West Shackelford	743	N-2	Outage of double circuit line between Clear Crossing and West Shackelford	**Y**	*not tested*
6	Big Hill	150	N-1	Outage of circuit between Big Hill and Twin Buttes	**Y**	N
7	Big Hill	150	N-2	Outage of circuits between Big Hill and Twin Buttes and between Big Hill and Bakersfield	**Y**	**Y**
8	Dermott	561	N-2	Outage of double-circuit line between Dermott and Scurry	**Y**	N
9	Dermott	561	N-4	Outage of double-circuit line between Dermott and Scurry and double-circuit line between Dermott and Cottonwood	**Y**	**Y**

Without mitigation measures, there is a strong potential for SSI with Type 3 wind turbine generators located very close to the West Shackelford, Big Hill and Dermott buses. The first

Type 3 model, in particular, showed vulnerability at these locations with SSI being observed at West Shackelford with no line outages.

Because the models assessed in the study are not representative of all WTG manufacturers and may not provide sufficient detail needed for a full assessment under the studied conditions, these results should be taken primarily as a caution and detailed studies should be conducted by the developers to ensure that the planned wind farm will not have SSI issues. Such studies should accurately represent the CREZ system actually built, any system level mitigation applied and any WTG level mitigation available from the manufacturers and included in the turbines being ordered.

While the simulations performed for the study can be considered somewhat theoretical, there is actual experience that emphasizes the importance of the recommended studies. A utility in the ERCOT system reported an incident in which a wind farm consisting of Type 3 wind turbines was radially connected to a series compensated line following an N-1 contingency. The response of the wind turbines to the new system conditions with a more direct influence from the series capacitor resulted in the tripping of the wind turbines, but not before equipment had been damaged. It has been reported that the damage was not limited to the WTGs themselves, but that the series capacitor also sustained some damage. Because of this experience, two recommendations are made regarding the protection of the series capacitors: 1) interconnection studies for new wind farms should include an evaluation of the potential for SSI and the anticipated impact on voltages at and currents through the CREZ series capacitors; and, 2) design efforts for the CREZ series capacitors should include an evaluation of the impact of various levels of subsynchronous currents, with protection schemes and/or SSI mitigation added if warranted by the evaluation results.

SSR with thermal generators: Subsynchronous resonance (SSR) between thermal generators and series compensated lines has been known since the 1970s. The phenomena can result in high stresses on the turbine-generator shaft which can lead to catastrophic results if the turbine-generator is not properly protected. With the introduction of series compensated lines on the CREZ system, some existing thermal generators may be susceptible to SSR. Screening studies have been performed on several generators that are near the CREZ series compensation. These studies were documented in separate reports that will not be made public because they contain proprietary confidential information and critical infrastructure information.

A related issue is the so-called induction generator effect that can also result in high levels of subsynchronous currents in the generators and the connected system. These do not involve the mechanical system of the turbine-generator shaft.

It is important for any future thermal generation developers to be aware of the issues surrounding SSR so that they can investigate the potential for undesirable resonances as part of their interconnection studies.

Mitigation methods: A few mitigation methods for SSI and SSR are explored in the study.

Bypass filters across the series capacitor, designed to provide an alternate path to subsynchronous currents were explored. Two philosophies – a "damping" filter and a "preventive" filter – were considered. The damping filter did not prove alone to be successful to fully eliminate SSI with wind turbine generators, but may be more successful in combination with other methods. The "preventive" filter parameters can be selected to eliminate SSI and SSR, but could result in a very costly design. There are no known installations of these types of high power bypass filters for SSI/SSR mitigation anywhere in the world. Estimates from a single vendor indicated a cost of 1.5-2.0 times that of a fixed series capacitor. The performance of the filters considered was unclear. Patents on bypass filters may limit the number of suppliers.

A thyristor controlled series capacitor (TCSC) – especially one with a so-called SVR control – was found to be very effective in eliminating SSI and SSR. TCSCs have been successfully deployed in many areas around the world by several vendors, but only one is known to have been deployed specifically to address SSR. A TCSC will be more expensive than a simple series capacitor. Estimates from various vendors ranged from 1.5 to 5.0 times that of a fixed series capacitor. Patents on TCSC controls, such as the SVR, may limit the number of suppliers that can provide the necessary performance.

