

ERCOT CREZ Reactive Power Compensation Study

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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.

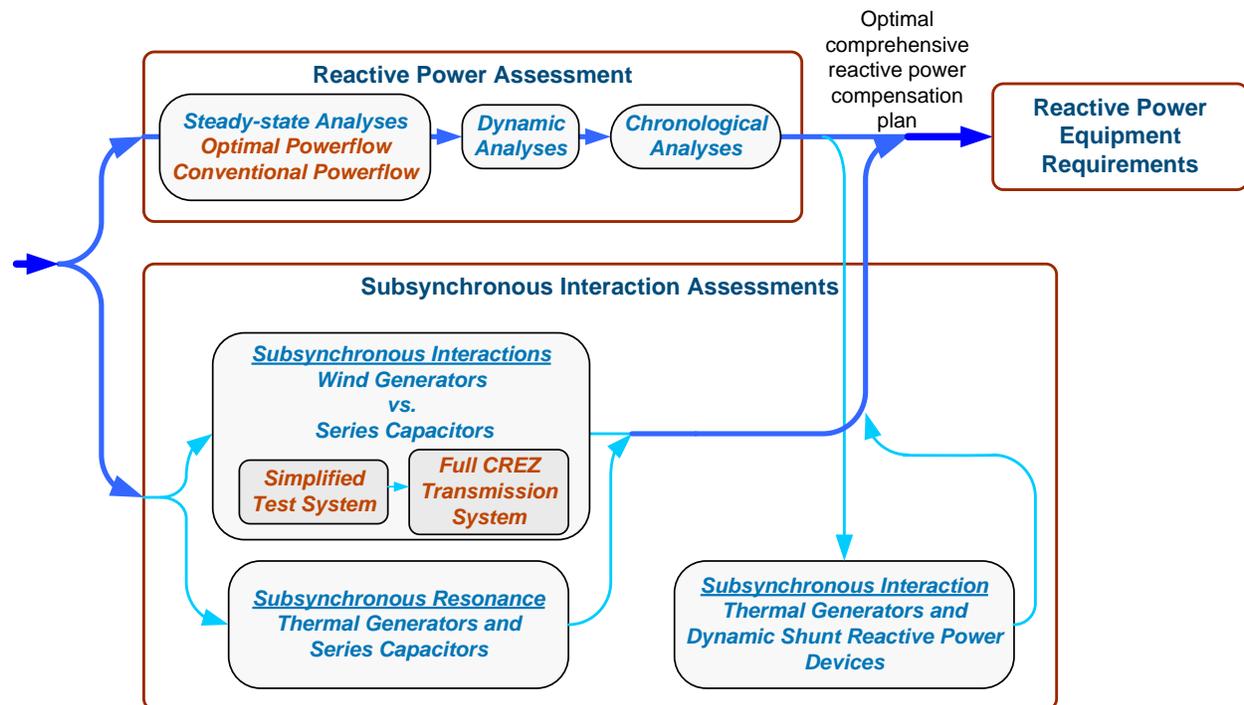


Figure S-1: General study approach

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

Zone	Initial Build		Minimum Export		Maximum Export		Maximum Edison	
	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)
Oklauion	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	<i>not tested</i>	Y
3	West Shackelford	743	N-2	Outage of double circuit line between Scurry and West Shackelford	<i>not tested</i>	Y
4	West Shackelford	743	N-2	Outage of double circuit line between West Shackelford and Romney	Y	<i>not tested</i>
5	West Shackelford	743	N-2	Outage of double circuit line between Clear Crossing and West Shackelford	Y	<i>not tested</i>
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.

Contents

Table of Figures	xvii
Table of Tables	xviii
1 Background	1
1.1 LEGISLATIVE ORDER	1
1.2 REACTIVE COMPENSATION STUDY	1
1.3 AN OBSERVATION	2
2 The CREZ Transmission Plan	4
2.1 THE NETWORK TOPOLOGY	4
2.2 CREZ TRANSMISSION LOADING SCENARIOS	7
3 Shunt Reactive Compensation Requirements	9
3.1 PURPOSES AND BENEFITS OF SHUNT REACTIVE POWER COMPENSATION	9
3.2 INITIAL BUILD REQUIREMENTS	12
3.2.1 <i>Static Shunt Reactors</i>	12
3.2.2 <i>Static Shunt Capacitors</i>	13
3.2.3 <i>Dynamic Shunt Compensation</i>	14
3.3 LONG-TERM PLANNING REQUIREMENTS	15
3.3.1 <i>Static Shunt Reactors</i>	15
3.3.2 <i>Static Shunt Capacitors</i>	15
3.3.3 <i>Dynamic Shunt Compensation</i>	16
3.4 STUDY APPROACH TO DETERMINING SHUNT REACTIVE COMPENSATION REQUIREMENTS ..	17
3.4.1 <i>Steady-State Analyses</i>	17
3.4.2 <i>Dynamic Analyses</i>	19
3.4.3 <i>Chronological Analyses</i>	19
3.5 ASSUMPTIONS MADE REGARDING WIND GENERATION REACTIVE PERFORMANCE	20
3.5.1 <i>Steady-State</i>	20
3.5.2 <i>Dynamics</i>	20
3.5.3 <i>Modeling of Type 3 (DFIG) New CREZ Generation</i>	21
3.5.4 <i>Modeling of Type 2 (Variable Rotor Resistance) New CREZ Generation</i>	22
3.5.5 <i>Compliance</i>	22
3.6 ADDITIONAL STEADY-STATE ASSESSMENTS	22
3.7 NETWORK CHALLENGES WITH DYNAMIC SHUNT COMPENSATION (SSTI)	24
4 Series Capacitor Compensation Requirements	28
4.1 PURPOSES AND BENEFITS OF SERIES CAPACITOR COMPENSATION	28
4.2 STUDY LOCATIONS OF SERIES CAPACITORS	29
4.3 STUDY APPROACH TO DETERMINING SERIES CAPACITOR REQUIREMENTS	29
4.3.1 <i>Series Capacitor Technology</i>	29
4.3.2 <i>Line Voltage Profiles</i>	32

4.3.3	<i>Maximum Continuous Current and 30 Minute Overload Ratings</i>	33
4.3.4	<i>Maximum Swing Currents</i>	33
4.3.5	<i>Maximum Fault Currents</i>	33
4.4	NETWORK CHALLENGES WITH SERIES COMPENSATION	34
4.4.1	<i>SSI with Wind Generation</i>	34
4.4.2	<i>SSR with Thermal Generation</i>	38
4.4.3	<i>Potential Mitigation Measures and Their Limitations</i>	42
5	Conclusions.....	50
6	References.....	55
	Appendix A – Dynamic Shunt Compensation Technologies.....	56
	A.1 – SVC TECHNOLOGY	56
	A.2 – STATCOM TECHNOLOGY	58
	A.3 – SYNCHRONOUS CONDENSER TECHNOLOGY	61

Table of Figures

Figure 1.2-1: General study approach	2
Figure 2.1-1: Initial CREZ system topology at the start of the CREZ Reactive Study.....	5
Figure 2.1-2: Final CREZ system topology used for reactive power compensation plan.....	6
Figure 3.6-1: Line voltage profile for 215 mi. line, 50 or 100 MVAR reactor at open end.....	23
Figure 3.6-2: Line voltage profile for 136 mi. line, no reactor or 50 MVAR reactor	23
Figure 3.6-3: Line voltage profile for 108 mi. line, no reactor.....	24
Figure 3.7-1: Generic Turbine-Generator System	25
Figure 3.7-2: Example Results from Speed-to-Torque Transfer Function Analysis.....	26
Figure 4.3-1: Series capacitor bank main components.....	30
Figure 4.3-2 – Line voltage profile for series capacitors at the end and middle of a line	32
Figure 4.4-1: Simplified radial test system for SSI evaluations.....	35
Figure 4.4-2: Generic Turbine-Generator System	39
Figure 4.4-3: Example series compensated network.....	40
Figure 4.4-4: TCSC scheme	45
Figure 4.4-5: TCSC virtual impedance with the SVR control scheme.....	46
Figure 4.4-6: Series capacitor and bypass filter configuration	46

Table of Tables

Table 2.2-1: Breakdown of wind generation in various study scenarios	8
Table 3.1-1: Cost Estimates for Various Shunt Compensation Options	11
Table 3.2-1: Shunt reactor requirements for the CREZ transmission system.....	13
Table 3.2-2: Shunt capacitor requirements for the CREZ initial build	13
Table 3.2-3: Dynamic shunt requirements for the CREZ initial build	14
Table 3.3-1: Shunt capacitor requirements for CREZ with high wind generation levels	15
Table 3.3-2: Dynamic shunt requirements for CREZ with high wind generation levels	17
Table 4.2-1: CREZ Series Capacitor Locations as Studied	29
Table 4.4-1: Conditions found to be conducive to SSI with Type 3 WTGs on CREZ system	37
Table 4.4-2: Conditions found to be conducive to SSI with Type 3 WTGs on CREZ system	44

1 Background

1.1 Legislative Order

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.

1.2 Reactive Compensation Study

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 1.2-1. Several aspects of the study are conducted in parallel but all ultimately influence, to a greater or lesser degree, the final comprehensive compensation plan.

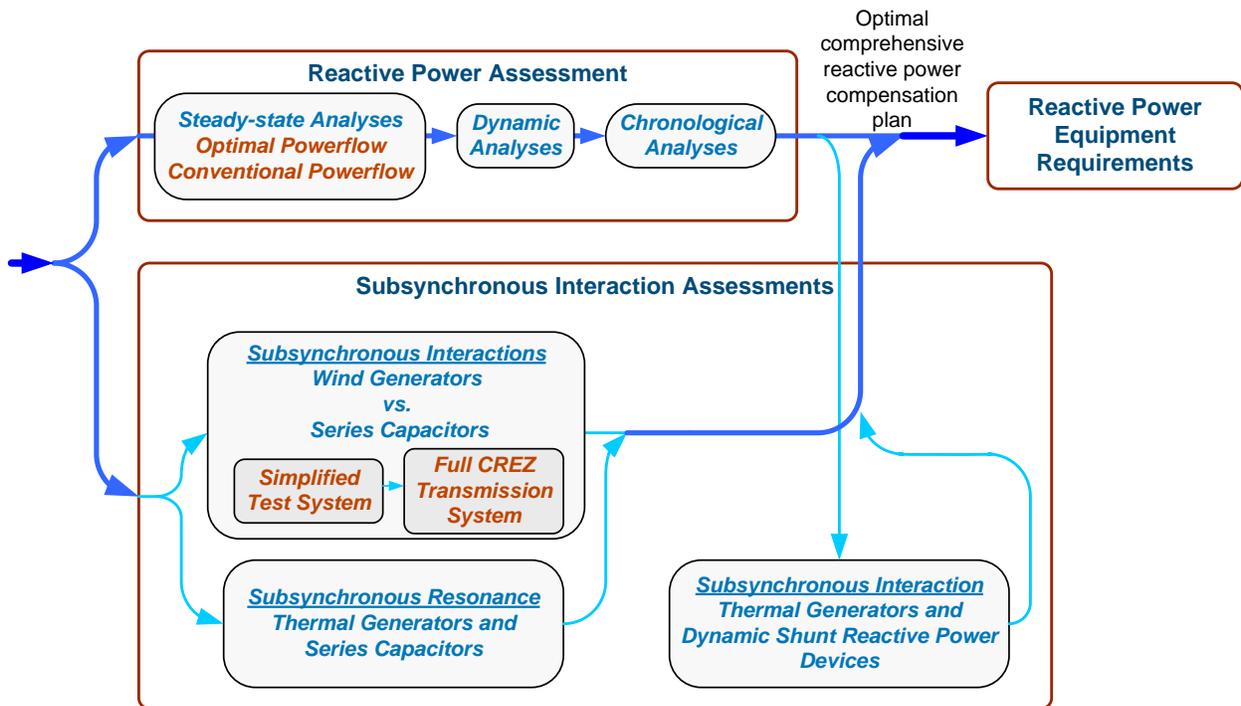


Figure 1.2-1: General study approach

Each of the analyses and assessments involved in the study are discussed in greater detail below. 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 and the CREZ TSPs through several other reports.

1.3 An Observation

This study is the first of its kind on the ERCOT system concerning the CREZ transmission. 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.

2 The CREZ Transmission Plan

2.1 The Network Topology

The CREZ transmission plan approved by the PUCT as of the start of the CREZ Reactive Study is shown in Figure 2.1-1, which identifies the various TSPs by different colors. In order to help clarify the interconnection with the existing system, a few existing 345kV circuits are also shown in gray.

Nine lines – one single circuit and four double-circuits – were identified for series capacitor compensation. These lines, as initially modeled, are:

- The Tesla-Silverton single-circuit with a single-segment, mid-line series capacitor;
- The Edith Clarke-West Shackelford double-circuit, each with two-segment series capacitors at Clear Crossing North;
- The Dermott-Willow Creek double-circuit, each with two-segment series capacitors at Clear Crossing East;
- 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-segment series capacitors at Edison.

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 a significant reduction in the reactive compensation requirements:

- 1) A common bus at the Clear Crossing station to which all of the series compensated lines 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 result in the final CREZ transmission system topology shown in Figure 2.1-2. The final series compensated lines as modeled in the study are:

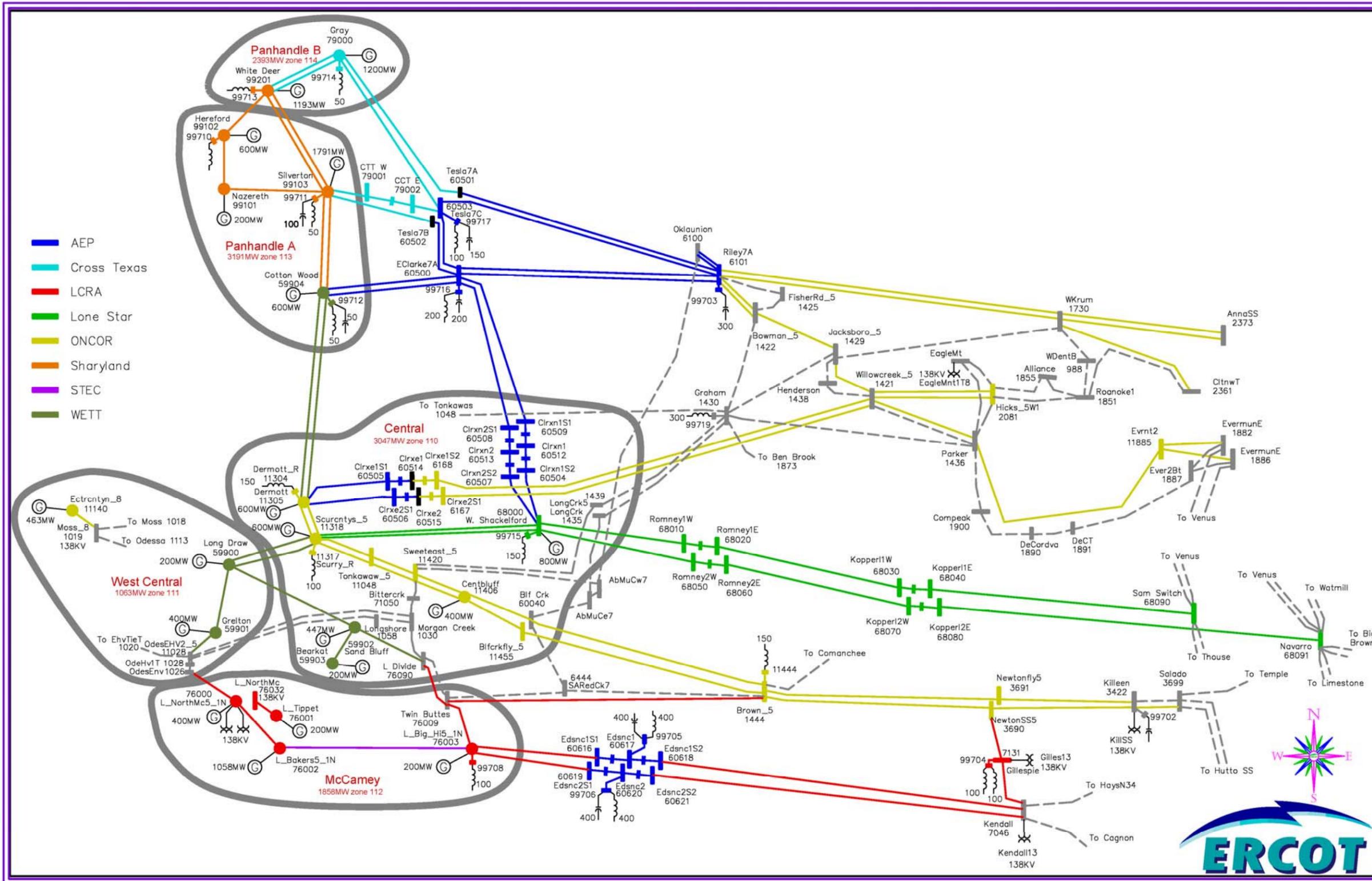


Figure 2.1-1: Initial CREZ system topology at the start of the CREZ Reactive Study

