Building Wind Farms Next to Series Capacitor Banks: Lessons Learned

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***Abstract*—Due to the recent sub-synchronous oscillations (SSO) events, most independent system operators (ISO) require a study that demonstrates immunity of wind projects with respect to SSO prior to energization. For this study, we consider a wind project sited in proximity of a series compensated transmission line, where it becomes radially connected to it under certain N-1 contingency conditions. Using a frequency scan screening and a detailed electromagnetic transient (EMT) study we show that the project is immune to SSO. However, the EMT results show that clearing a fault on the transmission line that leads to a radial connection of the wind project to the series compensated transmission line causes the project to trip offline due to voltage and reactive power issues stemming from the proximity of the project to the series capacitor bank but not due to SSO. We conclude that the impact of proximity of series capacitors and wind projects needs to be investigated beyond SSO for reliable operation of the grid.**

***Index Terms*—Sub-synchronous oscillations, Electromagnetic transients, frequency response, wind farms, series capacitors**

I. INTRODUCTION

Increased penetration of renewable energy resources into the grid has resulted in higher demand for special system studies to assess their impact on various aspects of the power system. One of these studies is sub-synchronous oscillations (SSO) study.

SSO has become a concern to Independent System Operators (ISO) and Transmission System Operators (TSO) since the two incidents of shaft damage experienced at the Mohave generating station [1]. The subject has received renewed attention due to the incident that occurred in Texas in 2009 [2] which revealed that wind turbines can be also be affected by SSO.

As a results of these incidents, most ISOs have grid codes that mandate completion of a study indicating immunity of the project to SSO before commercial operation of wind projects. In this paper, we present one such study and demonstrate the effectiveness of it. Moreover, we establish the advantages of more detailed Electromagnetic Transient (EMT) study and demonstrate that further steps are needed to establish secure and reliable operation of the project due to the other challenges posed by proximity of wind projects (WP) to series capacitors.

This paper is organized as follows: the system model is descried in section §II. The frequency scan study is provided in section §III. The detailed EMT study is presented in section §IV. The trip of the project after clearing the fault on the line connecting it to the series capacitor banks is investigated in section §V. Conclusions are summarized at the end of the paper.

II. SYSTEM MODEL

The system model is shown in figure 1. The WP is connected at bus A. The latest system model available from the ISO was employed for this analysis. The authors developed an equivalent model representation of the ISO system model to include the series compensation devices as well as surrounding buses such that the frequency scan performed at the point of interconnection (POI) has negligible changes when adding a more detailed model of the transmission network. This model is developed by converting the PSS®E load flow case into a PSCAD™ dynamic model. The area of interest to be analyzed as part of the SSO study is shown in figure 1. It should be noted that the buses in figure 1 are only a fraction of the buses included in the PSCAD™ model.

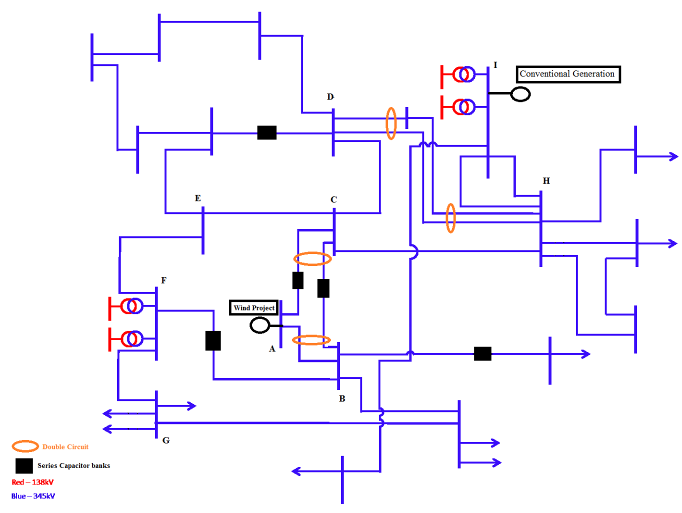

Fig. 1. Area under study

Prior to translating the ISO system model into PSCAD™, the WP was added to the PSS®E load flow case in order to complete the network model. The WP was added to the

