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PJM Interconnection Artificial Island (AI) Project Analysis & Risk Assessment

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Analysis & Risk Assessment

Prepared for

PJM Interconnection, L.L.C
2750 Monroe Blvd.
Valley Forge Corporate Center
Audubon, PA 19403

Prepared by

Exponent
Abdel-Aty Edris
149 Commonwealth Drive
Menlo Park, CA 94025

Date April 8, 2015

Doc. no. 1409231.000

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Acronyms and Abbreviations

AI	Artificial Island
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Capacitor
SSR	SubSynchronous Resonance
RTDS	Real Time Digital Simulator
C	Capacitance of the TCSC
L	Inductance of the thyristor controlled reactor of the TCSC
X_{tcsc}	Equivalent reactance of TCSC as function of the firing angle
X_c	Series capacitor reactance
X_l	Reactance of the reactor in parallel with the series capacitor
K	sqrt (X_c/X_l)
α	Firing angle
f_0	Synchronous frequency
f_n	Resonance frequency, Eigen frequency
$\boldsymbol{\alpha_{res}}$	Firing angle at which the TCSC is at parallel resonance state

Limitations

At the request of PJM Interconnection, Exponent conducted a review of a performed SubSynchronous Resonance (SSR) study and cost estimates of the proposed Static Var Compensator (SVC) and the two TCSCs to be implemented on the two 500 kV transmission lines connecting the Artificial Island (AI) nuclear unites.

The opinions and comments formulated during this review are based on information available at the time of the review.

The review results presented herein are made to a reasonable degree understanding and engineering certainty of the given information. If new information becomes available or there are perceived omissions or misstatements in this report regarding any aspect of those conditions, Exponent asks that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

Executive Summary

PJM Interconnection is in the process of organizing the final efforts that will be required with regard to selecting a solution related to the stability issues at their Artificial Island nuclear facility. One of the proposed solutions involves implementation of Thyristor Controlled Series Capacitor (TCSC) technology.

The report is providing the results of conducted analysis and risk assessment of a performed SSR study and the proposed TCSCs.

The following are the main conclusions of the conducted analyses and risk assessments.

- The performed SSR Study should, only, be considered a preliminary study and **is far from being considered conclusive** and as a final study quantifying the potential risk of SSR on the nuclear power plants.
- Detailed Spring-Mass models of the turbine-generator shaft system of the nuclear power plants should be considered when assessing the actual potential risk of SSR, particularly the torsional interactions.
- The proposed TCSCs were given without specific values of their respective L and C parameters. The designed L and C values determine the curvature of how the equivalent capacitive reactance X_{tcsc} is changing as function of the firing angle **α.** Furthermore, the L and C values determine the proximity of firing angle **α** at steady state with respect to $\boldsymbol{\alpha_{res}}$ and how the firing angle **α** becomes even closer to $\boldsymbol{\alpha_{res}}$ at the post-contingency where the compensation degree will be ramped up to 90% of the respective TCSCs. It is, therefore, very important to declare the designed parameters of the respective TCSC to make sure that there will be enough marginal distance such that the operating firing angle **α** will not drift to $\boldsymbol{\alpha_{res}}$ region at which the TCSC will be acting as a circuit breaker opening the compensated transmission line.
- A study to determine how the TCSCs at different compensation degree levels, would affect the voltage profile of the compensated line should be conducted. The objective of such a study is to quantify operational voltage problems of compensated transmission lines.
- To achieve a confident solution, conduct a hierarchical control analysis aiming at coordinating the control of the proposed SVC and the two TCSCs to maximize the system benefits of these controllable devices and to ensure there will not be any adverse control interaction among these devices and other controllable device in the system.
- Use of Real Time Digital Simulator (RTDS), where the transmission system is represented by the Network Equivalent reported in Siemens PTI SSR study, and more detailed modeling of the turbine-generator shaft system, and a detailed model of the SVC and the two TCSCs would certainly provide simulation results very close to what would be the field performance. Furthermore, RTDS could be used to study any control interaction of concern with other controlled devices, e.g. SVC. Moreover, RTDS is a powerful tool which is normally used to fine tune control and protection systems parameters. The exact control system designed for the TCSCs and SVC could be

simulated. At that time the effectiveness and robustness of the TCSCs control system and interactions with the neighboring controlled equipment would be validated.