NOTE: The shunt reactors and capacitors in the above figure were used as placeholders at the beginning of the study

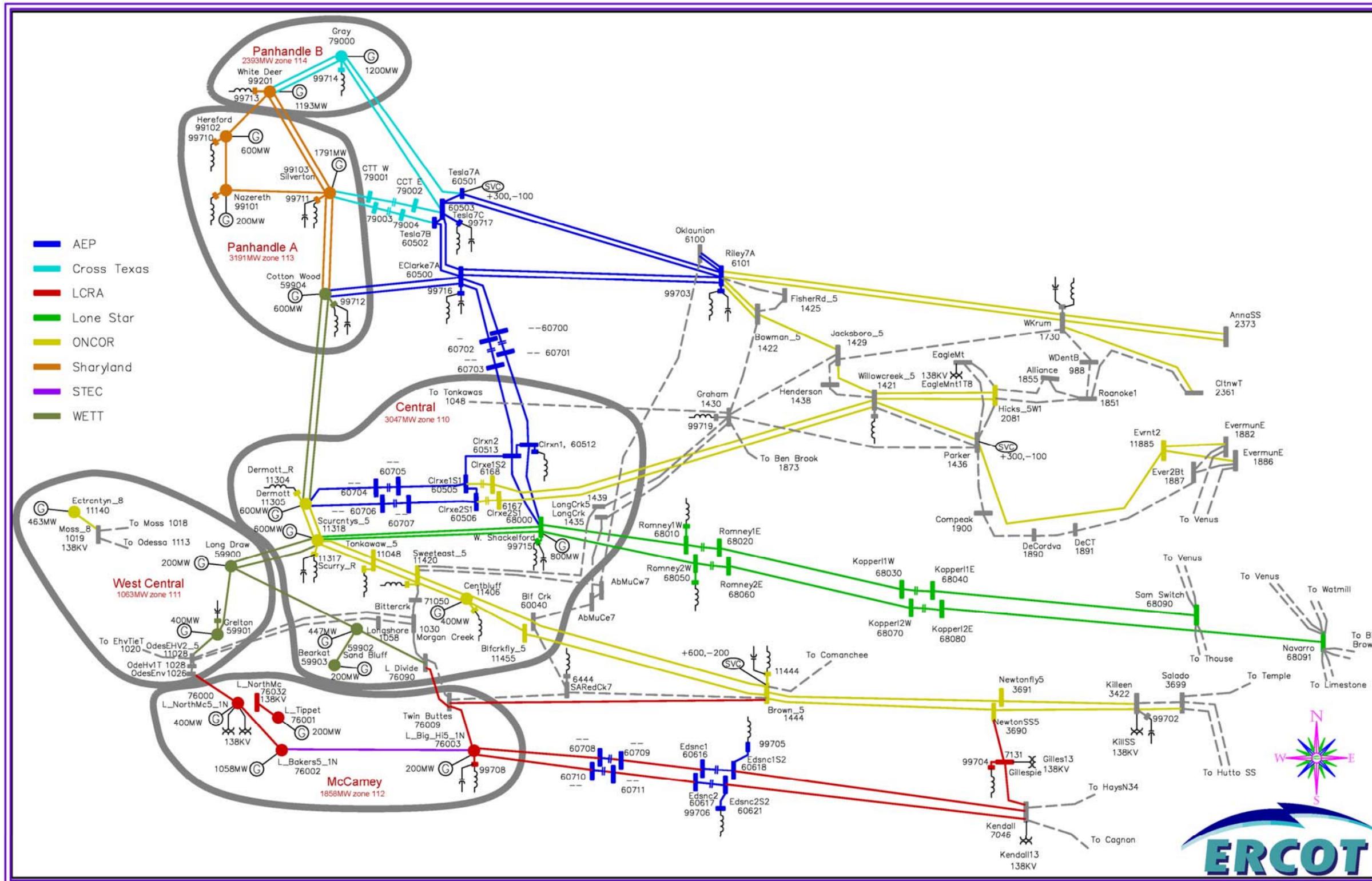


Figure 2.1-2: Final CREZ system topology used for reactive power compensation plan

NOTE: The reactive compensation in the above figure does not necessarily represent the final recommended locations or sizes

- 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 capacitor segments – one at Edison and the other midway between Big Hill and Edison.

This final CREZ system configuration is the one used for the development of the comprehensive reactive compensation plan.

2.2 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 2.2-1. 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 2.2-1: Breakdown of wind generation in various study scenarios

Zone	Initial Build		Minimum Export		Maximum Export		Maximum Edison	
	On-Line Capacity	Wind Gen	On-Line Capacity	Wind Gen	On-Line Capacity	Wind Gen	On-Line Capacity	Wind Gen
<i>Existing wind generation in CREZ</i>								
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
<i>New wind generation in CREZ (study assumptions)</i>								
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

An appreciation of the changes made to stress different lines can be gained by comparing the new wind generation levels at McCamey and Panhandle B for the Maximum Export and Maximum Edison scenarios. In order to stress the southern lines, the Panhandle generation is decreased while the McCamey generation is increased. Other adjustments are also made between the cases, but these are the most significant.

It is also worth noting the significant increase in Panhandle generation from the Initial Build scenario to the Maximum Export scenario. The increased power flows will have a large impact on the reactive needs between the time periods represented by these two cases.

3 Shunt Reactive Compensation Requirements

The following sections discuss the study conclusions regarding the shunt reactive compensation requirements. The purposes and benefits of shunt compensation are described first, followed by a listing of the shunt compensation equipment (reactive and capacitive, static and dynamic) that is needed immediately upon completion of the CREZ transmission system and then in the future when the amount of wind generation nears the capacity envisioned by the PUCT. A discussion of the study methods used to arrive at these results is provided at the end of the section.

3.1 Purposes and Benefits of Shunt Reactive Power Compensation

AC networks inherently require some level of reactive power control capability. The lines, transformers, motors and other power system elements all have varying levels of inductive reactance associated with the magnetic fields created by the flow of currents in the system. In addition, transmission lines and cables have relatively high levels of shunt capacitive reactance which is associated with the electric field between individual phase conductors and between those phase conductors and ground. These reactances result in reactive power being either “consumed” (inductive) or “supplied” (capacitive).

The inductive reactance of lines and transformers is the primary component associated with voltage drops around the network. When the levels of the current flowing through the equipment increase due to higher system loads or system contingencies, the magnitude of the voltage drops also increase. If the voltage drops become too severe, the system will become unable to adequately deliver the required power to the loads at the required voltages. Additionally, at very high loading levels or following severe contingencies, the system may even be unable to serve its own reactive losses and the reactive needs of the loads at any voltage. This leads to the phenomena of voltage instability and voltage collapse.

This effect of inductive reactance is somewhat compensated for by the capacitive charging reactance of the transmission lines. However, in most efficiently-designed overhead power systems the line charging is not sufficient to provide all of the needed compensation and additional shunt capacitance is required at select locations around the network.

On the other hand, during periods of light system loading, the voltages around the system may become too high for the safe and reliable operation of the connected equipment. These higher voltages are generally associated with line charging capacitance, which with the judicious use of shunt reactors around the network can be sufficiently compensated.

Unlike real power, which can be transmitted over long distances, reactive power is difficult to send far from the source because the transmission lines and transformers consume the reactive power. This means that reactive power compensation must also be applied close to where it is needed, usually resulting in a distribution of reactive power devices around the network.

The amount of reactive compensation needed at a location is referred to as “reactive deficiency” for that bus. Experience indicates that the larger the reactive deficiency the more likely it is that contingencies can lead to significant voltage excursions on the system. Large reactive deficiencies also tend to accelerate any voltage instability and result in fast system dynamic processes such as the stalling of motors.

The reactive power compensation equipment can come in two basic forms, static and dynamic. The static reactive power equipment is switched in and out by relatively slow mechanical switches (breakers) and is intended to meet the needs of the network over extended periods when only slow changes occur on the system – that is, in the steady state. Static reactive equipment consists of predetermined blocks which are switched individually.

Dynamic reactive power equipment responds to the faster changes in the network and can help to stabilize the system following a disturbance on the system. While it may be supplied by very fast acting (e.g. power electronic) switches inserting or removing blocks of the equipment as needed, it is also common for dynamic reactive equipment to have the ability to continuously control the amount of reactive power supplied.

In the CREZ system, continuous dynamic reactive control is particularly important because of the potential for significant angular excursions between the voltages at wind generation buses in the west relative to those near the load centers in the east. If those angles become too large, the entire system can become unstable. This is true even if the bulk of the wind generation is electronically controlled, as is the case with the most common wind turbine generators being installed today. However, the transmission system is still bound by power-angle limitations not unlike those associated with traditional synchronous generation.

In order to prevent instability, voltages at intermediate buses must be controlled in a continuous manner. In typical systems, such control is provided by power plants distributed throughout the transmission system. In the CREZ system, however, there may be few or no such intermediate plants and the burden of securing system stability following critical contingencies falls to the proposed dynamic compensation.

At present there are two primary devices available to provide dynamic shunt compensation: 1) the Static Var Compensator (SVC) and 2) the Static Compensator (STATCOM). The SVC enjoys many installations around the world by many manufacturers. Recent years have seen an increasing appreciation for the device to economically provide necessary reactive compensation as increasing loads push existing transmission systems toward dynamic stability limits and as generation plants are retired. STATCOM installations are more rare, partly because the technology is newer, but also because at present STATCOMs are more expensive than SVCs. However, STATCOMs have some benefits over the SVCs:

- 1) Their range is more balanced in that their inductive and capacitive ranges are limited by the same converter ratings;

- 2) Their effectiveness at lower system voltages does not degrade as quickly as SVCs;
- 3) They are inherently faster than SVCs because of the way that they are controlled (Pulse-Width Modulation vs. Line-Commutation). This makes them the preferred choice for some applications, such as for addressing flicker in the vicinity of an arc furnace.
- 4) They may have the ability to make the system appear stronger to devices with slower-acting controls. Strictly speaking, a STATCOM cannot increase system short-circuit levels. However, one that is designed to take advantage of its superior speed in controlling voltage could effectively appear as a constant voltage source (i.e. increased short-circuit level) by the slower controls. As discussed below in Section 3.3.2, high-frequency oscillations involving WTG controls were observed under conditions with extremely low short-circuit levels. If more in-depth studies confirmed the potential for such oscillations, then the feasibility of designing a STATCOM for the specific purpose of improving the performance of the WTGs and the system under such low short-circuit levels should also be investigated.

Additional descriptions of these devices are provided in Appendix A.

The costs for the different types of shunt compensation equipment can vary widely depending upon their ratings, the specified performance requirements and local installation issues. However, estimated costs for the various alternatives are provided in Table 3.1-1. These estimates were collected in mid-2010. Costs will vary over time due to fluctuations in currency exchange rates, changes in material costs, etc.

Table 3.1-1: Cost Estimates for Various Shunt Compensation Options

Alternative	Size or Dynamic Range	Estimated Cost Million \$	Comment
Shunt Reactor Banks	One breaker switched 100 MVAR bank	\$5.5	
Shunt Capacitor Banks	One breaker switched 150 MVAR bank	\$3.2	
SVC	-100 to 300 MVar	\$25	<i>Note 1</i>
STATCOM	-300 to 300 MVar	\$55	<i>Note 2</i>
Sync Condenser	350 MVA	\$75	<i>Note 3</i>

Note 1 - This is \$63/kVAr for a continuous controlled SVC with an inductive range. Estimates from vendors ranged from \$50/kVAr to \$100/kVAr but not all vendors stated the assumed SVC performance.

Note 2 - The estimates ranged from \$80/kVAr to \$130/kVAr with a full converter providing an inductive range equal to the capacitive range.

Note 3 - The estimates for large synchronous condensers were from \$180/kVA to \$210/kVA

3.2 Initial Build Requirements

Because the CREZ wind generation will take several years to reach the full planned installed capacity, ERCOT and the TSPs decided that it would be prudent to develop a reactive compensation plan that would address the needs immediately upon completion of the initial build of the transmission system. At that time, the lower amounts of wind generation will result in reduced levels of static shunt capacitor compensation and lower dynamic shunt compensation levels. The initial build requirements are discussed in the following sections.

The results assume a 5% margin on the wind generation levels in the Initial Build case. This allows for some of the inevitable differences between the levels and distributions assumed in that case and the actual build out. Data uncertainties in the powerflow and dynamic models are also contemplated in the 5% margin. When the actual CREZ build out starts to approach that of the Initial Build case, or if it is significantly different from that case, consideration should be given to the long term planning requirements discussed in Section 3.3.

3.2.1 Static Shunt Reactors

The optimal size and locations of the static shunt reactors have been determined primarily based on Minimum Export conditions under which the line capacitance plays a significant role in supporting the system voltages. Under these light load conditions, the voltages at various buses can become too high and the application of shunt reactors is required to maintain the voltages within the normal operating criteria. In addition, when lines are energized, they are first connected to the system at one end while the other end is left open. Under these conditions, the open-end voltage can rise significantly, again requiring shunt reactors to keep them at acceptable levels.

In addition, the TSPs have established criteria defining the largest steady-state change in bus voltage that is allowed upon switching of a reactive shunt device. These criteria govern both an increase and a decrease in bus voltage. The maximum reactive bank step size that can be used and satisfy these criteria was determined and used where applicable in recommending the equipment step sizes.

The ratings and locations for the shunt reactors determined using powerflow evaluations and confirmed using a chronological analysis (see Section 3.4) are listed in Table 3.2-1. This table lists the total reactive power requirements in MVAR for existing and proposed reactors, along with the recommended number of steps and step size in parentheses. All of these are to be applied at 345kV and are needed when the CREZ transmission lines are energized. Note the shunt reactor requirements are based on minimum loading of the CREZ system and do not change for the higher installed wind generation expected in later years. These requirements will only change if the CREZ transmission system itself changes.

Table 3.2-1: 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)
Oklunion	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)

3.2.2 Static Shunt Capacitors

The optimal size and locations of the static shunt capacitors have been determined primarily based on the system loading assumed in the Initial Build case. A comprehensive set of contingencies were evaluated to examine the pre- and post-contingency steady-state reactive power needs of the system. Based on these results, the shunt capacitors needed for the initial build loading levels are listed in Table 3.2-2. As discussed in Section 3.3, the ultimate build out will require shunt capacitors at additional locations. Some of these locations were approved in the CTP, but are not listed below as needed for the initial build.

Table 3.2-2: 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.

3.2.3 Dynamic Shunt Compensation

The dynamic shunt requirements for the Initial Build case have been determined based on the dynamic system response following the most critical NERC B contingencies. The dynamic shunt devices act to maintain both voltage and power angle stabilities of the entire CREZ system. The dynamic capacitive range is most critical, but an inductive range is also included and is needed during the dynamic response to the system contingencies. A continuous control capability across the entire dynamic range is required. The optimal size and locations of the recommended dynamic shunt devices for the initial build are listed in Table 3.2-3.