PSS®E case as an equivalent generator with an active and reactive power capability according to the project specifications. The PSS®E model was prepared for translation by running a load flow study including the WP to control the voltage at the POI. The authors then selected the buses shown in figure 1 within the PSS®E power flow case for direct inclusion in the PSCAD™ case. Afterwards, a frequency scan was performed in the PSCAD™ case at the POI of the project. The authors then added new buses from all directions around the WP until the frequency scan did not change in an appreciable manner from one scan to another as a result of the addition of the new buses. After selecting the buses that will be retained in the PSCAD™ case, the remainder of ISO system model was modeled as equivalent voltage sources behind impedances such that the power flow is preserved in the PSCAD™ case as in the PSS®E case. It should be noted that no generators other than WP were modeled in detail for this study; any generator translated into PSCAD™ was modeled as an ideal voltage source behind an impedance.

We modeled all of the series capacitor banks in figure 1 with a protection model provided by the TSO. The model has been set up according with the settings provided by TSO. It should be noted that all the series capacitor banks shown in figure 1 are a fixed impedance per the information provided by the TSO. It should be noted that the series capacitors have a compensation of more than 100% of the line length in all cases.

A detailed model of WP was developed in PSCAD™. The detailed model contains all project equipment up to the high side of the project main power transformer. Moreover, this model includes the ability to control feeder circuit breakers, shunt reactive devices, and the adjustable control to mitigate SSO. The transmission tie line was added to the output of the detailed model to complete the WP. The WP is assumed to operate under normal configuration with all feeder breakers, shunt reactive devices and the SSO mitigation enabled.

Surge arresters were added at the POI of the project at bus A. It should be noted that all series capacitors in the ISO case are installed at the midpoint of the respective transmission lines.

Finally, the WP detailed model was inserted into the PSCAD™ equivalent model based on the ISO provided model at bus A, replacing the equivalent representation of the project. The wind turbine model is capable of capturing synthetic inertia introduced to the rotor in case SSO is detected.

III. Frequency Scan Screening Study

A frequency scan screening study has been performed according to [3]. The feedback effect of the grid on the turbine impedance as given in [4] has not been taken into consideration to produce conservative results. The grid frequency scan is described in section III-A while the project side frequency scan is provided in section III-B. The combined grid and project frequency scan is presented in section III-C.

A. Grid Side Frequency Scan

A grid side frequency scan was performed to determine the contingencies, if any, up to N-5 that result in the WP to become near radial or radially connected to the series compensated transmission lines in figure 1. A frequency scan of the transmission system was performed for WP at the proposed POI at bus A. The frequency scan was used to calculate the equivalent resistance and reactance looking into the transmission network at the project's POI for different contingency conditions, up to N-5, that may show vulnerability to SSO due to becoming radially connected to series compensation capacitors.

Additionally, for each of these contingencies, various combinations of sensitivities were evaluated. These sensitivities pertain to whether the turbine SSO mitigation control is ON or OFF, whether the switched shunts provided in table I are switched ON or OFF and whether the series capacitor banks in figure 1 are ON or OFF.

TABLE I
Switched Shunts Sensitivities

Location	Type	# of steps and MVAr size	Configuration
Bus D	Reactor	4-50	ON/OFF
Bus D	Capacitor	2-130.9	ON/OFF
Bus C	Reactor	4-50	ON/OFF
Bus C	Capacitor	2-130.9	ON/OFF
Bus B	Reactor	6-50	ON/OFF
Bus G	Capacitor	2-80	ON/OFF
Bus H	Reactor	3-50	ON/OFF
Bus E	Reactor	3-50	ON/OFF
Bus E	Capacitor	2-50	ON/OFF

The sensitivity analysis with regards to the switched shunts provided in table I has revealed that the status of those switched shunts has minimal effect on the grid side frequency scan. During the sensitivity analysis with regards to the switched shunts, we elected to switch all shunts ON or OFF at once to observe the effect on the grid side frequency scans in order to determine a worst case scenario. Switching all shunts ON or OFF at once does not cause appreciable difference in the grid frequency scan for all contingencies considered. Thus, for all subsequent analysis, the switched shunts given in table I has been either turned ON or OFF completely for the purpose of studying other sensitivities.