- The cost estimates under Dominion Virginia Power 1A Project, as preliminary estimates, look reasonable. However, depending on the technical specifications which will be included in the Request for Bid for the actual installations of the SVC and the two TCSCs, the cost could be different from that estimates.
- It is recommended to revisit the justification of choosing the type of series capacitive compensations on the two transmission lines connected to the nuclear power plants to be 100% Thyristor Controlled Series Capacitor (TCSCs). It might be more economical to split the needed compensations into X% fixed series capacitor and Y% TCSC, where X+Y = 100% and Y could be chosen to be 10%-20%, depending on the dynamic control requirements of the transmission system.

1. Introduction

PJM Interconnection is in the process of organizing the final efforts that will be required with regard to selecting a transmission solution related to the stability issues at their Artificial Island nuclear facility. One of the proposed solutions involves implementation of Thyristor Controlled Series Capacitor (TCSC) technologies. PJM Interconnection has expressed interest in having Exponent assist PJM Interconnection in reviewing the results of a previously performed SubSynchronous Resonance (SSR) assessment in connection with the proposed implementation of TCSCs on the two 500 kV transmission lines connected to the Artificial Island (AI) nuclear facility. PJM also asked Exponent to discuss the potential next steps to validate the effectiveness and risk of the proposed TCSCs solution.

Additionally, PJM Interconnection is interested in reviewing the cost estimates of the proposed Static Var Compensator (SVC) and the two TCSCs.

Figure 1 is one-line diagram showing the existing transmission grid and the proposed additions, which include new facilities, 500 kV Static Var Compensator and two Thyristor Controlled Series Capacitor on the two 500 kV transmission lines connecting the nuclear power plants.

[redacted]

Figure 1 One-line diagram for the proposed SVC and the two TCSCs

2. Scope of Report

PJM Interconnection is interested mainly in reviewing a performed SSR study which is a main concern when considering series capacitive compensation of a transmission line connected to a nuclear power plant. The following are the main issues, related to the proposed implementation of TCSC, which Exponent has been asked to review:

- An analysis and risk assessment of the performed initial SSR assessment
    - An analysis and assessment of the modeling, data used, and overall study results and feedback related to their accuracy and relevance
    - An assessment of the credibility of the study and any relevant supporting documentation
    - Identification of any threats or gaps that would require further assessment
- An analysis and risk assessment of the proposed TCSC solution proposed under the Dominion 1A Project related to the stability issues
- Cost estimates of the proposed SVC and the two TCSCs
- Evaluation of the feasibility and development of damping controller to mitigate SubSynchronous Resonance (SSR) for TCSCs, Dominion proposal

Scope change

- **Feasibility and development of damping controller to mitigate Sub Synchronous Resonance (SSR) for TCSCs**

- **Design parameters of the TCSCs and their impact on the dynamic performance**

3. Analysis and risk assessment of the performed initial SSR assessment and the proposed TCSC solution

Dominion Virginia Power has proposed to PJM Interconnection implementation of two TCSCs, on two of the 500 kV transmission lines connected to the three nuclear power plants, in addition to an SVC to be installed at a new proposed substation. Siemens PTI conducted an SSR screening study to assess the potential of TCSC in creating SSR condition on the turbine-generator shafts of AI nuclear power plants.

Siemens PTI submitted its report to PJM Interconnection on January 16, 2015. The report was entitled "***SubSynchronous Resonance Screening Study for the PJM Regional Transmission Expansion Plan"***

3.1 Analysis and assessment of the modeling, data used, and overall study results of the SSR study

- The Study should be considered a preliminary study and **it is far from being considered conclusive** and a final study quantifying the potential risk of SSR on the nuclear power plants due to the following reasons.
- The Study results are based on a number of assumptions due to:

- Lack of the specific design detail of the proposed TCSCs
- Lack of the parameters of a Spring-Mass model of the turbine-generator shaft models of the nuclear power plants
- As a result of the lack of Spring-Mass models, the Study has modeled the turbine-generator shaft as two-mass model having a selected natural frequency equal to one of the given torsional modes of the respective nuclear plants.
- The simulation studies were, therefore, repeated considering the given torsional modes, one at a time, this does not reflect the actual responses considering a full Spring-Mass model of the complete turbine-generator shaft system
- The Study approach doesn't account for the engagement of the turbine-generator shaft masses in the respective torsional modes, mode shape characteristics, i.e., Eigen vector calculation for each Eigen frequency (torsional mode).
- That approach were used for Salem Unit 1, Salem Unit 2, and Hope Creek Unit
- The Study has not considered any mechanical damping, mutual damping between masses and self damping of respective masses. The mechanical damping is usually very small and is normally neglected in such type of Study.

- The Study adopted a sound approach for the development of network equivalent based on load flow matching, short circuit power strength, and frequency response. However, that developed equivalent model should be considered "*static equivalent*" not a "*dynamic equivalent*" since it did not consider the generator dynamics.