The need for fast-acting dynamic shunt compensation stems from the speed of the dynamic phenomena that they are intended to arrest. Simulation results show that in the absence of sufficient reactive support following critical contingencies the system will experience a voltage collapse. Further, on the CREZ system, such a collapse will be fast. This is due in part to the fast nature of the electronically controlled wind generation and in part because there are no mechanisms to slow down the collapse in voltages. In a typical transmission system the internal fluxes in conventional generators would help slow a voltage collapse, but the CREZ system has no conventional generation nor is it close to conventional generation on the remainder of the system.

Also, a typical system would have voltage sensitive loads that would provide relief as the voltage dropped. This relief would come in the form of a temporary reduction in the load or of a load dropout. This would provide some relief to the reactive demands on the system. This mechanism is not available on the CREZ system because it is primarily designed for the purpose of evacuating generation. Response time requirements are under 50ms, which is well within the capabilities of SVCs and STATCOMs, but is too fast to be reliably addressed with mechanically switched compensation or special protection systems (SPS).

Table 3.2-3: 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.

3.3 Long-Term Planning Requirements

As the wind generation levels in the CREZ increase the powerflow to the load centers will cause higher levels of reactive power to be consumed in the transmission system with corresponding increases in the reactive compensation requirements. Higher angular spreads between CREZ sending (generation) and receiving (load) ends also lead to increases in compensation requirements, particularly those for dynamic compensation. The Maximum Export and Maximum Edison cases were used to determine the compensation requirements for the ultimate levels of wind generation envisioned in the selected plan. If the ultimate development of wind generation in the CREZ system is significantly different from these cases, the reactive power requirements should be reviewed.

3.3.1 Static Shunt Reactors

Because the shunt reactor requirements are primarily determined by light load conditions, those listed in Table 3.2-1 are also those required for the ultimate build out of the CREZ.

3.3.2 Static Shunt Capacitors

The shunt capacitor requirements based on the cases with highly loaded lines increase both in geographic distribution and in reactive levels with respect to those identified for the initial build. The requirements for long-term planning purposes are listed in Table 3.3-1.

Table 3.3-1: Shunt capacitor requirements for CREZ with high wind generation levels

Bus Name¹	Bus voltage [kV]	Total shunt capacitance required for high generation levels [MVar]	Synchronous Condensers for Short Circuit Support
Riley	345	316.4	
Krum West	345	50	
Tesla	345	316.4	350
Edith Clarke	345	316.4	
Silverton	345		350
Cottonwood	345	50	
Scurry	345	100	
West Shackelford	345	200	
Grelton	345	50	
Brown	345	300	
Killeen	345	50	
Big Hill	345	576	
Hamilton	138	20	

¹ Final locations may change due to practical considerations. Such changes may influence required size.

This table also includes two Panhandle locations for 350 MVAR synchronous condensers. During the study, it was found that these were necessary under some severe contingencies that resulted in weak system conditions (low short-circuit strength). The wind generation models used in the study experienced high frequency oscillations (sometimes in excess of 10 Hz) when the high wind generation levels were a large percentage of the system short-circuit capacity. Similar phenomena can often be expected for devices that utilize power electronics and their associated controls under weak system conditions. Therefore, even though further investigation is needed to determine if the phenomena observed during the study are expected in actual operation, synchronous condensers were used to alleviate the simulation issues observed. If it is found that devices are necessary to increase the short-circuit strength at the Panhandle buses identified, they do not necessarily need to be synchronous condensers, since other options, such as properly designed STATCOMs, can also be used. In addition to improving the stability of the WTG controls, such a STATCOM could potentially provide performance superior to that of a synchronous condenser with lower capital and maintenance costs, increased (large signal) response capability, and no exposure to electromechanical type instability.

As in the Initial Build case, the main role for the switchable shunts (capacitors and reactors) is to off-load the reactive output from the CREZ wind farms and the proposed dynamic shunt compensation, thereby allowing their respective reactive range to be preserved for contingencies.

3.3.3 Dynamic Shunt Compensation

The increased wind generation levels anticipated in the Maximum Export and Maximum Edison cases result in a significant increase in the required dynamic shunt compensation. This is primarily due to the large angular excursions between the sending end (generation in the west) and receiving end (load in the east), but is also a result of larger reactive losses due to increased real power (MW) flows, particularly following critical contingencies.

In order to maintain voltage stability and to meet the requirements of power-angle type dynamics, several intermediate bus voltages must be controlled. To do this requires the dynamic shunt compensation listed in Table 3.3-2. The speed requirements are similar to those discussed for the Initial Build case, which is within the capabilities of SVCs and STATCOMs, but too fast for either mechanically switched compensation or SPSs.

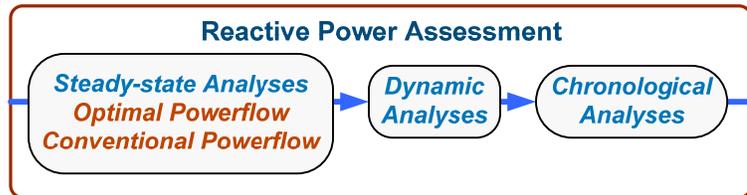
Table 3.3-2: Dynamic shunt requirements for CREZ with high wind generation levels

Bus Name ¹	Bus voltage [kV]	Dynamic shunt range required for maximum cases	
		Capacitive [MVar]	Inductive [MVar]
Riley	345	600	-200
Tesla	345	600	-200
Silverton	345	600	-200
Brown	345	1200	-400
Big Hill	345	600	-200
Hamilton	138	200	-50
Parker	345	900	-300
Bluff Creek	345	600	-200

¹ Final locations may change due to practical considerations. Such changes may influence required size.

3.4 Study Approach to Determining Shunt Reactive Compensation Requirements

In order to determine the levels of shunt reactive compensation required for a comprehensive reactive power plan for the CREZ system, several types of analyses



were performed, each flowing into the next. Specifically, steady-state assessments of the various system loading scenarios were made, followed by dynamic simulations of critical contingencies and chronological analyses designed to evaluate how the needs vary from hour-to-hour over a typical year.

3.4.1 Steady-State Analyses

The steady-state analyses helped to characterize any deficiencies in the supply of the reactive power needs of the system, to confirm that there are adequate margins for voltage stability, and to begin to highlight the needs for and locations of dynamic shunt devices such as SVCs and STATCOMs.

For each of the loading scenarios (Initial Build, Maximum Export, etc.) a comprehensive set of line and transformer outages (NERC categories B, C and D) were considered to identify those contingencies that are most critical for voltage stability and maintaining system voltages within the proper pre- and post-contingency operating ranges.

Note that under ERCOT practice, double circuit outages are assumed to be of the same severity as their single-circuit counterparts. This means, for example, that a three-phase fault leading to the loss of a double-circuit line is considered a Category B contingency. ERCOT also requires that certain power (MW) margins to voltage stability must be maintained as follows:

- NERC Category B contingencies – 5% margin
- NERC Category C contingencies – 2.5% margin

Conventional Powerflow

Multiple aspects of the study and the equipment rating calculations were determined using conventional powerflow and/or fault analysis using Siemens-PTI's commercially available PSS/E® package. This program is ideal for determining system voltages, current and power flows through lines and the like both before and after system contingencies or other network changes. PSS/E is the standard package used by the utilities in the ERCOT system for this purpose.

The comprehensive set of contingencies was first performed using conventional power flow techniques with the intent of identifying which contingencies led to voltage instability – usually those cases that could not converge on a solution or that would converge, but to very low voltages. Generally, those of most interest were Category B double-circuit contingencies and some Category D contingencies. These non-convergent cases were then examined using a conventional “QV-curve” analysis which examines the reactive needs to maintain acceptable voltages at various network buses. This effort was coupled with optimal powerflow techniques (described next) in order identify the best locations for the reactive power equipment.

Compliance with the MW margin requirements mentioned above was also independently verified using “PV-curve” type analyses.

Optimal Powerflow

Optimal power flow (OPF) is a tool within the PSS/E package that allows various system parameters to be optimized against a defined set of measurements and constraints. In this study, OPF was used to optimally determine the locations and rating of the reactive power equipment, as well as to determine the maximum currents anticipated to flow through the series capacitors.

As indicated above, OPF techniques were used to determine the minimum amount of and optimal locations for additional reactive compensation needed to obtain a solution to the contingency cases that could not otherwise converge. In conjunction with the QV-curve and PV-curve analyses this technique ensured that required margins were maintained for the optimal (least cost) solution.

3.4.2 Dynamic Analyses

Dynamic analyses are important in order to assess the behavior of the system over a short period of time (ten seconds or so) after a system disturbance. Following NERC Category B and C contingencies the system dynamics must be stable and well damped. Proper power (MW) margins to instability must also be maintained. The analyses also help to confirm the dynamic compensation that is needed on the system.

Special models of the power system equipment that properly represent their behavior for dynamic simulation purposes must be used. The dynamic models used in this study were provided by ERCOT. Models of conventional system equipment, such as generators and loads, are well developed and can easily be used. On the other hand, however, the models representing the various existing wind turbine generators around the ERCOT system are newer, are often supplied by the developers, and do not always function ideally under all dynamic system conditions. This proved to be challenging in many instances during the dynamic evaluations.

At the direction of ERCOT and the TSPs, the new CREZ wind generation was assumed to be 85% in the form of GE Type 3 (DFIG) generation and 15% in the form of Vestas Type 2 (variable rotor resistance) generation.

During the course of the dynamic simulations, a potential control instability was noticed in the simulation models representing the new CREZ generation, particularly Type 3 generators. High frequency oscillations (sometimes in excess of 10 Hz) were observed in the simulations following critical contingencies. The oscillations are likely to be associated with a low ratio between the available short-circuit capacity of the system at certain locations and the nearby wind generation levels. This ratio is called the short-circuit ratio, or SCR. At ERCOT's request it was decided to add two 350MVA synchronous condensers in the Panhandle area as part of the dynamic compensation. The condensers are partially intended to increase the SCR in that area, but a more in-depth analysis of the issues is needed. As such, the synchronous condensers play a "place-holder" until future analyses, beyond the scope of this reactive power study, can confirm whether or not the oscillations are indeed a problem or a result of model shortcomings. If they are real, the future analyses should determine the most cost effective solutions.

3.4.3 Chronological Analyses

Wind generation is well known for its variability and in the context of the CREZ system, this variability translates into variability in the power flow through the transmission system, which in turn translates into varying demands for reactive power. In order to assess the effects of this variability, chronological studies were conducted by performing a series of 8760 base case (all lines in service) powerflows with each reflecting the hourly wind generation changes over one year. The changes were based on 2009 wind generation data provided by ERCOT.

The primary result coming from the chronological analyses is the effect on the switched shunts – the extent of their use and how often they are switched.

3.5 Assumptions made regarding Wind Generation Reactive Performance

In most systems wind generation is just one element of an otherwise diverse generation portfolio. However, the CREZ wind generation can be viewed as being the system. Because of this, the assumed steady-state and dynamic performance of the wind generation becomes an integral part of the recommended compensation strategy. Actual performance that is less than that assumed in the studies will likely lead to increased compensation requirements. The assumptions made in modeling the CREZ wind generation are described below.

3.5.1 Steady-State

In steady-state (including contingency) analyses, the CREZ wind farms were modeled at their respective Points of Interconnection (POIs). In accordance with ERCOT requirements, each plant was assumed to have a sufficient reactive capability to provide a power factor of ± 0.95 , or roughly $\pm 1/3$ of its respective installed capacity. The aggregate of the installed capacities in each CREZ are listed above in Table 2.2-1.

3.5.2 Dynamics

For dynamic analyses, the wind generation was modeled as being connected (through step-up transformers) to simplified representations of collector systems, which were in turn connected to the bulk transmission systems through transformers.

The existing wind generation was modeled as instructed by ERCOT, and was comprised of approximately 60% Type 3, 20% Type 1, 5% Type 2, and the remaining 15% Type 4.

As previously indicated, the new CREZ generation was modeled as 85% DFIG (Type 3), and the remaining 15% as variable rotor resistance type (Type 2). As also indicated earlier, when developing the base cases for dynamic simulation, shunt compensation in the bulk transmission system was assumed to be dispatched to minimize the reactive output/input from the wind farms at their POIs, thereby preserving their reactive capability for disturbances.

In order to further ensure the availability of the farms' reactive capability, fixed shunt compensation was modeled in collector systems to cancel out reactive losses between the generator terminals and the POI. In other words, the assumption was one of strict compliance with ERCOT requirements of ± 0.95 pf reactive power availability at all times. However, the actual availability of these reactive reserves for dynamic simulations varied for the two types of assumed wind generation, as discussed below.

3.5.3 Modeling of Type 3 (DFIG) New CREZ Generation

The 85% of new CREZ wind generation assumed to be of the DFIG type was represented utilizing a PSS/E model of GE machines. Block diagrams and typical data for such models may be found in a number of technical publications and in the PSS/E program documentation.

The reactive control part of such model can be visualized as comprising three layers of control:

- a) **A Wind Farm-Level Voltage Control**, with a Proportional+Integral control with gains of K_{pv} and K_{iv} , respectively. Input to that control is the difference between actual and desired voltages at the POI, and the output is a reactive power command driving Layer b), with limits that were chosen to be the same as those required by ERCOT; i.e., ± 0.95 pf of installed capacity.
- b) **A Unit-Level Reactive Control**, with Integral control with a K_{qi} gain, using as input the difference between desired (from Layer a)) and actual reactive powers at generator terminals, and scheduled voltage output driving Layer c), with 1.1 to 0.9 pu voltage limits.
- c) **A Unit-Level Voltage Control**, with Integral control of K_{qv} (or K_{vi}) gain, having the difference between desired (from Layer b)) and actual generator terminal voltages as an input, and driving the machine's internal voltage, and, consequently, its reactive output. The output limits from this controller are sufficient to allow the full ± 0.95 pf reactive output range from the generator, provided the generator is operated at reasonable voltages. To that end, load tap changers (LTC) were assumed on the high side of the transformer connecting collector and bulk transmission systems at the point of interconnection.

Given the high speed of the dynamics of interest in the CREZ system (in many cases less than 50 ms), it is important to note the typical speeds for each of the above three layers of control. In this case, "speed" is defined as the time required in reaching 63% of the final value. Based on the data assumed in the studies, these speeds are:

- Layer a) – Wind-Farm-Level Voltage Control. ~ 5 sec ($K_{pv}=2$, $K_{iv}=1$; these assumed settings are conservative but robust).
- Layer b) – Unit-Level Reactive Control. ~ 4 sec ($K_{qi}=0.1$)
- Layer c) – Unit-Level Voltage Control. ~ 0.075 sec ($K_{qv}/K_{vi}=40$)

Based on these speeds, it can be concluded that controlling machine terminal voltages by the last layer of control (Layer c)) is of greatest importance to the dynamic performance of the CREZ system – and by extension, to the dynamic compensation requirements. The other two layers are too slow to have any meaningful impact on the simulation results. It is recommended that the Layer c) control be particularly tested and monitored on Type 3 (and Type 4) wind farms

on an adequate sampling of units, because failure to meet the assumed performance may render the proposed compensation strategy insufficient.

3.5.4 Modeling of Type 2 (Variable Rotor Resistance) New CREZ Generation

Type 2 generation has no inherent means of controlling reactive power, so the following two assumptions were made in this study:

- Fixed capacitors were simulated at generator terminals, exactly canceling out the reactive needs of generators in the base-cases.
- For every 100 MW of on-line installed capacity, a ± 16 MVar SVC was modeled at the collector system side of the transformer connecting the wind farm to the POI. Note that this is less than the ± 33 MVar per ERCOT requirements. The remaining compensation was assumed to be furnished in the form of mechanically switched capacitors and reactors, and assumed to be too slow for the CREZ system dynamic needs. Consequently, it was not modeled in dynamic simulation but was assumed to be present in the steady-state analyses, as previously described. The SVC was tuned for fast response, and was assumed initialized at 0 MVars, i.e., with its full range available for disturbances.