It is important to note that for each contingency case considered, the power flow case was convergent and solved for high and low wind conditions. The grid side frequency scan in the base case with no contingencies is given in figure 2. Note that the grid frequency scan is the same for both the cases when all switched shunts are OFF or ON. The grid side frequency scan for all contingency cases are shown in figure 3. It is to be noted that the grid has relatively small impedance even under the base case with no contingencies

The results of the system side frequency scan indicate that the reactance of the system can become negative for all

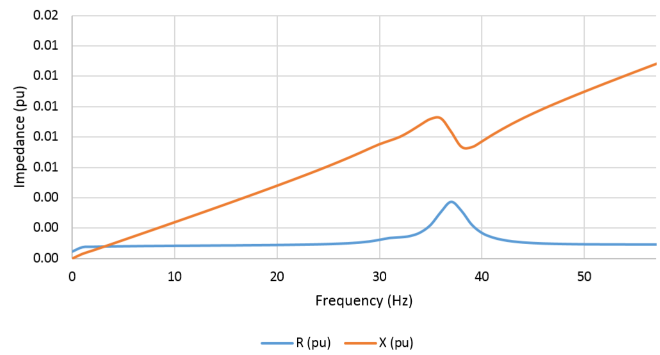

Fig. 2. Grid side frequency scan with no contingencies (Impedance is in per unit of system base)

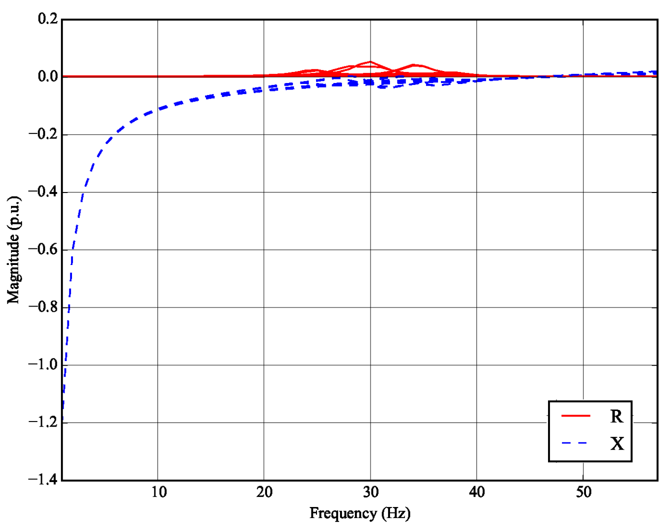

Fig. 3. Grid side frequency scan for all contingencies considered along with their sensitivities

contingency conditions up to and including N-5 contingencies for all sensitivities considered. However, for all contingency conditions up to and including N-5 contingencies, the system resistance is positive, albeit small.

B. Project Side Frequency Scan

A project side frequency scan of the WP was performed with and without the SSO mitigation control to determine the total net impedance of the WP given its specifications. This frequency scan looked into the WP from the POI and included the wind turbines, the most recent collection system design and layout as well as the current main power transformer and pad mount transformer specifications.

The purpose of this study is to observe the impedance of the WP over the range of frequencies under consideration to determine if the WP provides a positive resistance at the POI to dampen out any resonance created from system disturbances.

The results from the project frequency scan shows that the reactance of the project is positive for all frequencies under study. The project frequency scans are shown in figure 4, figure 5, figure 6and figure 7for 10% and 100% output, respectively with and without the SSO mitigation control. The SSO mitigation control being engaged shows a benefit in shifting the low resistance point of the wind turbine to be further away from the typical SSO resonance point and therefore was recommended to be engaged for the liftetime of the project.

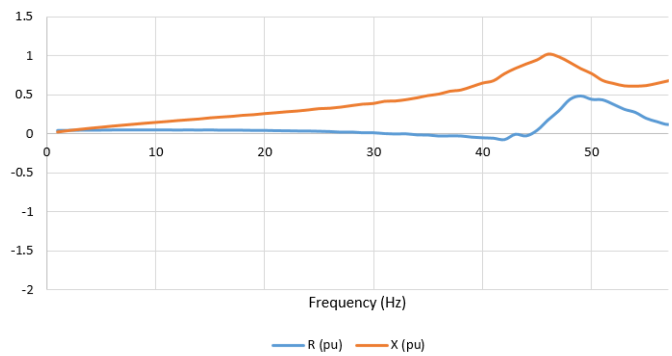

Fig. 4. Project side frequency scan for 10% turbine output without series compensation option