3.2 Analysis and risk assessment of the proposed TCSC solution proposed under the Dominion 1A Project

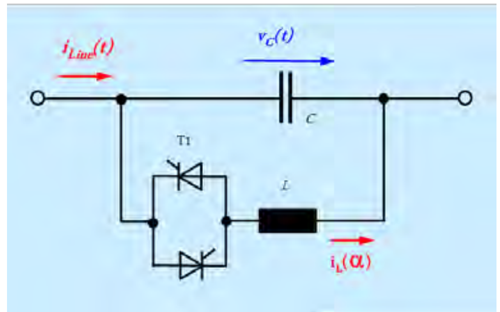

Figure 2 TCSC Scheme

The equivalent capacitive reactance X_{tcsc}, at the fundamental frequency, as function of the firing angle α, the reactance of the capacitor C, X_c , and the reactance of the inductance L, X_l, is given by the following expression:

$$X_{tcsc} = X_c - \frac{2\cdot(\pi-\alpha)+\sin 2(\pi-\alpha)}{\pi}\cdot\left[X_c + \frac{X_c\cdot X_l}{X_c - X_l}\right] + \frac{\left(\frac{X_c\cdot X_l}{X_c-X_l}\right)^2 4\cos^2(\pi-\alpha)}{X_l}\cdot\frac{\sqrt{\frac{X_c}{X_l}}\cdot\tan\left(\sqrt{\frac{X_c}{X_l}}\,\pi - \sqrt{\frac{X_c}{X_l}}\,\alpha\right) - \tan(\pi-\alpha)}{\pi}$$

The ratio of X_{tcsc}/X_c is, therefore expressed as follows:

$$\frac{X_{tcsc}}{X_C} = 1 - \left(\frac{k^2}{k^2-1}\right) * \left(\frac{2\beta + \sin(2\beta)}{\pi}\right) + \frac{4}{\pi} * (\cos^2(\beta)) * \left(\frac{k}{k-1}\right)^2 * (k\tan(k\beta) - \tan(\beta))$$

Where $k = sqrt(X_c/X_l)$

$\beta = \pi - \alpha$

Where α is controlled in the region: $\pi/2 \leq \alpha \leq \pi$ and the ratio of X_c/X_l will determine the firing angle α_{res} corresponding to the parallel resonance condition, at which the equivalent value of X_{tcsc} equal to infinity,

Figure 3 shows a typical characteristic of X_{tcsc} as function of the firing angle **α**

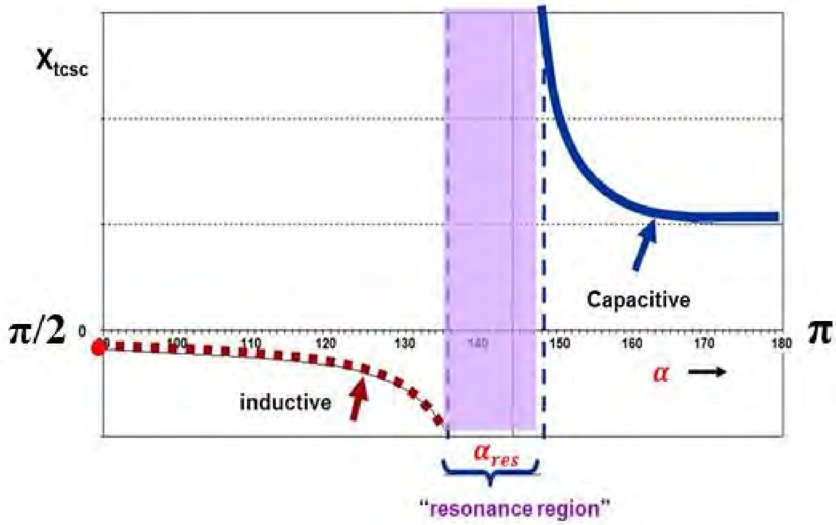

Figure 3 Equivalent $\mathbf{X_{tcsc}}$ reactance, as function of the firing angle $\boldsymbol{\alpha}$

The solution under the Dominion 1A Project is proposing installation of one 750/-375 Mvar Static Var Compensator (SVC) plus two Thyristor Controlled Series Capacitors (TCSCs) on the two 500 kV transmission lines connected to the nuclear power plants. The ratings of the SVC and the two TCSCs are determined based on stability studies conducted by Dominion. The TCSCs determined ratings are as follows:

1. Hope Creek –New Freedom ([redacted], 500 kV transmission line)
   At steady state the compensation degree 40%, TCSC rating = 283.5 Mvar
   Post contingency the compensation will increase to 90%