3.5.5 Compliance

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. Extensive testing and monitoring of wind farms is recommended to ensure that such support will be available when needed, in the required quantity and with the required quality (speed).

3.6 Additional Steady-State Assessments

In addition to the evaluations described above, two assessments were made that influenced the sizing and types of shunt reactive compensation. The first was an assessment to determine the maximum bank size that can be switched and keep the magnitude of voltages changes at the buses to within acceptable levels defined by the TSPs.

The second was an assessment of the line voltage profiles for transmission lines with one end open. This was used to help determine the size of the shunt reactors required to maintain mid-line voltages to within the transmission line design criteria of 110% of nominal operating voltages. Because series capacitors are typically bypassed when energizing a line, the series capacitors were assumed bypassed for these assessments.

Several line lengths were reviewed and the voltage profile along the line was determined for shunt reactors of different sizes connected to the open end. The results are illustrated in Figure 3.6-1 for a 215 mile line, in Figure 3.6-2 for a 136 mile line and in Figure 3.6-3 for a 108 mile line. These line lengths are within the typical range for the CREZ 345kV lines.

In generally, the results indicate that for lines with length between 140 miles and 200 miles a 50 MVAR shunt line reactor will be needed to limit the line voltage to less than 110%. For lines over 200 miles a shunt reactor of 100 MVARs will be required. Using these guidelines, the TSPs will need to base their shunt reactor installations on the total system requirements, the size and number of banks they prefer, and any spares that they determine are necessary.

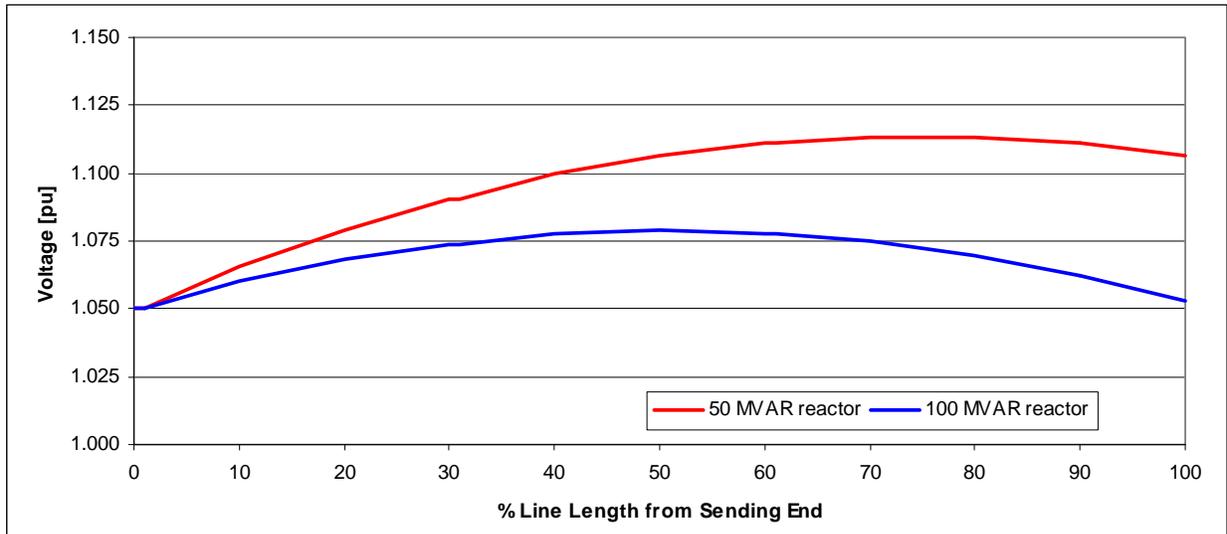


Figure 3.6-1: Line voltage profile for 215 mi. line, 50 or 100 MVAR reactor at open end

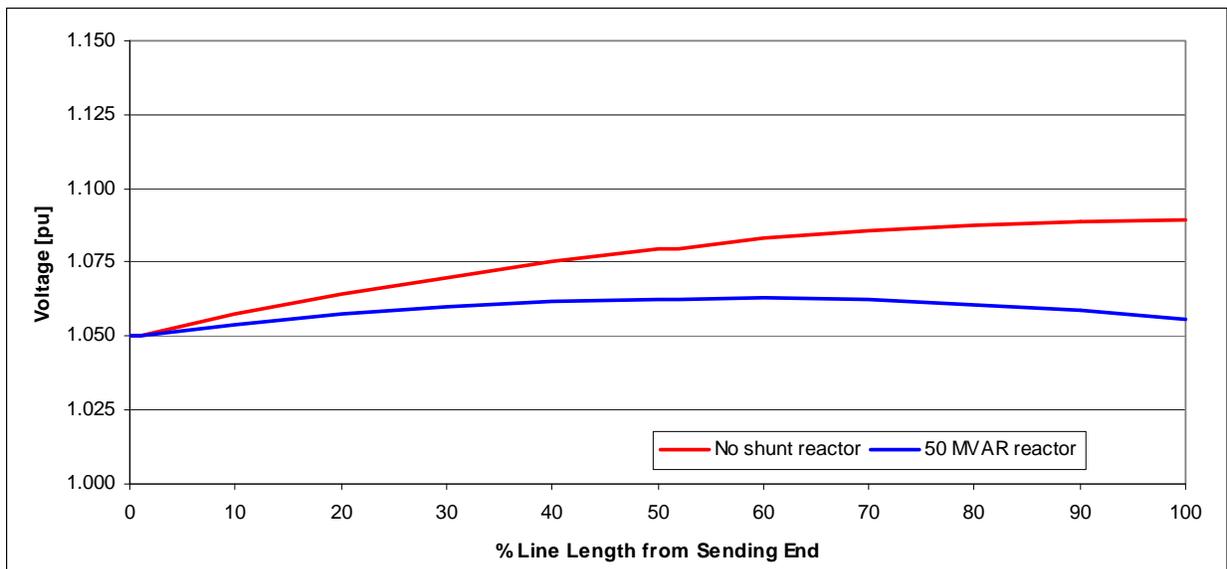


Figure 3.6-2: Line voltage profile for 136 mi. line, no reactor or 50 MVAR reactor

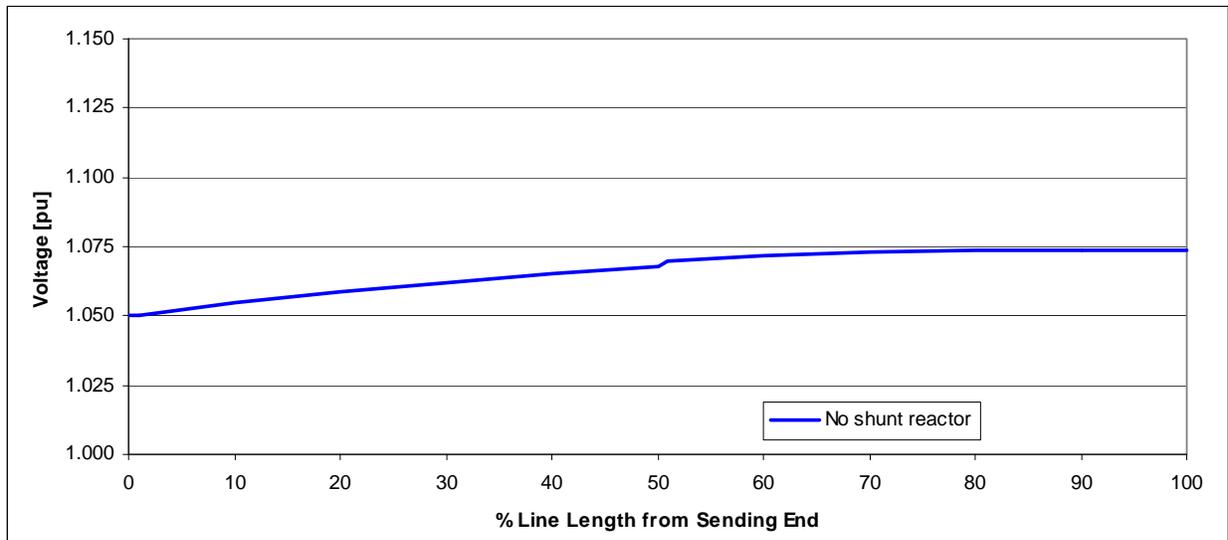
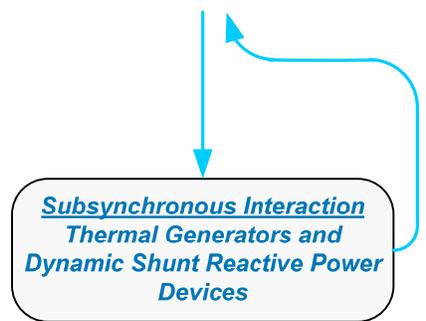


Figure 3.6-3: Line voltage profile for 108 mi. line, no reactor

3.7 Network Challenges with Dynamic Shunt Compensation (SSTI)



When designing dynamic shunt compensation devices, such as SVCs and STATCOMs, consideration must be given to the network on which the device will be connected. For example, the impedance of the network as seen from the point of interconnection over a broad frequency range must be determined to ensure that there will be no detrimental resonances between the system and the equipment elements comprising the device (e.g. filters and thyristor switched capacitors). In addition, the system strength at the point of interconnection must be considered because a too low short-circuit ratio could lead to the controls of the device becoming unstable. However, a potential challenge that must be considered but is lesser known is subsynchronous torsional interaction (SSTI) between the device and nearby conventional turbine generators.

SSTI is the interaction between a device with active controls and the torques applied to a turbine generator shaft. While the turbines themselves apply the primary mechanical torque to move the generators and produce the power, the electrical network itself provides a balancing electrical torque. Variations on the electrical network will change the electrical torque at the machine and if these variations occur in the “right” way and at the “right” frequency, they can destabilize one or more of the mechanical torsional modes associated with various masses on the turbine generator shaft. In the worst case, this interaction can result in catastrophic failure of a generator shaft.

SSTI was first observed in 1977 at Square Butte, Montana where it was found that the current control loop of an HVDC converter near the generating plant acted to destabilize a specific

torsional mode. This observation led to techniques for modifying the HVDC controls to avoid interaction with nearby generator torsional modes.

SVCs and STATCOMs also have sufficient control bandwidth to interact with generator shaft torsional modes. This fact was actually put to beneficial use in one application where an SVC was installed at the terminals of a generator as a subsynchronous resonance (SSR) countermeasure. This SVC application helped to stabilize the shaft torsional modes in the presence of a series compensated transmission line. More recently, system studies have pointed out the potential for interaction between the SVC voltage control loop and nearby generator shaft torsional modes. These studies have been used to develop appropriate SVC control modifications to prevent adverse torsional interaction [1].

The SSTI phenomenon can be understood by considering both the torsional modes of turbine-generators and the control methods used for the power-electronic equipment. A generic turbine-generator system is illustrated in Figure 3.7-1. In this case there are six masses – the high-pressure and intermediate pressure turbines, the two segments of the low-pressure turbine, the generator and the exciter. Any given system may have more or less masses on the shaft.

If the system has N masses there will be $N-1$ oscillatory mechanical torsional modes. The frequency of each oscillatory mode and how well it is damped (decays away) will be dependent upon the relative sizes of the masses, the stiffness of the shaft and the magnitude of various losses in the mechanical system. Of these modes, those that occur at frequencies below the system frequency – in other words, at subsynchronous frequencies – are of particular concern.

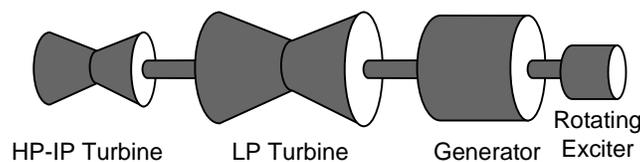


Figure 3.7-1: Generic Turbine-Generator System

The various masses on the shaft will have different degrees of participation in the different modes. The modes in which the generator itself has significant participation will be more susceptible to SSTI. For these modes, a disturbance of the electrical system, such as a fault, will cause a corresponding torsional disturbance on the generator which is translated to the shaft by the machine. This results in modulations of the ac voltage at the bus to which the power electronic device (e.g. SVC or STATCOM) is connected. Depending upon the characteristics of the controls, the device can provide either a stabilizing or destabilizing effect to the generator shaft at the torsional frequencies. Normally, the active devices are located far from generators and the electrical network is sufficiently strong to prevent adverse interaction. The potential for an adverse interaction will increase when the active device is electrically close to a generator or when the active device's rating is large compared to the generator rating.

The potential for adverse SSTI can be assessed by using well developed simulation techniques that carefully model the details of the active device with its controls and the generator. If data is

available, the mechanical shaft can also be represented, but the electrical torques are of primary interest for such an evaluation. The transfer function between generator electrical torque and machine speed is determined across most of the subsynchronous frequency range with the system, the active device and the generator carefully modeled. The portion of this transfer function associated with damping the torsional oscillations – that is, the electrical damping coefficient – is considered. Example results are illustrated in Figure 3.7-2. If the electrical damping is negative at a frequency corresponding to one of the mechanical torsional modes, it may overcome the inherent damping of the mechanical system at that modal frequency and destabilize the mode. If this occurs additional study and/or control modifications to the dynamic shunt device may be warranted.

Each simulation to produce a damping coefficient vs. frequency curve will represent only the results for the system conditions simulated; that is, with specific equipment in service and with the active device at a specific operating point. It is generally necessary to investigate the electrical damping characteristics under a variety of system conditions, producing a family of curves similar to that shown in the figure.

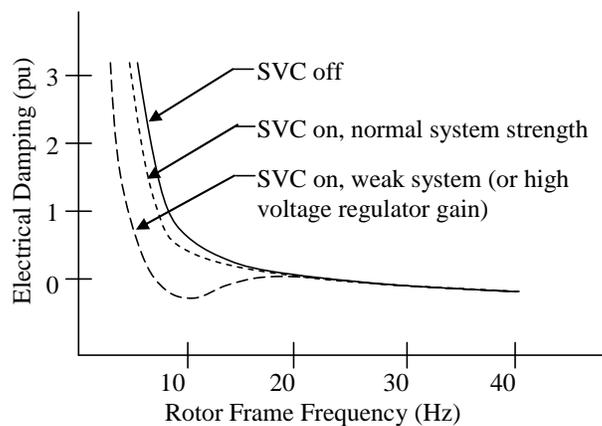


Figure 3.7-2: Example Results from Speed-to-Torque Transfer Function Analysis

The main benefit of curves similar to those shown is the ability to highlight the *differential* impact of different system conditions and shunt device operating conditions for comparison. The results with the dynamic shunt device off-line helps to establish a baseline for determining whether changes with it on line may be of concern. There is never a concern at frequencies for which the electrical damping is positive. At frequencies where the electrical damping with the dynamic shunt is more positive than without the shunt, the shunt provides beneficial damping of any torsional modes at those frequencies. If the action of the shunt device results in damping that is more negative than without the shunt, then further consideration may be warranted. Marginal changes are not likely to be of concern.

SSTI evaluations have been conducted for the Willow Creek plant and the Comanche Peak nuclear plant because of their close proximity to at least one of the recommended initial build

dynamic shunts¹. Based on the results, there is little concern for these generators. The generic SVCs, modeled with relatively fast acting controls (i.e. high gain) generally proved to be beneficial to the electrical damping of the studied generators over the subsynchronous frequency range. STATCOMs are expected to provide similar performance to the SVCs considered.

The generic SVC model and generic controls used in the evaluation are sufficient to provide a general assessment and set expectations that the controls can be designed to prevent detrimental SSTI. However, because each manufacturer's controls are different, when the final equipment is selected and designed, a full SSTI evaluation using the actual control functions and settings of the selected equipment is recommended. This may be particularly important if STATCOMs are installed because the industry has less operational experience with STATCOMs than SVCs.