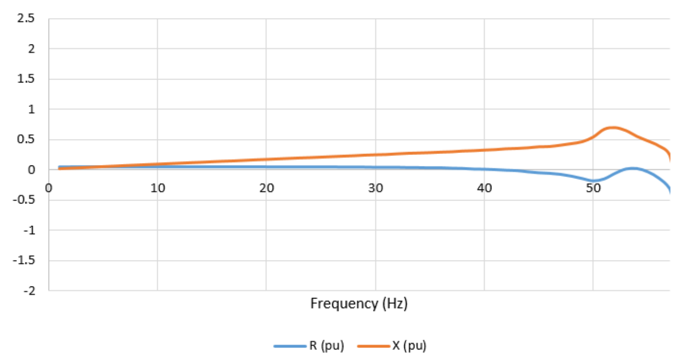

Fig. 5. Project side frequency scan for 100% turbine output without series compensation option

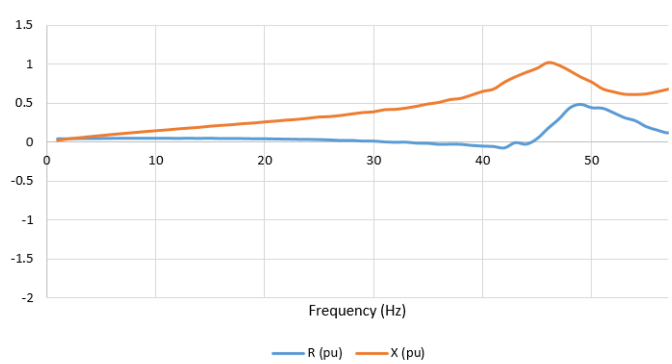

Fig. 6. Project side frequency scan for 10% turbine output with series compensation option

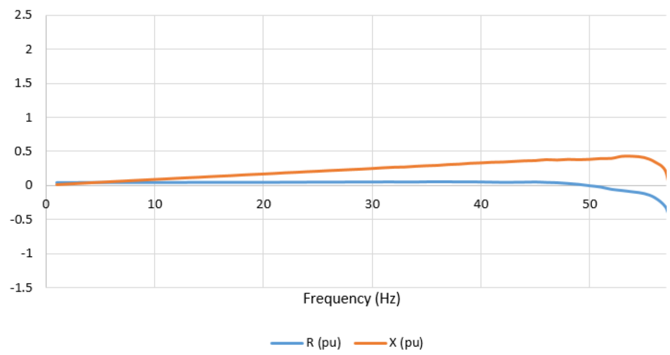

Fig. 7. Project side frequency scan for 100% turbine output with series compensation option

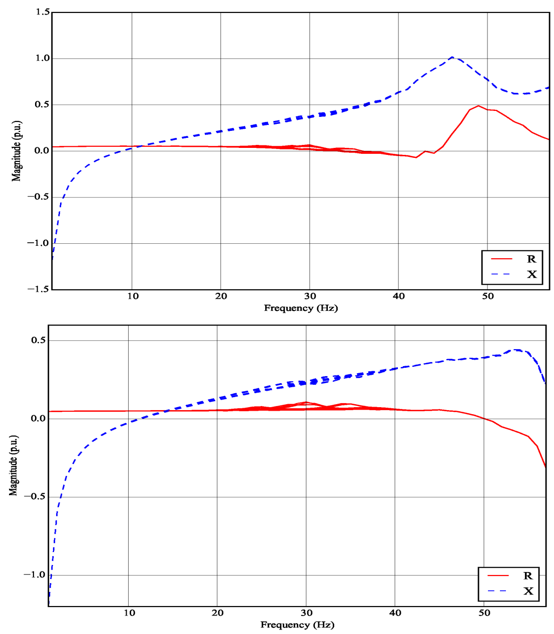

Fig. 8. Combined gird and project frequency scan (10% output in the top and 100% in the lower graph)

C. Combined Frequency Scan

The system frequency scans given in figure 3 and the project frequency scans shown previously section III-B are combined in figure 8 for both the 10% and 100% project output.