2. Salem–New Freedom ([redacted], 500 kV transmission line)
   Steady state compensation degree 45%, TCSC rating = 364.5 Mvar
   Post contingency the compensation will increase to 90%

Analysis and risk assessment of the proposed TCSCs

- Dominion did not provide any design detail of the TCSCs in terms of the size of the C and L in the TCSC scheme shown in figure 2. The designed sizes of the C and L determine the curvature of how the equivalent capacitive reactance X_{tcsc} is changing as function of the firing angle $\boldsymbol{\alpha}$**.** Furthermore, the proximity of the operating, steady state. firing angle $\boldsymbol{\alpha}$ with respect to $\boldsymbol{\alpha_{res}}$ and how close the firing angle at post-contingency, where the compensation degree will be ramped up to 90% compensation, to $\boldsymbol{\alpha_{res}}$. It is, therefore, very important to appropriately design the C and L parameters of the respective TCSC to make sure that there will be enough marginal distance such that the operating firing angle $\boldsymbol{\alpha}$ will not drift to $\boldsymbol{\alpha_{res}}$ region at which the TCSC will be acting as a circuit breaker, open circuiting the compensated transmission line.

Since X_c is determined by the steady state compensation degree at $\boldsymbol{\alpha}$ equal to $\boldsymbol{\pi}$ the choice of X_l will determine the shape, curvature, of the X_{tcsc} characteristic as function of the firing angle $\boldsymbol{\alpha}$ and the permissible range of variation of $\boldsymbol{\alpha}$ before reaching $\boldsymbol{\alpha_{res}}$. In other words, the value of *sqrt* (X_c/X_l), in the above X_{tcsc} expression, is a very critical parameter in designing the TCSC since it affects the operating characteristic of the equivalent compensation degree as function of the firing angle $\boldsymbol{\alpha}$ and the proximity of the operating point to the parallel resonance point. For a practically functioning TCSC, the *sqrt* (X_c/X_l) must be greater than one and lower than a critical value. If the *sqrt* (X_c/X_l) is less than one, X_{tcsc} will only have the capacitive part of the characteristic on the whole range of $\boldsymbol{\alpha}$**,** i.e., $\boldsymbol{\pi/2 \le \alpha \le \pi}$. On the other hand if the *sqrt* (X_c/X_l) is larger than a critical value the X_{tcsc} characteristic shown in figure 3 will have more than one resonance points, which means a serious limitation of the operating function of the TCSC. Therefore, the value of X_l should be optimally designed to obtain the desired characteristic of X_{tcsc} , in terms of curvature, proximity of the operating point to the resonance point, and the practical operating region of the firing angle $\boldsymbol{\alpha}$ between $\boldsymbol{\pi}$ and $\boldsymbol{\alpha_{res}}$.

For illustration, Figure 4 shows the characteristic of X_{tcsc}/X_c as function of the firing angle α at different values of $k = sqrt(X_c/X_l)$