¹ Note that four additional plants – Hays, Odessa-Ector, Oklaunion and Tradinghouse – were evaluated for the subsynchronous resonance issues discussed in Section 4.4.2. These are not considered here for SSTI because they are not in as close proximity to the initial build dynamic compensation locations as are Willow Creek and Comanche Peak.

4 Series Capacitor Compensation Requirements

4.1 Purposes and Benefits of Series Capacitor Compensation

As noted previously, transmission lines inherently have an inductive reactance that is in series with flow of current between the source and the load. This impedance is responsible for a significant portion of the voltage drops in the transmission systems and is proportional to the length of the transmission lines. Transmission line designers will attempt to keep the line reactance as low as possible because it provides significant benefit to keeping the system tightly connected – that is, it keeps the sources of generation electrically closer to the load.

Higher transmission voltages can effectively reduce the influence of line reactance, not only because of differences in the line designs, but primarily because significantly reduced levels of current flow for a given amount of power being transmitted resulting in correspondingly reduced levels of voltage drop along the line. Based on a cost-effectiveness analysis, 345kV was selected as the appropriate voltage level for the CTP.

The long distances associated with the transmission of the wind energy from the CREZ to the load centers results in several long transmission lines between the various system buses. Some of these are so long, that system stability is impacted and it becomes necessary to find a way to reduce the reactance associated with these lines. One method is to increase the number of circuits along the critical paths, but this is not economically desirable – particularly considering that the circuits will be under utilized for the amount of power to be transferred. A well known and understood method is to compensate a portion of the series line inductive reactance with a series capacitor. At normal system operating frequencies and from the perspective of total line reactance, this is the same as reducing the line length in proportion to the level of series compensation.

Ideally, the total line reactance would be zero (or at least, very low) suggesting that 100% compensation is desirable. However, there are other design considerations, such as the voltages along the length of the line and resonances that can result in severe interactions with conventional thermal generation, which must also be considered in selecting the optimal level of series compensation. Several of these design issues are discussed in more detail in Sections 4.3 and 4.4. In order to address some of these design issues, series capacitors can be designed with multiple smaller segments placed at different locations along the line. Typically only one or two segments are used.

In selecting the final series compensation levels for the CREZ transmission lines, multiple issues including line voltage profiles, voltage stability, system angular stability and subsynchronous resonances were evaluated. Several compensation levels up to 75% were considered, but, driven primarily by the TSP's proposed line design criteria ERCOT supported the findings that compensation levels of approximately 50% represented a good compromise

among competing constraints. 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.

4.2 Study Locations of Series Capacitors

Based on interim study results, several changes were made to the CTP during the course of the study. The final series compensated lines and series capacitor locations shown in Table 4.2-1 were used for the study.

Table 4.2-1: 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.

The comprehensive reactive compensation plan developed for the CREZ initial build was developed assuming the series compensation levels indicated on the lines listed. It is therefore assumed that the series compensation is installed as an integral part of the initial build of the CREZ transmission system.

4.3 Study Approach to Determining Series Capacitor Requirements

4.3.1 Series Capacitor Technology

Series compensation to reduce the effective impedance of a transmission line can be accomplished by putting a capacitor bank in series with the line. This series capacitor bank will

be installed on a platform that is insulated against the full line voltage since all of the equipment will be operating at the line voltage potential.

A typical series capacitor bank consists of the arrangement shown in Figure 4.3-1. The actual design of these series capacitor banks is subject to detail design studies considering the actual network data and system requirements. The main components of the series compensation include the series capacitor bank, the MOV overvoltage protection, a bypass gap and/or bypass switch. All of the components, except the disconnectors and the bypass switch, are normally on the capacitor platform.

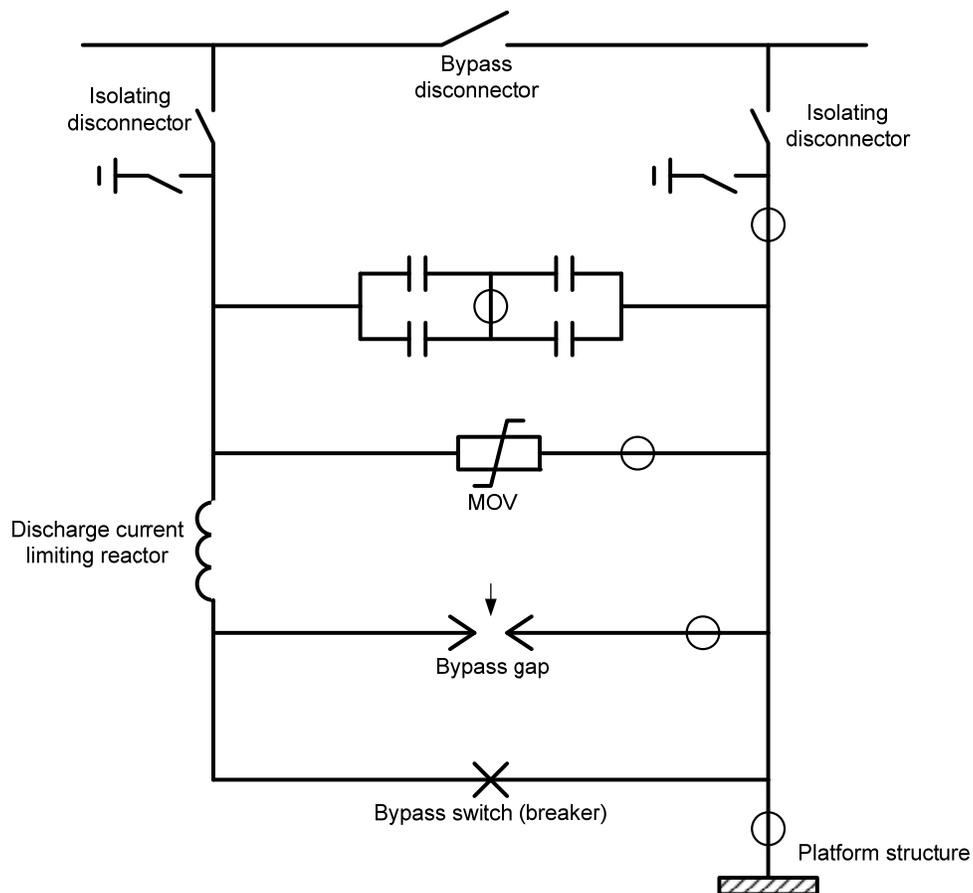


Figure 4.3-1: Series capacitor bank main components

During fault conditions, series capacitor units are generally subjected to overvoltages which are related to the fault current levels. When, like in the CREZ system, the series capacitors are at substations with limited transformations and long transmission lines, the highest fault currents – and therefore the highest overvoltages – are expected with three-phase faults. When a station has large transformers and shorter lines, it is possible for single-phase faults to result in higher fault currents. The fault current levels and the resulting overvoltages on the series capacitors need to be confirmed during the design stage.

Fault related overvoltages may persist until the fault is cleared by opening of the line circuit breakers to the faulted circuit element. Modern series capacitor banks use highly non-linear Metal Oxide Varistors (MOV) to limit the voltage across the series capacitor to a desired protective level, which typically ranges between 2.0 and 2.5 times the voltage across the capacitor at the rated bank current. When limiting the voltage across the series capacitor to the protective level during fault conditions, the MOV must conduct the excess fault current and thereby absorb energy. The MOV energy is kept within the MOV's absorption capability by bypassing the parallel capacitor/MOV combination using two devices. The first is a very fast acting device called a triggered spark gap. After the spark gap is triggered, a slower acting bypass breaker will close. From a system performance point of view, overvoltage protection bypasses the series capacitor, thereby increasing the impedance of the circuit. This may, in turn, adversely impact network stability. The effect is not significant for faults that occur on the line section in which the series capacitors are located (i.e. "internal" faults), because the line section containing the series capacitor bank is eventually removed from service to allow fault clearing.

For faults not on the same line as the series capacitor (i.e. external faults) the impact on system stability can be significant. Therefore, whichever type of overvoltage protection scheme is adopted, it is usually designed so that the capacitor bank is not bypassed during external faults. Protective bypassing is restricted by design to act only for the more severe internal faults exceeding the specified energy and fault current.

Series capacitor compensation includes a microprocessor based control and protection system and the inputs are the currents measured at several points on the capacitor platform.

The main system requirements for rating the series capacitor banks are:

- Rated capacitor reactive impedance (ohms)
- Continuous capacitor current requirements (amperes)
- 30 minute overload current requirements (amperes)
- Maximum swing current following system disturbances
- Maximum fault current for external faults
- Maximum fault current for internal faults

The rated reactive power and rated bank (series voltage) are determined based on the first two items. The MOV ratings are determined based on the fault currents.

As mentioned previously, the total series capacitor impedance for each compensated CREZ line was selected to be approximately 50% of the line impedance based on the analysis of multiple issues. For those lines with two segments, each segment was approximately 25% of the line impedance.

4.3.2 Line Voltage Profiles

The decision to limit the total compensation of the series compensated CREZ lines to 50% was based primarily on the profile of the voltages along the length of the lines. The TSPs' design criteria limit the voltage at any point on the line to 105% under normal conditions and 110% on contingencies for up to 30 minutes. In order to meet the voltage criteria, the series compensation had to be limited to 50% and placed in the middle of the lines except for the Clear Crossing-Willow Creek lines for which a similar action is recommended.

Although some initial study work considered higher compensation levels, which showed improved system performance, these higher levels of compensation were not able to meet the voltage limit criteria. However, higher levels of series compensation and/or locations at the end of lines could be accommodated if line designs allow for higher line voltages. Figure 4.3-2 below is an example of the line voltage profile for series capacitors at the end of the line and in the middle of a line for the same voltage and power transfers.

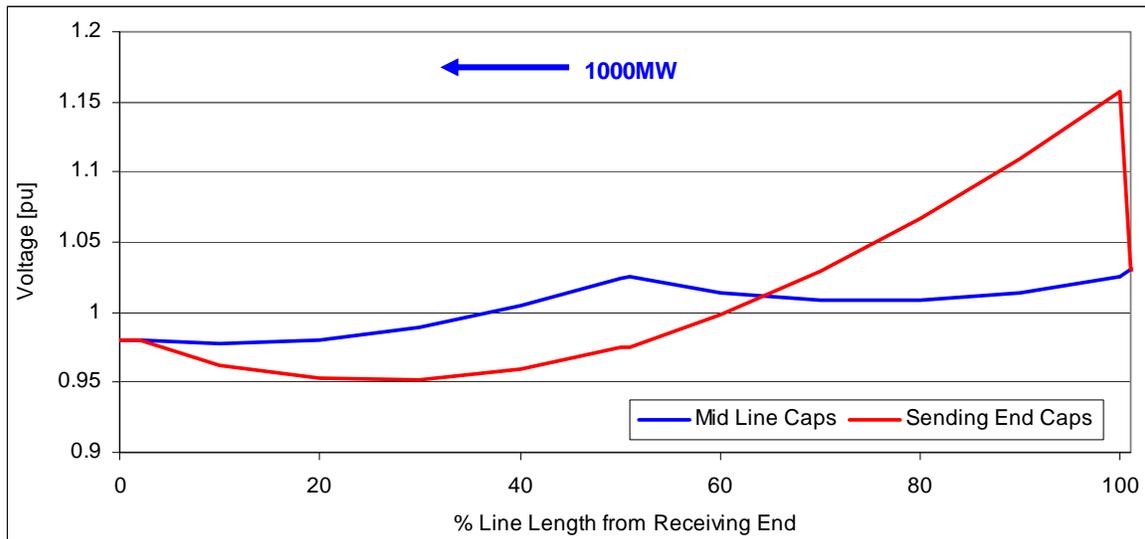


Figure 4.3-2 – Line voltage profile for series capacitors at the end and middle of a line

The line lengths – and by extension the line impedances – used for the study are, of necessity, preliminary since the routes of the lines have not been finalized. The changes in final line impedances will have some impact on the study results since the final routings may increase the length of the lines. There are several options to address the line length increases:

- Maintain a constant net line impedance to ensure the same performance as seen in the study. As the line length increases, this will require higher levels of compensation and line voltage profiles will need to be reviewed to ensure that the design criteria are met.

- Hold the series compensation to 50% of the line impedance and run additional studies to determine if more or larger SVCs are needed to provide acceptable system performance.
- Hold the series compensation to 50% of the line impedance and run additional studies to determine if series compensation is needed in other lines to provide acceptable system performance.

Shorter line lengths than those used in the study are not a concern since they will have lower impedances.

4.3.3 Maximum Continuous Current and 30 Minute Overload Ratings

The fundamental ratings for the continuous operating currents and the 30 minute overload currents were established using the results of the fundamental frequency study discussed in Section 3 – specifically the generator dispatches and system contingencies that maximize the current flows through the series capacitors. With a redispatch of 10% additional wind generation to maximize the line loading through the series capacitors, the worst case contingency under a worst case wind dispatch (determined from optimal powerflow analyses) established the maximum series capacitor currents.

Series capacitors are typically designed to have a 30 minute overload rating. This overload capability is generally used following contingencies where the system can be readjusted within the 30 minutes to reduce the loading. Since the maximum currents were determined as discussed above, the 30 minute rating could be established by these maximum currents. The continuous rating could be selected to meet normal system requirements. This would allow for a more economical design. However, the TSPs may want to have the continuous rating be established by the maximum currents in order to meet any unknown future requirements.

4.3.4 Maximum Swing Currents

Following a contingency on the system, particularly one that results in line outages, the power flows through the system will change as the network settles into a new operating condition, many times experiencing overshoots during the process. The currents associated with these dynamic swings are temporary, but may be higher than the steady-state maximum currents. Some dynamic analyses were performed to monitor the highest anticipated swing currents in the CREZ system. These have been reported to ERCOT and the TSPs for their consideration in rating the series capacitors.

4.3.5 Maximum Fault Currents

The maximum fault currents through the series capacitors are also an important consideration for the design of the capacitor protections. The location of the faults relative to the series compensated line must be considered. Those faults that occur on the line with the series capacitor segment being considered are known as “internal faults,” while those not on that line

are called “external faults.” The maximum fault currents determined from a protective case and also from the various power flow scenarios (e.g. Initial Build, Maximum Edison, etc.) were determined for both internal and external faults for all series capacitor segments. The results have been reported to ERCOT and the TSPs for their consideration in the series capacitor protection design.

4.4 Network Challenges with Series Compensation

Series capacitor compensation has been used successfully in many locations around the world, and is a relatively common feature in the transmission systems of the utilities in the west and southwest U.S. However, the resonances that occur between the series capacitor, the transmission system and electric machines have the potential to result in catastrophic failure of the machines. Because the series capacitors are always selected to compensate only a portion of the transmission line of which they are a part, these resonances will always occur at frequencies below the normal system frequency – in other words, at subsynchronous frequencies.

Regarding such subsynchronous resonances (SSR) with conventional thermal generators, the phenomena is well understood and the issues can generally be avoided by judicious design of the transmission system, by operation of the system around conditions leading to problems and/or by protection of the machines when undesirable resonant conditions are detected.

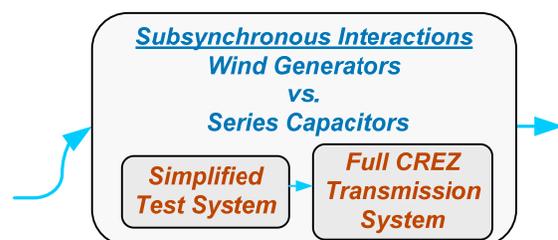
With regard to the resonances with wind generation, some events have been experienced and the industry is quickly gaining a fuller appreciation for and understanding of the phenomena involved. Papers are becoming more common to address aspects of the issues and to propose some methods of mitigation, but as of the date of this report, no solution has actually been implemented and fully tested in the field.