The combined grid and project scans show that the combined reactance can become below zero from 0 Hz to 12 Hz of the frequency range under consideration for both the 10% and 100% dispatch levels with and without the SSO mitigation control engaged for all contingency conditions along with the sensitivities considered. For the 10% percent dispatch level, the combined resistance can become negative from 33 Hz to 44 Hz in case the SSO mitigation control is engaged and 25 Hz to 34 Hz in case the SSO mitigation control is not engaged for the majority of the contingencies and sensitivities considered. Thus the combined resistance is never negative when the combined reactance crosses zero.

We concluded that the WP is unlikely to be susceptible to SSO for all cases considered even when the wind project is not equipped with the SSO mitigation control.

A detailed EMT study was then performed in section §IV to fully assess the susceptibility of the WP for SSO for the N-1 contingency conditions and corresponding sensitivities. This is done to provide a firm answer on whether the negative resistance in case of the 10% dispatch level can cause SSO and to answer whether the resistance is high enough to damp any SSO in case the 100% dispatch level.

IV. Detailed EMT Study

The system model was set up according to what has been mentioned in section §II. After that, we modified the PSCAD™ case manually by introducing a fault logic to the transmission line from bus A to B. The outage of this line causes the project to be radially connected to the series capacitor banks installed on the transmission line from A to C. The fault logic would create a bolted three phase to ground fault on the midpoint of the transmission line from A to B and clear the fault by opening the circuit breakers at both line ends after five (5) cycles.

After that, the fault logic would be activated after the PSCAD™ case reaches steady state. In all of the cases in this study, it was found that the PSCAD™ cases reach steady state at 1.3 seconds. The fault logic is then invoked at 1.3 seconds by creating the bolted three phase to ground fault on the midpoint of the transmission line from A to B and then clearing the fault in five (5) cycles (t = 1.383 seconds). The active power, reactive power, three phase voltage, RMS voltage, as well as three phase currents at the POI of the project were all monitored for ten (10) seconds.

Analysis revealed that the WP will trip offline following clearing of the fault on the transmission line from A to B for all of the scenarios considered. In some cases, the project would trip due to overcurrent while in other cases the trip was due to overvoltage. The current output of the project, MW and MVAr as well as the POI voltage are shown in figure 9, figure 10 and figure 11, respectively.

V. Investigation of the Trip After Clearing the Fault

As can be seen from figure 10, following the clearing of the fault the project absorbs high amount of reactive power. Additionally as evident from figure 11, the instantaneous voltage at the POI is beyond the high voltage ride through capability of any ISO. It is to be noted that the surge arrester at the POI is not able to clip the voltage to acceptable values due to the unusually high amount of reactive power that is absorbed by the project.

Root cause analysis has shown that the reactive power is being pushed from the series capacitor banks to the project after clearing the fault. The TSO has designed the protection of all of the series capacitor banks in the system such that they ride through the most severe fault. A fault on the transmission line from A to B is not an exception to this. This is mainly