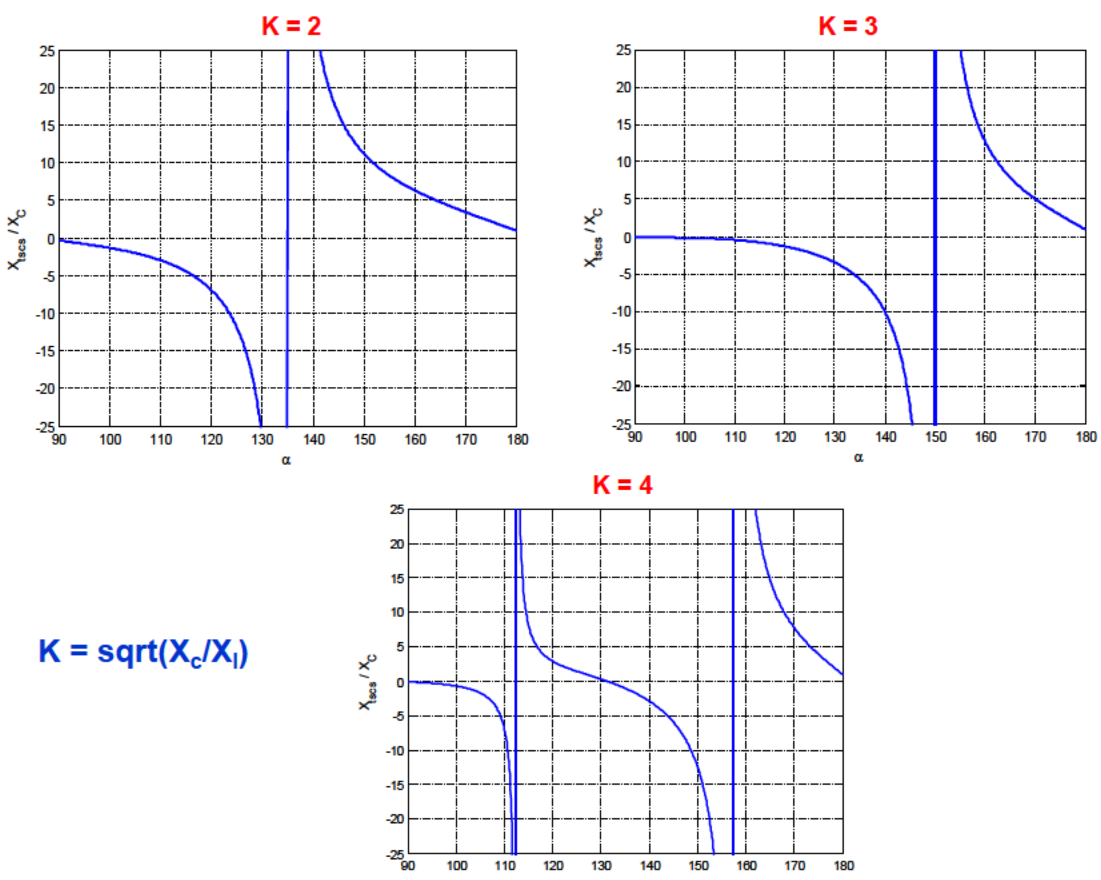

Figure 4 X_{tcsc}/X_c characteristics as function of the firing angle α at different K values

- Other missing information, from the Dominion proposal, is how the two TCSCs will be controlled, will they be current controlled or impedance controlled. While, in general, the TCSC, inherently, does not participate in or contribute to SSR, operating TCSC under constant impedance control may contribute to SSR. Therefore, there is a need to run SSR studies to show a comparison for the TCSC performance under current control and under impedance control modes. Furthermore, no control scheme has been developed to coordinate the control of the two TCSCs and the SVC. Coordination of these three controlling devices, SVC and the two TCSCs, would result in additional operation benefits and assuring no adverse control interactions among them.

- Impact of TCSCs compensation degrees, particularly at higher degrees of compensation, on operational voltage profile.
  A high degree of series capacitive compensation can cause voltage operational problems; it can lead to either low voltage or high voltages depending on the loading conditions of the compensated lines. This is based on the fact that a series capacitive compensation generates capacitive reactive power as function of the square of the line loading current. This is a topic that, to my knowledge, was not addressed under the proposed Dominion 1A Project. This topic is, particularly, important at higher capacitive compensation degrees. Therefore, a study should be conducted to quantify the operational voltage variation at different compensation degrees and different loading condition. The objectives of the studies should be to find out the effects of capacitive series compensation on operational voltages and whether it will lead to any operational problems or not and, therefore, whether there will be a need to shunt reactors on the compensated line or not. This is, probably, the reason why the proposed SVC has 375 Mvar inductive capabilities. Dominion, in their proposal, did not provide a technical justification for the inductive part of the proposed SVC.
  A practical upper limit of the degree of series capacitive compensation is, normally, 70%-80% to have an operational marginal distance from exposing the system to a resonance condition at the power frequency. With 100% series compensation degree the effective reactance of the compensated line will be equal to zero, so that a smallest disturbance in the power angle of the connected generator would result in a flow of very large currents. Furthermore, the compensated transmission line with 100% would also be at series resonance at the power frequency (60 Hz) and it would, therefore, be difficult to control transient voltages and currents during disturbances.

4. Gaps needed to be bridged for better assessment of the SSR potential and TCSC performance

As indicated in section 3, there are a number of gaps in the performed SSR Study. The following section identifies the gaps that need to be considered to ensure more credible assessment of SSR potential risks.

1. More accurate **Spring-Mass model** representation of turbine-generator shaft system of the nuclear power plants, Salem1 Unit, Salem 2 Unit and Hope Creek Unit.

   The manufacturers of those nuclear units should be consulted to provide the parameters shown in the figure below based on design values of the respective turbine-generator shaft systems.