Nevertheless, because the CREZ transmission plan includes multiple series capacitors, ERCOT and the TSPs considered it prudent to include evaluations of the phenomena to estimate their potential for occurring on the CREZ system and to test (via simulation) various mitigation methods. The follow sections describe this work.

4.4.1 SSI with Wind Generation

While the potentially detrimental, series capacitor related phenomena evaluated in this study are associated with subsynchronous resonances, they do not always appear to be solely associated with the electrical resonance itself. In some cases, they appear to be exacerbated by the controls for the power electronic converters used on some types of wind turbine generators.

Because the causes may be more generic than just the subsynchronous resonance, the term



subsynchronous interaction (SSI) was selected for use in this report to discuss the phenomena affecting wind generation. Specifically, the following types of SSI are considered

- **Self-excitation** – a phenomenon that occurs because of the natural response (resonances) of the various system components to each other. It is typically stimulated by some system perturbation; and,
- **Control interactions** – phenomena that occur, in part, because of the response of active system devices such as the WTG controls.

The phenomena leading to different types of SSI can be complicated given the complexity of the controls used in some types of wind turbine generators. Because of this, the SSI issues with WTG were first evaluated with the wind farms connected to a simplified radial test system and then confirmed on the full interconnected CREZ system.

The simplified radial test system is illustrated in Figure 4.4-1. This topology is most susceptible to SSI and allowed a more rapid assessment of the issues. Tests were made representing each of the different types of wind turbines at the wind farm collector bus. They were started with the series capacitor bypass breaker closed and their susceptibility to SSI was tested by simply opening the bypass breakers. This was generally enough of a “disturbance” to trigger any interaction.

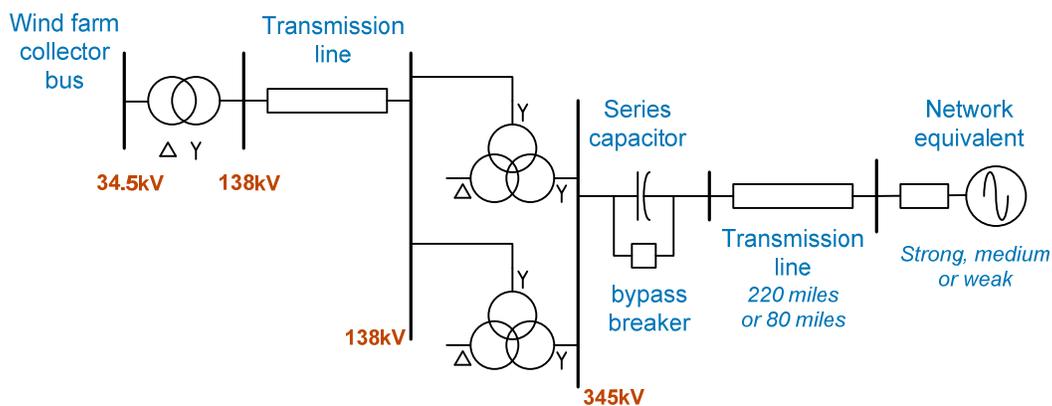


Figure 4.4-1: Simplified radial test system for SSI evaluations

The confirmation of the test system results on the full interconnected CREZ system, with wind farms at the locations currently projected by ERCOT, permitted an assessment of the likelihood for SSI at these locations.

WTG Types

Four basic types of wind turbine generators have been identified in the industry based on their configuration and operation. These four types are:

- **Type 1** is a fixed speed wind turbine connected to an induction generator that is, in turn, directly connected to the grid.

- **Type 2** is a variable speed wind turbine connected to a wound rotor induction generator which has a controlled variable external rotor resistance that is used to increase the operating speed range of the generator.
- **Type 3** is a doubly-fed induction generator (DFIG) which is also called by some authors a doubly-fed asynchronous generator (DFAG). It uses a variable-speed wind turbine connected to a wound rotor induction generator. A back-to-back converter is connected between the generator rotor and the stator in parallel to the machine. Because the full machine power does not flow through the converter, it can be rated for only a fraction of the WTG rating. It has a wider operating speed range than Type 1 and Type 2.
- **Type 4** is a variable-speed wind turbine with a generator (either asynchronous or synchronous generator) connected to the grid through a back-to-back converter. The power of the generator flows directly through the converter so it must be rated for full generator power. The converter acts to decouple the turbine and generator from many phenomena occurring on the grid.

Self-excitation with Type 1 and Type 2 Machines

Several models of Type 1 and Type 2 WTGs were provided by ERCOT for evaluation of SSI issues. Not unexpectedly, a phenomenon known as self-excitation was observed with these types of machines under certain conditions on the simplified radial test system. Self-excitation is a well understood phenomenon that is a direct consequence of the resonance between the series capacitor and the system and machine inductances on the system. Excellent papers (see references [2] and [3]) were written many years ago that are still pertinent for understanding the conditions conducive to self-excitation and that provide insight into how it can be mitigated. The potential for its occurrence with wind turbine generators was noted in reference [4].

Whether or not SSI was observed on the radial test system strongly depended upon the losses in the system and the parameters of the particular machine. Higher amounts of resistance in the system between the wind farm and the series capacitor (due to lower voltage transmission systems, for example) will decrease the likelihood of any undamped resonance conditions occurring.

At present, ERCOT anticipates that only about 15% of the new wind turbine generators to be added to the system will be Type 1 or Type 2. But it is generally recommended that the new plant owners perform a study to assess the potential for self-excitation of their machines if they will be connecting in the vicinity of any of the series compensated lines, or if a reasonable number of system line outages would place their plant nearly radially connected through a series capacitor.

SSI with Type 3 Machines

Out of the various types of wind turbine generators, Type 3 was found to be the most susceptible to SSI. This appears to be because of interactions with the controls and the subsynchronous series resonance.

Only two models were made available for assessment in this study and the susceptibility to SSI was found to differ between the models. The first, more susceptible model had a more detailed representation of the converter and its controls. This along with parameter differences may account for its greater susceptibility to SSI.

Because the Type 3 machines' high susceptibility, and because ERCOT currently anticipates that a significant portion of the new wind turbines installed in the CREZ may be of this type, they were carefully tested on a model of the full CREZ system. Representations were made of wind farms at the same locations that they were represented in the fundamental frequency analyses. These simulations showed particular inclination toward SSI at specific locations as listed in Table 4.4-1. This table also indicates the system conditions for which the SSI occurred and how each of the two Type 3 models responded.

Table 4.4-1: 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	<i>not tested</i>	Y
3	West Shackelford	743	N-2	Outage of double circuit line between Scurry and West Shackelford	<i>not tested</i>	Y
4	West Shackelford	743	N-2	Outage of double circuit line between West Shackelford and Romney	Y	<i>not tested</i>
5	West Shackelford	743	N-2	Outage of double circuit line between Clear Crossing and West Shackelford	Y	<i>not tested</i>
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.

Several potential mitigation methods, their effectiveness and their limitations are discussed below in Section 4.4.3.

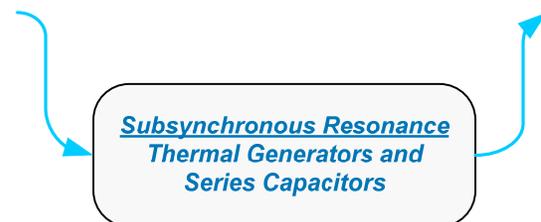
While the simulations performed for the study can be considered somewhat theoretical, there is actual experience that emphasizes the importance of the recommended studies. A utility on the ERCOT system reported an incident in which a wind farm consisting of Type 3 wind turbines was radially connected 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.

Type 4 Machines

In the evaluations made for this study, the Type 4 WTGs were not found to be affected by the presence of the series capacitors on the system. This is believed to be due to the decoupling that the full back-to-back converter provides. Although not observed here with the limited number of models available for assessment, it is theoretically possible that some control issues could occur. The evaluation into any such issues is left to when they manifest themselves.

4.4.2 SSR with Thermal Generation

Subsynchronous Resonance (SSR) is a well-known phenomenon in which a series resonance between a generator and a series compensated ac transmission circuit can destabilize one or more



torsional modes of oscillation on a generator shaft. Since the discovery in 1971 of the SSR problem on the Mohave generators of the Southern California Edison Co. there has been only one event where damage occurred because of the SSR problem with series compensation. Because of the partial – but high percentage – compensation (63%) of the 500kV line between the Mohave plant and the Lugo Substation, when a short line between the McCullough Substation and Mohave was opened, the system was tuned to a torsional mode involving the shaft between the generator and a directly-connected exciter. Other instances of SSR have also occurred at other locations, but damage to the generators involved has been avoided through proper mitigation or protection methods.

Because the proposed CREZ transmission includes many series capacitors, ERCOT has taken a prudent step and asked ABB to perform an SSR screening analysis to assess the potential of SSR between the CREZ transmission and several nearby thermal generating plants. These screening analyses have considered both the potential for SSR and for the induction generator effect (self-excitation involving only the electrical aspects of the system).

The SSR Phenomena

In order to understand the SSR phenomena as it relates to conventional thermal plants, consideration must be given to both the torsional modes of turbine-generators and the electrical resonance created by the series compensated line.

Generator Torsional Modes

As discussed in Section 3.7, a mechanical system with N masses will have $N-1$ oscillatory mechanical torsional modes. Consider again the generic turbine-generator system as illustrated in Figure 3.7-1 and repeated in Figure 4.4-2. In this case there are six masses – the high-pressure and intermediate pressure turbines, the two segments of the low-pressure turbine, the generator and the exciter. Any given system may have more or less masses on the shaft.

The frequency of each oscillatory mode and how well it is damped (decays away) will be dependent upon the relative sizes of the masses, the stiffness of the shaft and the magnitude of various losses in the mechanical system. Of these modes, those that occur at frequencies below the system frequency – in other words, at subsynchronous frequencies – are of particular concern.

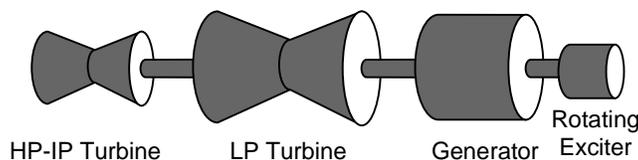


Figure 4.4-2: Generic Turbine-Generator System

The various masses on the shaft will have different degrees of participation in the different modes. The modes in which the generator itself has significant participation will be more

susceptible to SSR. For these modes, a disturbance of the electrical system, such as a fault, will cause a corresponding torsional disturbance on the generator which is translated to the shaft by the machine which will also disturb the mechanical system. This will cause the masses to oscillate against each other at their various natural frequencies, with some modes stimulated more than others.

The mechanical system always acts to damp out these oscillations over time (i.e. it is positively damped). The amount of mechanical damping is higher when the generators are fully loaded than when they are at minimum load.

Subsynchronous Resonance (SSR)

For the modes in which the generator participates, currents associated with the mechanical mode oscillations will be generated and injected into the electrical system. The electrical system will usually provide positive damping against these currents, but under proper conditions negative damping can result. If electrical system damping is negative but is not sufficient to completely overcome the damping of the mechanical system, then the oscillations will simply take more time to decay, which is not usually a concern. However, if the electrical system provides enough negative damping to overcome the positive mechanical damping, then the oscillations will grow and, if proper protection is not applied, can result in catastrophic damage to the turbine generator.

The conditions leading to negative electrical damping can be set up with series compensation system such as that in Figure 4.4-3. In this figure, the resistance of the elements and the details of the generator flux dynamics are ignored for simplicity.

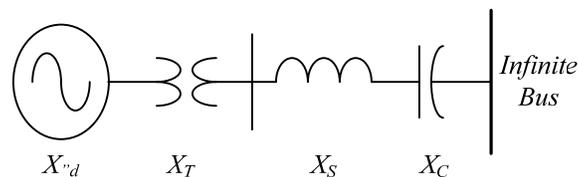


Figure 4.4-3: Example series compensated network

This electrical network consists of the inductive generator sub-transient reactance ($X'd$), the inductive transformer leakage reactance (X_T), the inductive line reactance (X_S) and the capacitive series compensation reactance (X_C). Therefore, the total inductive reactance is

$$X_L = X'd + X_T + X_S$$

A series resonance results with the combination of X_L and X_C at a frequency of

$$f_n = f_0 \sqrt{\frac{X_C}{X_L}}$$

where f_0 is the normal system frequency (60Hz)

Because series compensation is not designed to fully compensate the entire transmission line (not to mention any transformer or generator reactance) X_C will always be less than X_L and the resonant frequency will be below f_0 . If f_n is at or near the subsynchronous sideband frequency associated with the currents injected into the system due to the mechanical oscillations, then energy can readily transfer between the mechanical and electrical systems. From the rotor side of the machine these frequencies will result in apparent resistances in the machine that are negative and which can overcome the positive resistive losses of the electrical system. This will cause the electrical system to provide negative damping on the turbine-generator shaft. If this negative damping is large enough to overcome the mechanical damping, then the torsional mode becomes destabilized and oscillations at the modal frequency will be sustained indefinitely or grow.

Such SSR has historically been a problem primarily for large steam generators. A generator that is connected radially to a highly series-compensated transmission line can be at considerable risk for undamped subsynchronous oscillations. The risk also exists for generators in an interconnected network, although to a lesser degree for highly meshed systems.

Induction Generator Effect

The induction generator effect is also associated with the subsynchronous resonances of the machine with the network. However, it involves only the electrical network and not the mechanical system. At frequencies below the nominal system frequency, synchronous generators appear as induction machines, so the same phenomenon that results in self-excitation of induction generators discussed above can occur. However, this effect is usually called the Induction Generator Effect (IGE) when speaking about synchronous machines.

Fortunately, the same analysis used to screen for SSR, as discussed next, is ideal for evaluating induction generator effect.

SSR Screening Analyses

Analyses were conducted for selected thermal plants in the ERCOT system near the series compensated lines to screen for the likelihood of SSR. The six plants that were screened are:

- Comanche Peak nuclear plant
- Hays combined cycle plant
- Odessa-Ector combined cycle plant
- Oklaunion coal plant
- Tradinghouse coal plant
- Willow Creek combined cycle plant

Screening methods based on frequency scans of the network impedance from behind the generator under study can be made based on principles discussed in [5]. Care must be taken to

adequately represent the system components so that their influence is properly taken into account. In particular, the representation of the loads and generators, including that of multiple units, is essential. The frequency scan approach for SSR screening is limited to a one-machine-at-a-time approach. Therefore, when studying multiple units at a common high-side bus care is required in interpreting and handling the data.

In addition, the scans must be made under multiple system conditions. Under contingency conditions, the outages of lines may result in the generators being more directly coupled to the series capacitors increasing the potential for SSR. Outages can also cause the frequency of the resonance to shift, aligning it with a generator mechanical mode that was not previously at risk. A large number of outage conditions were considered for each studied plant to consider all conditions from normal operation with all lines out, to a direct radial connection between the studied generator and the nearby series capacitors.

A separate report for each plant has been provided to ERCOT. The reports will be provided by ERCOT to the individual plant owners. The data and results of these studies contain protected confidential information and may be considered Critical Energy Infrastructure Information. They will, therefore, not be made publicly available.

It was noted during the study that the frequency dependent nature of the impedance presented by the WTGs to the system is critical to the proper screening for SSR and proper calculation of induction generator effects at the thermal generators. The representation of Type 1 machines is straight forward. Type 2 can become somewhat more complicated but is expected to be similar to Type 1. Representations for Type 3 and Type 4 must be derived from models of WTG operation. 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.

4.4.3 Potential Mitigation Measures and Their Limitations

Because of the severity of potential SSI (including SSR) issues, three potential mitigation methods were evaluated:

- **Thyristor Controlled Series Capacitors (TCSC).** This is an active device that uses a thyristor controlled reactor in parallel to the series capacitor. The TCSC controls can regulate how the capacitor appears to the system. This allows the TCSC to be used for other purposes such as to help damp out large area power swings or make a given capacitor appear to have more capacitance at normal system frequencies (i.e. boost). With proper controls (see below) it is possible for the TCSC to appear as an inductor over most of the subsynchronous frequency range, thereby eliminating most concern for SSI issues with both wind and thermal generation

- **Series capacitor bypass filters.** This is a passive device placed in parallel to the series capacitor. It allows an alternate path to currents at frequencies other than those at the normal system frequency (60Hz). This changes how the series capacitor appears to the system at the subsynchronous frequencies.