The modification of WTG controls – particularly for Type 3 turbines – is another mitigation method that is showing promise. It is known that significant work is being performed in both industry and academia to address this issue and the reports appear promising. However, unless any successful control modifications can address SSI alone, it may prove necessary to couple the solution with other partial solutions such as a damping bypass filter. This would divide the solution between a system level solution and a local development level solution. It can be observed here that this type of split solution may prove challenging in several areas including the coordination between the different technologies and allocation of the mitigation responsibility. Also, unless multiple manufacturers are able to address the SSI problems, patent issues may limit the number of suppliers.

Limitation of wind turbine types – at critical locations, limiting the types of WTGs to those not susceptible to SSI may be an option. The results of this study (with a limited number of models) indicate that Type 4 turbines may be able to operate without control modifications at locations where other technologies may have SSI issues.

Operate around the issue – under some conditions, such as when SSI is only expected when certain lines near the wind turbines are out of service, it may be possible to utilize special protection schemes to prevent SSI issues. Such schemes require careful study and may include tripping wind generators or bypassing the series capacitors. It is noted, however, that bypassing the series capacitors under contingency conditions is not usually prudent because the series capacitors generally become particularly important under such contingency conditions. Further, tripping of the wind farms may not be an acceptable, first level response to SSI.

- **Modeling needs for future studies**

  This study has highlighted some of the limitations of the present models being used for evaluating wind generation. Several of the issues are highlighted below based on the types of studies for which they are used.

  Fundamental frequency models: The main issue observed in this study was the sensitivity of the models to low short-circuit ratios between the system strength and the installed wind generation. Under these conditions high frequency oscillations (sometimes in excess of 10 Hz) were observed. It was not clear if these oscillations are a result of modeling issues or would actually exist in the system. Additional work would be needed to confirm which is the case. If it is found that the phenomenon is a modeling issue, then it is strongly recommended that work be done to improve the models to prevent unwarranted conclusions from being drawn based on study results using the model. (Note that in this study, it was determined to address the issue by using "place holder" synchronous condensers to increase the short-circuit ratios. If such an increase is actually needed, other technologies may also be available to mitigate weak systems)

  Another modeling issue observed in the study was the poor performance of some dynamic models provided by wind developers to ERCOT. These models were most likely created by the wind turbine manufacturers. It is emphasized that most of the models worked well for the purposes of the study, but the poor performance of a few created numerous difficulties.

  In the future, developers will still be required to provide appropriate models for their wind farms. It is recommended that a set of tests be developed which all future models must pass before they are accepted by ERCOT

  Electromagnetic transient models:

  The evaluation of the potential for SSI with wind turbines and series capacitors is currently limited to simulations in electromagnetic transient programs such as PSCAD. The number of available models which wind turbine manufacturers are prepared to release is very limited. This is a situation that is simply unsustainable because it is likely that future studies will need to combine appropriate models of equipment from multiple vendors. It is recommended that the wind turbine manufacturers develop "black-box" models that allow the user access to appropriate control parameters while hiding those controls and parameters that are proprietary. Such models should be backed by the vendors as being suitable for evaluations involving subsynchronous, synchronous and higher frequency studies, with a clear explanation of their limitations.

Frequency scan models:

The SSR screening studies showed that the representation of the Type 3 and Type 4 impedance characteristics are important for accurate assessment of SSR and induction generator effects. It is recommended that WTG suppliers be required to provide the impedance characteristics of their machines when looking into the wind farm from the system. These characteristics should cover a frequency range of 0Hz to 120Hz in 1Hz or smaller increments for normal screening studies. Higher frequencies may be needed for other types of harmonic impedance calculation studies and should also be provided up to approximately 1kHz.

Applicability of Study Results

A number of assumptions have been made regarding the locations and chronological development of the wind generation. Further items such as real estate availability in substations (e.g. to maintain required clearances), increased annual maintenance and possible forced outages are not part of the study. Also, actual experience will likely differ somewhat from the assumptions made in the study. Therefore, the results of the study should be used as input for the initial design efforts and as a guide for future planning. If actual experience is found to be significantly different from the assumptions made in the study, some of the results may need to be re-examined. If the transmission providers significantly change the location of some reactive compensation the impact of the relocation on system performance and stability should be studied.