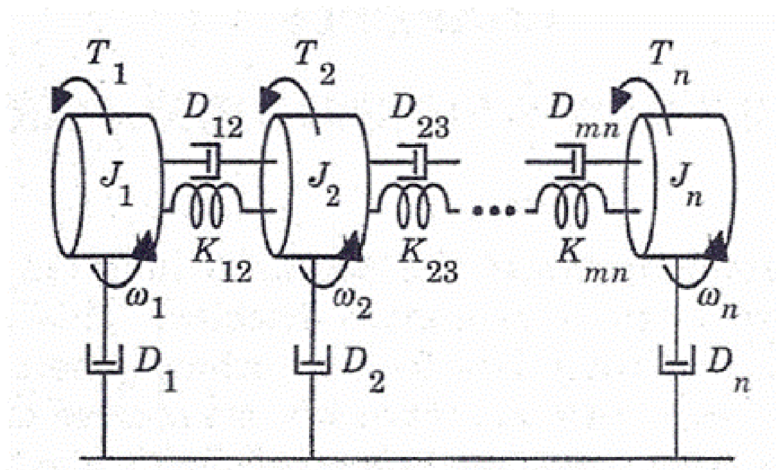

Figure 5 Spring-Mass model for n-mass turbine-generator shaft system

K_{mn} Spring constant (stiffness constant) of the coupling between mass m and n

D_{mn} Damping coefficient between mass m and n

D_n Damping coefficient of mass n

2. **Design detail of the TCSCs**, the capacitance C, the inductance L, and, therefore, the firing angle α corresponding to the required compensation degree, as indicated in the figure 2. This will result in determining the shape of the $\mathbf{X_{tcsc}}$ characteristic shown in figure 4 and firing angle $\boldsymbol{\alpha_{res}}$ that should not be allowed to avoid the parallel resonance condition of the TCSC.

3. Conducting a study determining how the TCSCs, at different compensation degree levels, affect the voltage profile of the compensated line and, therefore, avoid operational problems.

4. Conduct control coordination studies aiming at maximizing the benefits of the functional features of the SVC and the two TCSCs and eliminating adverse control interactions among them.

5. **Real Time Digital Simulator (RTDS).** It would be more accurate to rely on RTDS in running simulated tests on developed setup simulation cases based on the network equivalent reported in Siemens PTI studies and more detailed modeling of, the turbine-generator shaft system, Spring-Mass model of the respective nuclear plants, and the proposed design parameters and control of the respective TCSC. RTDS will provide simulation results very close to what would be the field performance of the TCSCs and their interaction with the turbine-generator shaft system of the nuclear power plants. Furthermore, RTDS could be used to study any control interaction of concern with other controlled devices, e.g. SVC. Moreover, RTDS is a powerful tool which is normally used to fine tune control and protection systems parameters. Furthermore, a setup test on RTDS would provide an excellent access to test the reliability performance and interaction of future planned transmission system upgrade, load growth, generation retiring, control interaction among controlled devices, etc.

6. It is recommended to revisit the justification of choosing the type of series capacitive compensations on the two transmission lines connected to the nuclear power plants to be 100% Thyristor Controlled Series Capacitor (TCSCs). It might be more practical and economically attractive to split the needed compensations into X% fixed series capacitor and Y% TCSC, where X+Y = 100% and Y could be chosen to be 10%-20%, depending on the dynamic control requirements of the transmission system.

5. Cost Estimates of the SVC and the Two TCSCs

Under Dominion Virginia Power 1A Project the following are the proposed ratings and the corresponding cost estimates:

- **SVC rated -375/+750 Mvar at 500 kV Cost estimate $46.6 M**
- **Two TCSCs rated at 500 kV, 284/365 Mvar Cost estimate $35.8 M**

SVC cost estimate

Based on my knowledge and expertise, working at ABB in Sweden and the US, in the area of reactive power compensation, SVC cost estimate, on the average, is in the neighborhood of $40-$60/ KVA depending on the structure and functional specifications. The proposed SVC is rated -375/+750 Mvar, total 1125 Mvar and its cost estimate is $46 M which means about $52/KVA, **i.e., the proposed cost estimate is reasonable**.

TCSC cost estimate

Again based on my knowledge and expertise in this area, cost estimate, on the average, is neighborhood of $50-$60/KVA, depending on technical and functional specifications of the TCSC. The proposed TCSCs are rated (284 Mvar+365 Mvar = 649 Mvar) and their cost estimate is $35.8 M, which means about $55/KVA, **i.e., the proposed cost estimate is reasonable.**

The cost estimates under Dominion Virginia Power 1A Project, as preliminary estimates, look reasonable. However, depending on the technical specifications which will be included in the Request for Bid for the actual installations of the SVC and the two TCSCs, the cost could be different from that estimates.

6. Dominion's Proposed Subsynchronous Damper Investigation

Dominion has submitted to PJM a proposal entitled "Feasibility and Development of Damping Controller to Mitigate Subsynchronous Resonance (SSR) for TCSCs". The proposal has five tasks and the total estimated effort is 26 man-weeks.