Two philosophies can be used for selecting the parameters of these filters. The first (“damping-type”) focuses on damping undesirable currents so it increases the system resistance at subsynchronous frequencies. This can be tailored to focus on specific issues or frequencies.

The second philosophy (“preventive-type”) focuses on preventing undesirable currents by making the series capacitor appear inductive over much of the subsynchronous frequency range, eliminating most concern for SSI issues with both wind and thermal generation.

- **WTG control modifications.** This is limited to the Type 3 wind turbines. If any SSI issues were to be found with Type 4, this would also be an option.

The effectiveness of the first two solutions was evaluated for Type 3 WTGs in the full interconnected CREZ system for many of the system conditions that led to SSI as discussed in Section 4.4.1. The results are shown in Table 4.4-2

As can be seen by comparing Table 4.4-2 to Table 4.4-1, the preventive type bypass filter and the TCSC were effective in addressing the SSI issues for the Type 3 wind turbines evaluated in the study. The last condition (N-4 outage at Dermott) represented a very weak system and control issues became a problem during the simulation so the effectiveness is undetermined in this case. The TCSC or a preventive bypass filter with similar subsynchronous impedance characteristics was also found through the SSR screening studies to be effective in eliminating concerns for SSR when universally applied.

The damping type bypass filter was not found to be effective by itself. However, in combination with control modifications at the WTG it may be more effective. It is also noted that an exhaustive effort was not made to determine the optimal designs of the bypass filters. It may be possible that a design not evaluated would show greater effectiveness than that shown here.

Table 4.4-2: Conditions found to be conducive to SSI with Type 3 WTGs on CREZ system

#	Wind turbine generator location	System contingency conditions	Case description	Model 1 SSI with filter type 1*	Model 1 SSI with filter type 2**	Model 2 SSI with filter type 2**	Model 1 SSI with TCSC	Model 2 SSI with TCSC
1	West Shackelford	N-0	Normal system conditions	Y	N	not tested	N	not tested
2	West Shackelford	N-1	Outage of one circuit of the double circuit line between Scurry and West Shackelford	not tested	not tested	not tested	not tested	not tested
3	West Shackelford	N-2	Outage of double circuit line between Scurry and West Shackelford	not tested	N	N	N	N
4	West Shackelford	N-2	Outage of double circuit line between West Shackelford and Romney	Y	not tested	not tested	N	not tested
5	West Shackelford	N-2	Outage of double circuit line between Clear Crossing and West Shackelford	Y	not tested	not tested	N	not tested
6	Big Hill	N-1	Outage of circuit between Big Hill and Twin Buttes	Y	N	not tested	N	not tested
7	Big Hill	N-2	Outage of circuits between Big Hill and Twin Buttes and between Big Hill and Bakersfield	Y	N	N	N	N
8	Dermott	N-2	Outage of double-circuit line between Dermott and Scurry	Y	not tested	not tested	N	not tested
9	Dermott	N-4	Outage of double-circuit line between Dermott and Scurry and double-circuit line between Dermott and Cottonwood	Y	Weak system control issue	N	Weak system control issue	N

* - damping type filter ** - preventive type

The following sections provide brief discussions on the various technologies

TCSC

As illustrated in Figure 4.4-4, the TCSC consists of series capacitors in parallel with a thyristor controlled reactor that can boost the voltage across the series capacitors and make the combination appear as a larger capacitive impedance at fundamental frequency. For example, the fixed series capacitors may have an impedance of 20% of the line impedance and the thyristor controlled inductor can inject a current that will boost the voltage by a factor of three, allowing the TCSC to compensate 60% of the line reactance.

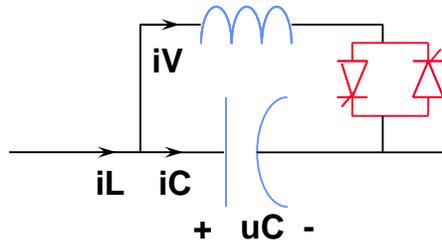


Figure 4.4-4: TCSC scheme

During TCSC operation, the line current remains almost purely sinusoidal with little distortion caused by thyristor switching. Near each of the zero crossings of the capacitor voltage the thyristors are fired to provide a current pulse that circulates through the TCSC capacitor and inductor causing an increase in the capacitor voltage during the current pulse. The boost provided to this voltage (i.e. boost factor) can be adjusted by regulating the timing of the thyristor switching. This boosted voltage with the given line currents presents an effective impedance to the system that is larger than the fundamental frequency impedance of the capacitor itself.

In the design considered here, the TCSC boost factor can typically be adjusted between 1.0 and 3.0. The magnitude of the line current is dependent on the total power flow (real and reactive) on the transmission line. The magnitude of the thyristor current is dependent on the boost level setting.

The TCSC modeled in this study uses a specially developed Synchronous Voltage Reversal (SVR) control to determine the firing of the thyristor valve. The SVR control strategy eliminates any series resonance in the subsynchronous range between the inductor/valve and the series capacitors. With the SVR, the effective impedance presented by the TCSC to the system is inductive over most of the subsynchronous frequency range, which naturally eliminates SSI by eliminating the subsynchronous resonances between the system and the series capacitor. Figure 4.4-5 shows the effective TCSC impedance. See reference [6] for a more complete description of how SVR results in this effective impedance characteristic.

The effective impedance of the TCSC as modeled in the study has an inductive impedance for frequencies below 42 Hz, meaning that the TCSC is inductive rather than capacitive over most of the subsynchronous frequency range, while it is capacitive at fundamental frequency. At frequencies lower than this 42 Hz cross-over frequency the TCSC is not capacitive and cannot create a series resonance. This characteristic can eliminate SSI and even has the ability to mitigate most concerns for subsynchronous resonance (SSR) with thermal generators. There are multiple installations of TCSCs operating successfully around the world. To date, however, none have been explicitly applied to address SSI with wind turbine generators. Note also, that there is a patent pending on the SVR control. It is not known what methods the various vendors may have available to provide similar performance.

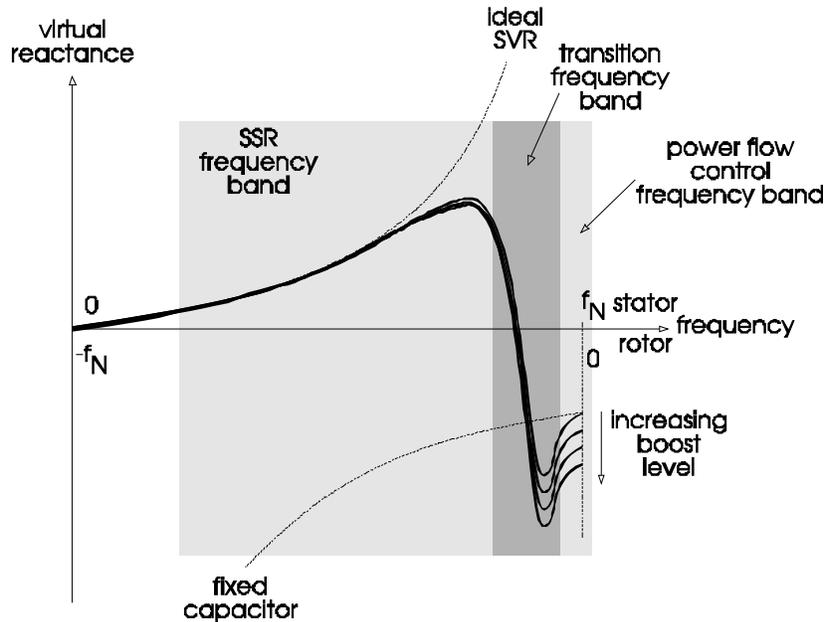


Figure 4.4-5: TCSC virtual impedance with the SVR control scheme

At fundamental frequency, the TCSC will provide an impedance equivalent to that of the conventional series capacitors. For the proposed design with a 1.2 boost, the actual impedance of the capacitors in the TCSC will only be 83.3% of the conventional series capacitors. The TCSC capacitors will need to be rated for the maximum line current plus the peak current from the thyristor circuit. Due to this current from the thyristor circuit, the TCSC capacitors will also have a higher voltage for which the capacitors will need to be designed.

Series Capacitor Bypass Filter

The basic topology for the bypass filter is shown in Figure 4.4-6. The filter consists of a capacitor/inductor (C_f and L_f) parallel combination with a series resistor (R_d) for damping. R_L is resistance of the inductor coil and C_{SC} is the series capacitor itself.

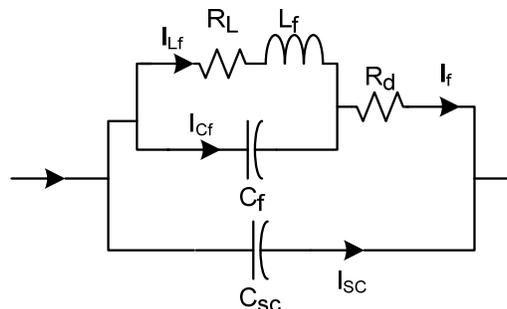


Figure 4.4-6: Series capacitor and bypass filter configuration

There are different design philosophies that can be pursued for a series capacitor bypass filter. The first is based on the classical solution to self-excitation – providing sufficient damping to prevent the phenomenon or to cause it to decay before it becomes critical to system

performance. This type of design can be considered as a “damping” filter. The second philosophy is based on providing the operational benefit seen in the TCSC – presenting an inductive characteristic for as much of the subsynchronous frequency range as possible. In this case, it is the characteristic of the total impedance of the bypass filter in parallel with the series capacitor that is of interest. The elimination of a capacitive characteristic at some subsynchronous frequencies removes the possibility of resonances at those frequencies. This type of design can be considered to be a “preventive” filter. The frequency at which the “preventive” filter design crosses over from inductive to capacitive can be determined by proper selection of the filter components. The lowest cross-over frequency that was found to prevent SSI on all of the contingencies evaluated is 41Hz. The resulting impedance characteristics of the series capacitor-bypass filter combination are similar to those of the TCSC.

With either philosophy, the filter’s inductor and capacitor are selected so that they form a tank circuit that prevents the flow of 60Hz system current through the filter branch. This forces the normal currents to flow through the series capacitor and is necessary to limit the filter losses to acceptable levels.

Wind Turbine Generator Control Modifications

As indicated, another option for addressing SSI with Type 3 wind turbine generators is to modify the controls of the converter. Such modifications would be considered proprietary by the turbine manufacturers and no models with modified controls were made available during the course of the study. Therefore, the effectiveness of the solutions – alone or in combination with damping bypass filters – could not be assessed. However, investigations are being made on many fronts, from academia to the turbine manufacturers, to develop methods for addressing this issue by means of control modifications. As of the date of this report, no solution is known to have been implemented and field tested, but indications are that the work that has been done is promising.

Limitations of the Various Mitigation Options

As with any technology, limitations to and concerns about the applicability of the mitigation methods described above have been noted.

- **TCSC** The benefit seen from the TCSC is largely contingent upon the impedance characteristics shown using the SVR controls. The controls modeled are proprietary and have a patent pending that may limit the number of potential suppliers. However, it is unknown what other vendors’ may have available to provide similar performance or to broadly address SSI and SSR.

Reliability concerns have also been raised concerning the use of an active device such as a TCSC. It is true that such active devices will have additional maintenance above that required for passive solutions, but arguments against use of power electronics are questionable. The power electronic switches used are the same as those used in HVDC converters, SVCs and medium voltage motor drives, each of which have many, if not

thousands (drives) of reliable installations around the world by multiple manufacturers that have been operating for many years – even decades. In fact, most major manufacturers who have the ability to supply TCSCs state that they have functioning installations around the world that are operating reliably.

There are only a couple of known instances for which a TCSC has been applied specifically to address subsynchronous issues. In one of these installations, the TCSC was used to address SSR with thermal generators by splitting the series capacitor so that part was fixed and part was TCSC. This adjusted the resonant frequency so that it was not a concern for any torsional mode on the machine. Since no installation exists to specifically address SSI with wind turbine generators, the beneficial characteristics of the device have been demonstrated only by engineering calculation and in simulation. Because of this, the confidence of potential owners of the technology is somewhat muted. Further, the potential owners would like to have a guarantee that the technology will eliminate SSI issues, but manufacturers are hesitant to accept the liability associated with such a guarantee given the novelty and limited understanding of the phenomena involved.

Prices for a TCSC have been reported to be around 1.8 times that of a conventional series capacitor of the same ratings – although one manufacturer reported a price of 4 to 5 times that of a conventional series capacitor.

- **Bypass filter** Like the TCSC, the bypass filter is covered by patents (albeit by a different equipment manufacturer) that may limit the number of suppliers available to the potential owners, who have been hesitant to accept a technology limited to a single supplier. It eliminates the opportunity for a competitive bid process and increases the risk of limited future support for the equipment.

While the bypass filter has the advantage of using passive elements, there are no known installations for SSI/SSR mitigation, so any evaluations to date are largely academic exercises. As indicated above, the evaluations performed for this study have shown the *preventive* bypass filter to provide adequate performance, but the equipment parameter calculations show that the filter capacitor is as large, or nearly so, as the series capacitor itself and very high circulating currents are needed, resulting in very large filter reactors that must have very low losses (i.e. high Q). The magnetic field clearances needed for the reactors may significantly increase the land area required.

For the *damping* bypass filter, the components can be much smaller and result in lower losses in the filter. However, as shown above, it may not be able to address SSI issues with WTGs by itself. If used for this purpose it would likely have to be coupled with another solution such as WTG control modifications, thereby dividing 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.

For either the preventive bypass filter or the damping bypass filters, some TSPs have indicated a strong preference for any supplier to guarantee performance in alleviating or mitigating SSI issues.

The cost for the bypass filters was available from only one manufacturer and only for a damping type filter. This manufacturer suggested that the price for a series capacitor with a damping bypass filter would be 1.5 to 2 times that of a conventional series capacitor.

- **WTG control modifications** As of the date of this report, there are no known installed and field tested Type 3 WTGs with control modifications that have been designed to address SSI. 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. Again, this would divide the solution between a system level solution and a local development level solution. Coordinating the different technologies and determining the proper allocation of mitigation responsibility may prove to be difficult.

Unless multiple manufacturers are able to address the issue, patent issues may present a similar problem to that indicated above for the TCSC and bypass filters.

It would not be unexpected for any manufacturer to have an additional charge on each WTG that has the SSI mitigation controls, but it is not possible to estimate what that additional cost may be.

At the time of writing, it appears that one manufacturer has successfully implemented control modifications that allow operation of their Type 3 turbines at the end of a radial, series compensated transmission line. It is not known how robust the solution will be for application at other sites. The solution may prove to be dependent upon the specific system parameters for this interconnection, but the results are quite encouraging.

The concerns expressed in regard to the potential patent issues noted for each of the technologies could be alleviated if the patent holders demonstrated a willingness to license the technology in a manner that would allow others to supply it at a competitive price. While rare, this is not an unknown practice that has had the benefit of opening up a very large market that benefited multiple vendors instead of limiting it to a much smaller niche market.

5 Conclusions

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 50% is required on six 345kV double-circuit transmission lines (12 circuits total). 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 recommended sizes and locations for switched shunt reactors have been identified. These reactors are required to keep bus voltage at acceptable levels under conditions with low power flow on the CREZ system. The reactors are needed at the time of the initial build of the system.

In addition, the recommended sizes and locations for switched shunt capacitors needed for voltage support during periods with large amounts of wind generation have been identified for both the initial build of the CREZ system and for the long term build out envisioned in the study assumptions. The levels required for the initial build are significantly less than those for the ultimate build out.