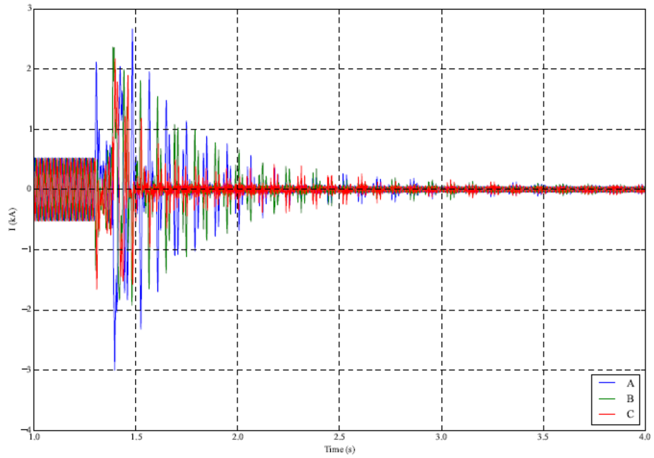

Fig. 9. Output current of the WP

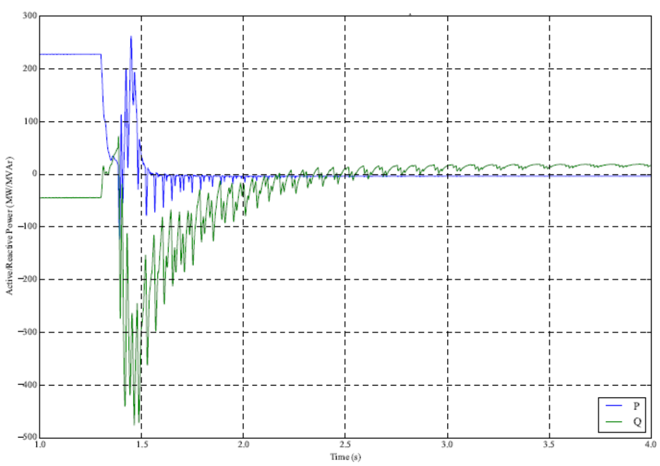

Fig. 10. Active and reactive power output of the WP

done for stability enhancement and increasing the power transfer capability in the region under certain loading and generation scenarios.

The problem can be understood by referring to figure 12. In this figure, it can be seen that once the fault occurs on the transmission line from A to B, the voltage across the capacitor banks become close to the rated line to line voltage of 345 kV and the capacitor bank stores a massive amount of reactive power as a result. However, once the fault is cleared by opening the circuit breakers at both ends of the transmission line from A to B, the voltage across the capacitor bank returns to normal which is around 27 kV. Since the voltage across the capacitor cannot change instantaneously, the capacitor bank releases the previously stored energy back to the system in both directions and the voltage across the capacitor bank starts to overshoot. Since the WP is radially connected and very close electrically to the series capacitor banks, it attracts most of the reactive power. The reactive power absorbed greatly exceeds capability of the the turbines and they trip offline as a result.

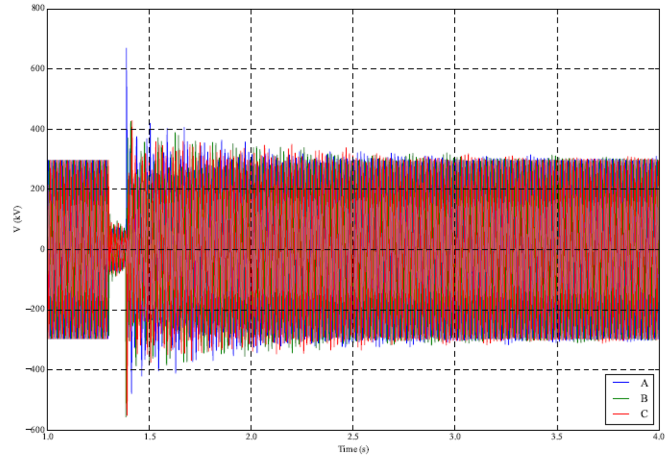

Fig. 11. Voltage at POI

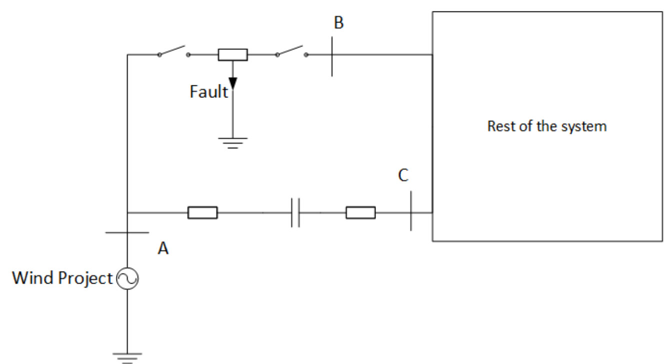

Fig. 12. Clearing the fault on line A-B

VI. Conclusions

A study has been performed to assess whether the WP under construction will be susceptible to SSO. A frequency scan screening study was performed and indicated that the WP is unlikely to suffer SSO even though is right next door to a large series compensation device. A detailed EMT study was performed to to confirm the findings of the frequency scan screening study. EMT simulations showed that the project will trip after clearing the fault on the transmission line that will cause the project to be radially connected to the series compensation capacitor. Investigations were carried out to understand the nature of this trip. The authors concluded that the trip is due to the high voltage and reactive power surge coming back from the series capacitors after the fault is cleared. The project was thus not susceptible to SSO. The ISO was notified of the findings and approved the study.

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