Evaluation of the proposal

Task 1

- The proposal has "correctly" addressed the need of a detailed Spring-Mass models of the turbine generator shaft system of the three nuclear power plants. This was one of the points which have been mentioned in section 3.1, Analysis and assessment of the modeling, data used, and the overall study results of the SSR study.
- The availability of credible Spring-Mass models and verifying a computed Eigen-Values, Eigen frequencies, against the given mechanical oscillation modes of the turbine-generator shaft system of the nuclear power plants, is an assurance for a more credible assessment of SSR potential.

Task 2

- This task is not clearly written and need to be revised in order to be evaluated.

Task 3 & 4

- The main objectives of those two tasks should have been modeling of the network, modeling of turbine-generator shaft systems in spring-mass format, modeling TCSCs based on their respective design data, and to run SSR time simulation studies considering transmission contingencies. In case the studies are showing SSR problem Task 4 should be devoted to develop an effective countermeasure mitigating SSR. The SubSynchronous Damping Controller (SSDC) stated in Task 4 could be considered countermeasures among other countermeasures to be studied to mitigate potential SSR problem.

Task 5

- The objective of this task is to test the designed SSR countermeasures, SSDC or other ones. The proposed testing platforms are Matlab/Simulink and PSCAD. As indicated in section 4; "Gaps needed to be bridged" RTDS "Real Time Digital Simulator" would be a more credible platform to assess the designed SSDC and fine tune the control parameters.

In conclusion, the submitted Dominion proposal is important to conduct to concretely map the actual SSR potential and to determine the right design parameters of the TCSCs and, therefore, to develop a SubSynchronous Resonance countermeasure if it turns out to be needed. The proposed man-week needs to be more, realistically, estimated.

7. Conclusions

PJM Interconnection is in the process of organizing the final efforts that will be required with regard to selecting a transmission solution related to the stability issues at their Artificial Island nuclear facility. One of the proposed solutions involves implementation of Thyristor Controlled Series Capacitor (TCSC) technologies.

The report is providing the results of conducted analysis and risk assessment of a performed SSR study and the proposed TCSCs.

The following are the main conclusions of the conducted analyses and risk assessments.

- The performed SSR Study should, only, be considered a preliminary study and **is far from being considered conclusive** and as a final study quantifying the potential risk of SSR on the nuclear power plants.
- Detailed Spring-Mass models of the turbine-generator shaft system of the nuclear power plants must be considered when assessing the actual potential risk of SSR, particularly torsional interactions, as explained in the Appendix.
- The proposed TCSCs were given without specific values of their respective L and C parameters. The designed L and C values determine the curvature of how the equivalent capacitive reactance X_{tcsc} is changing as function of the firing angle **α.** Furthermore, the L and C values determine the proximity of firing angle **α** at steady state with respect to **α_{res}** and how the firing angle **α** becomes even closer to **α_{res}** at the post-contingency where the compensation degree will be ramped up to 90% of the respective TCSCs. It is, therefore, very important to declare the designed parameters of the respective TCSC to make sure that there will be enough marginal distance such that the operating firing angle **α** will not drift to **α_{res}** region at which the TCSC will be acting as a circuit breaker opening the compensated transmission line.
- There is a need to conduct a study to determine how the TCSCs, at different compensation degree levels, would affect the voltage profile of the compensated line and, therefore, avoid operational problems
- It would be very beneficial to conduct hierarchical control analysis aiming at coordinating the control of the proposed SVC and the two TCSCs to maximize the system benefits of these controllable devices and to ensure there will not be any adverse control interaction among these devices and other controllable device in the system.
- Use of Real Time Digital Simulator (RTDS), where the transmission system is represented by the Network Equivalent reported in Siemens PTI SSR study, and more detailed modeling of the turbine-generator shaft system, and a detailed model of the SVC and the two TCSCs would certainly provide simulation results very close to what would be the field performance. Furthermore, RTDS could be used to study any control interaction of concern with other controlled devices, e.g. SVC. Moreover, RTDS is a powerful tool which is normally used to fine tune control and protection systems parameters.

- The cost estimates under Dominion Virginia Power 1A Project, as preliminary estimates, look reasonable. However, depending on the technical specifications which will be included in the Request for Bid for the actual installations of the SVC and the two TCSCs, the cost could be different from that estimates.
- It is recommended to revisit the justification of choosing the type of series capacitive compensations on the two transmission lines connected to the nuclear power plants to be 100% Thyristor Controlled Series Capacitor (TCSCs). It might be more economical to split the needed compensations into X% fixed series capacitor and Y% TCSC, where X+Y = 100% and Y could be chosen to be 10%-20%, depending on the dynamic control requirements of the transmission system.