Finally, the size and locations for dynamic reactive compensation have been identified for both the initial CREZ build and the long term plan. Due to the higher levels of wind generation in the long term plan, the dynamic reactive requirements are significantly higher than for the initial build. 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 SVCs and STATCOMs.

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 (to preserve their reactive capability 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. It is possible for such interactions to lead to severe damage of the generators. The results indicate that it should be possible to design the controls of the dynamic shunt devices to eliminate any detrimental SSTI.

- **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 relates to wind farm and has been identified in the report as subsynchronous interactions (SSI). Type 1 and Type 2 wind turbine generators 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.

. Type 4 (full converter) machines have not shown any sensitivity to SSI in this study.

The locations in the CREZ system to which wind turbine generators are most likely to be affected by SSI have been identified.

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 on 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 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, the 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 if they 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.

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.

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Appendix A – Dynamic Shunt Compensation Technologies

A.1 – SVC Technology

A Static Var Compensator (SVC) is a regulated source of leading or lagging reactive power. By varying its reactive power output in response to the demand of an automatic voltage regulator, an SVC can maintain virtually constant voltage for dynamic events at the point in the network to which it is connected. During steady-state it can also reset itself to minimum output. An SVC is comprised of standard inductive and capacitive branches that are controlled by thyristor valves and connected in shunt to the transmission network via a step-up transformer. Thyristor control gives the SVC the characteristic of a variable shunt susceptance. Unlike mechanically switched compensation, an SVC can operate repeatedly and is not encumbered by the delays associated with mechanical switching. This lets the SVC respond very rapidly to changing network conditions such as line or generator outage contingencies.

An SVC can have an inductive and a capacitive capability. The algebraic difference between these two capabilities is called the dynamic range. There are three main building blocks available to make-up the required SVC capability. These are the thyristor-switched capacitor (TSC), the thyristor-controlled reactor (TCR) and the harmonic filter (HF). The TSC is a synchronized on-off device. The TCR reactive power absorption is continuously variable from zero to its rated value due to phase control of its conduction interval which controls the fundamental frequency component of reactor current. If a TCR is used, harmonic filters are usually required to limit voltage distortion in the network to acceptable values. The HF is capacitive at the fundamental frequency and contributes to the net capacitive output of the SVC. The HF is normally not switched but fixed to the SVC bus and is therefore often referred to as a fixed capacitor (FC).

There are three basic SVC configurations as shown in Figure A.1-1. The first consists of a thyristor-switched reactor (TSR) and a thyristor-switched capacitor (TSC). Since no reactor phase control is used no filters are needed. The second consists of a TCR and TSC (TCR/TSC) which may also include a fixed filter capacitor. The third consists of a TCR and a fixed filter capacitor (TCR/FC). In transmission applications the SVC is coupled to the network through a step-up transformer and the first two configurations are the most common for transmission requirements. The required reactive power is measured on the high side of the transformer.

Some manufacturers design SVCs with significant redundancy built in. The control system is completely redundant and one control system can be taken out of service for maintenance without interrupting the operation of the SVC. The thyristor valves have extra thyristors in series to provide redundancy. There is an extensive monitoring system as part of the SVC. For example, if a thyristor fails its location is noted and logged so that it can be replaced during the next schedule maintenance. The cooling system is a closed system with redundancy built in

including redundant pumps. Due to this redundancy maintenance can be performed on the cooling system without interrupting the operation of the SVC.

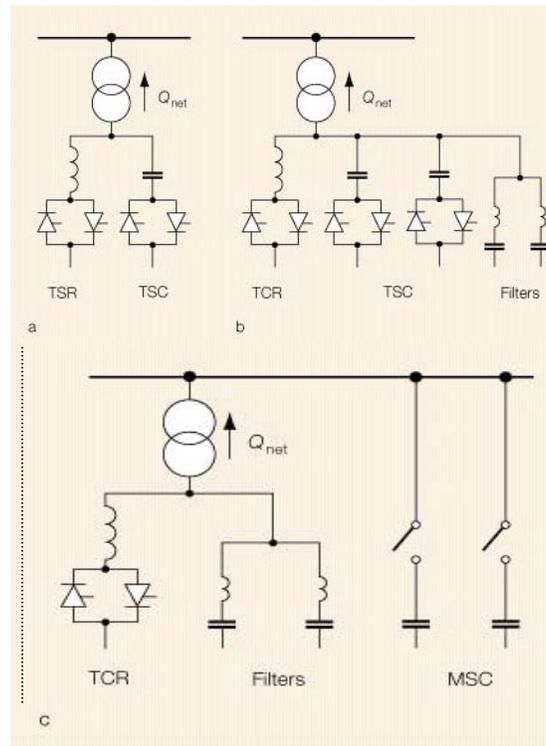


Figure A.1-1: Common SVC configurations

Variations of the above basic configurations can be made to optimize the SVC system design. This is especially true for the higher rated SVC applications where it is common to have multiple TSC branches with overall continuous control achieved with a TCR. Factors influencing the design include continuous and dynamic ratings, loss evaluation, redundancy requirements, harmonic generation, audible noise, environmental conditions and area constraints. The transformer and some SVC branches need not be rated continuously. If the maximum output of the SVC is only required dynamically during system swings for instance, some SVC branches and the transformer can be rated on a short-term basis. If reliability and redundancy are extremely critical, the SVC can be split in two halves with each connected to a separate transformer secondary winding, one wye and the other delta. To extend the overall capacitive range or restore the SVC output to within its dynamic regulating range or continuous rating following systems contingencies, a mechanically switched capacitor bank can be installed on the high voltage bus. Such a configuration is called a static var system (SVS).

The range of SVC operation is shown by its static voltage – current (V-I) characteristic illustrated in the following figure.

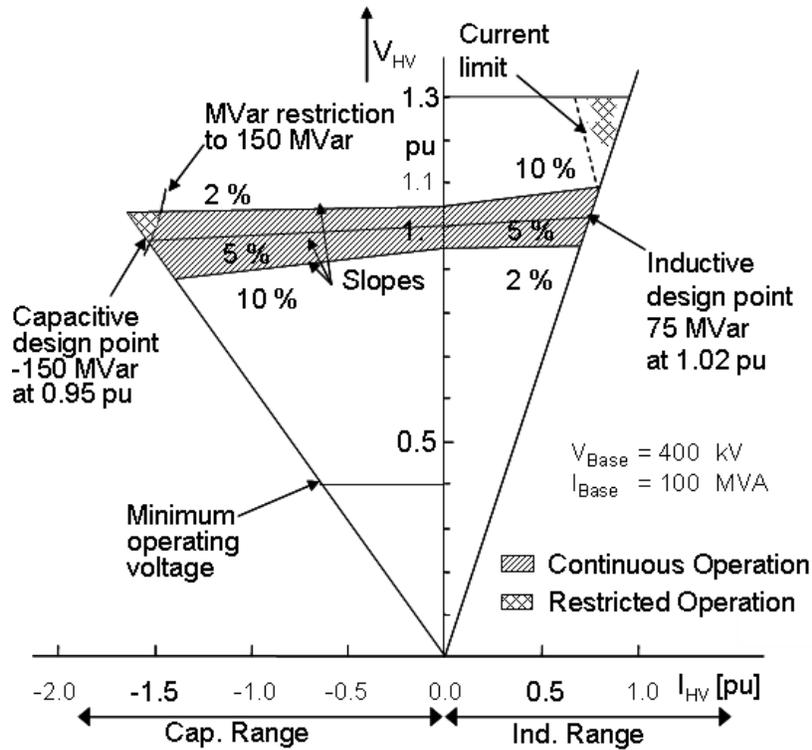


Figure A.1-2: SVC static V-I characteristic viewed from the transformer HV side

The normal continuous operating area for an example SVC is defined by the shaded area in the above figure. This normal operating area is bounded by the inductive and capacitive susceptance limits and the minimum and maximum slopes of the voltage regulator characteristic. Operation is allowed on a restricted basis on the capacitive side above a MVar limit and on the inductive side above the maximum continuous voltage where the TCR current is limited with increasing system voltage. An SVC can respond dynamically in 20 to 60 milliseconds.

An example of large SVC systems is described in “Preventing voltage collapse by large SVCs at power system faults” by Ahmed H. Al-Mubarak, Saleh M. Bamsak, Bjorn Thorvaldsson, Mikael Halonen and Rolf Grünbaum (IEEE paper # 978-1-4244-3811-2/09). This paper includes a single-line diagram for one of three +600/-60MVar systems and also discusses some control issues encountered on the relatively weak system to which they were connected.

A.2 – STATCOM Technology

The Static Synchronous Compensator (STATCOM) is comprised of a voltage source converter (VSC) connected in shunt as illustrated in Figure A.2-1. The shunt-connected VSC is based on converter technology with valves comprised of solid-state switching components with turn-off capability and anti-parallel diodes. Performance of the STATCOM is analogous to that of a synchronous machine generating a balanced three-phase set of sinusoidal voltages at the

fundamental frequency with controllable amplitude and phase angle. The device, however, has no inertia and does not contribute to the short circuit capacity.

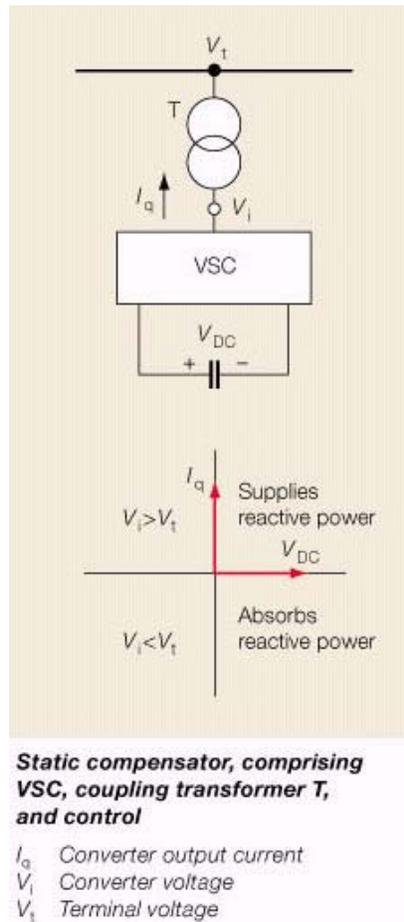


Figure A.2-1: Basic STATCOM configuration

The STATCOM consists of a voltage source converter operating as an inverter with a capacitor as the DC energy source. It is controlled to regulate the voltage in much the same way as an SVC. A coupling transformer is used to connect to the transmission voltage level. In this application only the voltage magnitude is controlled, not the phase angle (except for the small angle deviations necessary to keep the capacitor charged within acceptable limits). By controlling the converter output voltage relative to the system voltage, the reactive power magnitude and direction can be regulated. If the VSC AC output voltage is lower than the system voltage, reactive power is absorbed. If the VSC AC output voltage is higher than the system voltage, reactive power is produced.

In its simplest form, and subject to device switching frequency restrictions, the VSC is operated in what is commonly referred to as square wave operation where the switching of each valve only occurs once per cycle. Operating in this fashion generates a staircase approximation of a sine wave. If multiple VSCs are used and fed by different shifted sets of phase voltages via

special transformer connections, the pulse number can be reduced and the resulting “staircase” waveforms more closely approximate a fundamental frequency sine wave, thereby reducing the need for filtering.

The following figure illustrates waveform generation from a three-level VSC employing pulse width modulation (PWM) control. The VSC is coupled to the AC bus through series air-core reactors. Low pass filters tuned to the switching frequency may need to be connected on the line side of these reactors. Together they form a low-pass filter such that only the fundamental frequency voltages appear on the line side of the reactors. If the AC voltage becomes too low and the output of the VSC hits its current limit the maximum reactive power varies with the voltage rather than voltage squared as with an SVC. With PWM it is possible to vary the modulation index and add an additional degree of boost up to some maximum value.

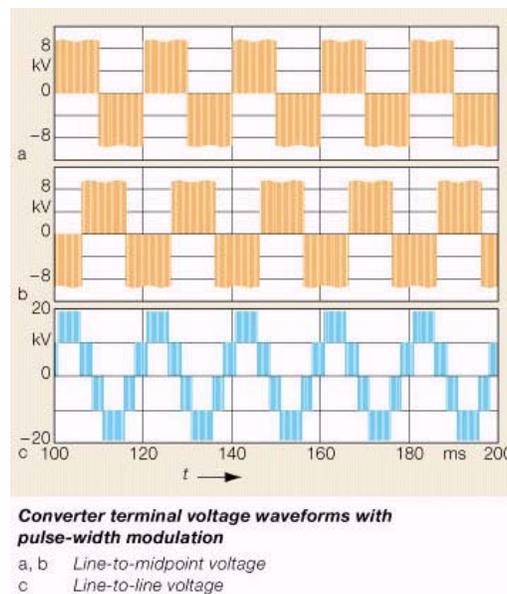


Figure A.2-2: Pulse Width Modulation of STATCOM

In a transmission network a STATCOM has much the same function as an SVC:

- Steady state and dynamic voltage support and regulation
- Improved voltage stability
- Improved synchronous stability and transfer capability

A STATCOM can respond in 4 - 5 milliseconds so for power quality applications such as an arc furnace application, the STATCOM (especially one with PWM) offers:

- Improved dynamic load balancing
- Improved flicker control
- Faster response for load compensation

The VSC converter used for reactive power control is able to generate or absorb reactive power continuously from 0 up to its full MVA rating. Thus the dynamic range of the device is twice its MVA rating. Some high pass filtering is needed to handle the switching harmonics. The filtering results in the net output being biased in the capacitive direction. If the need for dynamic reactive power is more capacitive than inductive, additional shunt capacitance can be employed to bias the net output still further.

One other interesting application of the STATCOMs was suggested by these CREZ studies; namely, increasing the apparent strength of the system as “seen” by slower acting controlled devices. As mentioned above, the STATCOM cannot, strictly speaking, increase short-circuit levels. However, one that is designed to take advantage of its superior capability to maximize the speed with which voltage is controlled (i.e. above those typically needed for SVC-type applications) could effectively appear as a constant voltage source (stronger system or higher short-circuit level) by the slower-acting controls. As discussed in Section 3.3.2, high-frequency oscillations involving WTG controls were observed in these CREZ studies under conditions with extremely low short-circuit levels. If more in-depth studies confirmed the potential for such oscillations, then the feasibility of designing a STATCOM for the specific purpose of improving the performance of the WTGs and the system under such low short-circuit levels should also be investigated. In addition to improving the stability of the other controls on the system, such a STATCOM could potentially provide performance superior to that of a synchronous condenser in the following areas:

- Lower capital and maintenance costs
- Increased (large signal) response capability
- No exposure to electromechanical instability

The STATCOM has the same type of redundancy as described for the SVC.

A.3 – Synchronous Condenser Technology

Under conditions with low short-circuit levels some of the wind turbine models (provided by the wind developers to ERCOT) demonstrated poor performance. When consulted, the WTG manufacturers indicated that when such behavior is observed, detailed studies for the individual wind farms are usually recommended. For this reactive compensation study, an increased short-circuit level was required to allow the models to be used for some cases. For study purposes, this increased short-circuit capability was assumed to be provided by synchronous condensers, although this is not necessarily the technology that will be installed in the substations.

Generators provide the power used by the electrical system and they also provide a major part of the voltage control. A synchronous condenser is similar to a generator except without a

turbine system that can provide real power. It can provide reactive power and control voltage similar to a generator.

Synchronous condensers have an exciter and automatic voltage regulator that control the supply or absorption of reactive power from the condenser within the limits of the unit. Even when utilizing high-gain and high-ceiling excitation systems, the overall response of synchronous condensers to network disturbances is limited by the inertia of the generator flux dynamics, making it slower than an SVC or STATCOM, which are only encumbered by the speed of electronic switches and controls. The stability simulations described in the body of this study report indicate that the synchronous condensers do not respond fast enough to prevent the voltage from collapsing in the Max Export Case, but that they are useful in increasing the short circuit level in the Panhandle area of the CREZ system.