Appendix A

SubSynchronous Resonance (SSR) Phenomenon

SubSynchronous Resonance (SSR) is the build-up of electrical and mechanical vibrations in power system as a result of interactions and energy interchanges between a turbine-generator shaft set and the rest of the power system which may lead to significant shaft damages Power plants close to the series compensation may be prone to several SubSynchronous interactions, hence the risk analysis studies should be conducted to assess SSR potential.

Types of SSR

An uncompensated transmission system will have positive electrical damping in the subsynchronous frequency range. Adding series capacitor compensation in a power system with synchronous frequency f_0 can cause negative electrical damping at electrical resonance frequency f_n. When the complementary frequency $f_0 - f_n$ matches a resonance frequency of the mechanical system of one turbo-generator in the system, torsional interaction occurs. Torsional interaction with the negative damping effect becomes unstable and excessive if the inherent mechanical damping is lower than the negative damping effect. This phenomenon is called subsynchronous Resonance and it should be examined under the following different categories:

1) Induction Generator Effect: Induction generator effect causes self-excitation of a series capacitive compensated electrical system alone. Since the rotor windings are rotating faster than the rotating magnetic field produced by the subsynchronous armature currents, the rotor resistance to subsynchronous currents viewed from the armature terminals is negative. If the generator negative resistance exceeds the external system resistance, regenerated energy is not absorbed by the system and the currents of this particular frequency are self-excited. Such self-excitation would be expected to result in excessive voltages and currents.

2) Torsional Interaction: Torsional interaction is a form of self-excitation due to the interaction between the turbine-generator shaft system and a series compensated electrical network. Any small disturbances in a power system cause simultaneous excitation of all natural modes of the electrical and mechanical systems. When a torsional oscillation occurs to the turbines and generator rotating system at a subsynchronous frequency f_n, while the generator field winding itself on the rotor is rotating at an average speed corresponding to the system frequency f_0, there will be voltages and currents induced in the generator armature three-phase winding at frequencies f_0-f_n. Should the induced current of the subsynchronous frequency f_0 -f_n coincide or be very close to an electric resonance frequency $f_e = f_0 - f_n$ of the generator and transmission system, the torsional oscillation and the electrical resonance will be mutually excited or reinforced resulting in sustained or growing oscillations. In such a case, the electrical resonance acts as negative damping to the electrical resonance.

3) Torque Amplification: Following a significant system disturbance in a series compensated system; the resulting electromagnetic torque oscillates at a frequency $f_0 – f_e$. If this frequency is close to any natural frequency of the turbine-generator shaft system, the resulting shaft torques could be much larger than those produced by a three phase fault in an uncompensated system due to the resonance between the electrical and mechanical system.

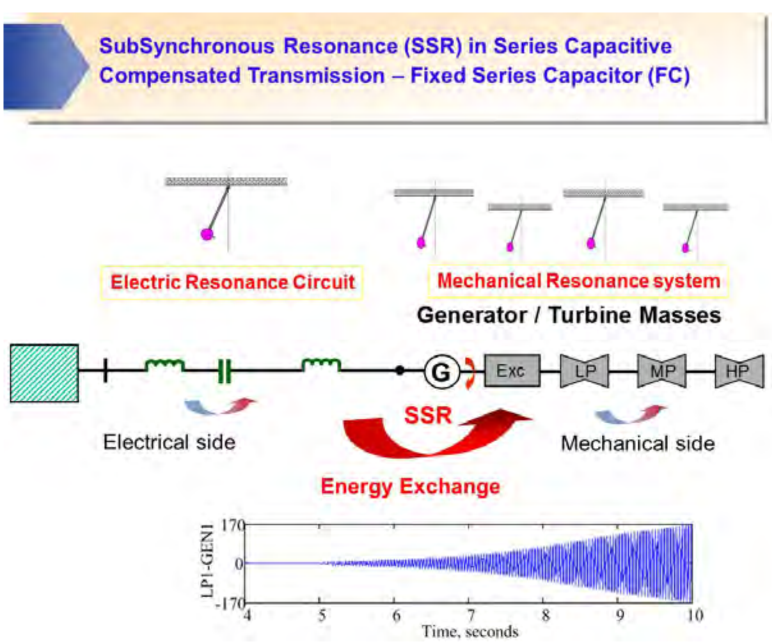

Figure A-1 SubSynchronous Resonance (SSR) in series capacitive Compensated transmission line- fixed capacitor