Assessment & Alternatives for SSR in a Series Capacitor Wind Farm Employing TCSC

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Abstract. Wind energy systems are going to build their footprint in the electricity grid around the world as one of the most viable renewable and environmentally friendly sources of energy. Keeping this scenario in mind and predicting further growth in installations, power systems should be prepared for the assimilation of such large wind farms. Almost every system has been outfitted with electricity compensation processes to enhance a sustainable transfer of electricity generation. This would have the possibility to trigger SSR difficulties in a variety of power grid circumstances. An analysis and SSR solutions will be discussed and recommendations. SSR inhibition is accomplished via the TCSC that also aids in increasing the transmitting station's power flow. So if coupled to closed-loop control loops, TCSC dampens SSO. Efficacy is evaluated using SIMULINK studies in the MATLAB environment to results demonstrate the effectiveness of TCSC throughout the SSR damping process.

Keywords: Series Compensation (SC), Wind Farm, Sub-Synchronous Resonance (SSR), Thyristor Controlled Series Capacitor (TCSC), Sub-Synchronous Oscillation (SSO).

1. Introduction

According to the last 50 years of data, power generation is increasing by 3.4% each year and energy demand is rising by 3.6% annually. Today, RE has been commonly used to produce electric power, as per research studies, 35% of overall energy production arrives from renewable sources. [1-2] Wind is a more sustainable source of energy besides RE in such a smarter manner. The wind seems to be the world's fourth-largest RE source. To best serve the province's energy requirements overall, the essential services have been functioning on the power exchange capacity of the existing transmitting line [3, 4].

Series capacitors that use enhance the electric power capabilities of the transmission line. But there are thermal, stability limits to increase the power transmission line. Connections between turbine
generators with a series-compensated line have an impact on SSR. An SSR is introduced into the Series Compensated Transmission Network in two ways: one of those is through the induction generator effect (IGE), and the other one appears to be through the torsional interaction (TI). The induction generator phenomenon occurs in the transmission network result of interaction between the generator as well as the stator circuit. [5, 6] There may be an interaction between the mechanical system as well as the electrical torsion effect across the line that affects the normal operation of the transmission line. The Flexible Alternating Current Transmission System (FACTS) is an effective basic approach to enhance these same power transmission capabilities of the transmission line. TCSC not only improves power transfer capability but also helps to address the impact of the neglectful SSR. [7,9] Power system dampers and FACTS enhanced with auxiliary controllers that provide damping signals are the best way to resolve SSR so far, many counter-measures have been used, such as SSSC (Static Synchronous Series Compensators) and TCSC and UPFC (Unified Power Flow Controller) from the FACTS family to suppress SSR.

TCSC is used to regulate the level of compensation for transmission as well as its capacity to absorb the fluctuations of an SSR [11, 12]. SSR in such a series-compensated line may raise the risk of system instability. SVC could even successfully damp SSO while supplying dynamic voltage support at the IG terminal. The TCSC consists of the FSC and the TCR. It provides basic series compensation by controlling the angles of fire, by changing its apparent reactivity to its active power, by controlling it, and by using capacitor banks, by controlling the reactive power. By injecting current in series with a transmission link, the voltage is kept stable. This article is divided into the following section. Section 2 describes the subsynchronous resonance due to series compensation. Section 3 is the modeling of the thyristor-controlled series capacitor. Section 4 described the test system of subsynchronous resonance. Section 5 describes the mitigation of SSR with TCSC.

2. SSR as a result of Series Compensation

The W TGs understand the world as an elevated source of electricity. Wind generation capacity has now increased to more than 50 GW. This change with wind power would then eventually lead to a combination of bulky wind turbine generators into an electrical grid. And it will be possible to share the electricity generated via the outgoing electricity grids, which should be designed to withstand larger power drifts. These have long been known that SC is now an effective way of achieving power transfer with power systems. Serial compensation has, even so, actually been proven to induce a particularly destructive mechanism called SSR throughout the power system. An SSR is a scenario in which the electrical grid interacts with the turbine generator at one or more of the cumulative system's natural frequencies just under the synchronous frequency. This same Connect Compensation Series tends to result in the perturbation of subharmonic currents at a high electrical frequency (b)

$$f_{sr} = f_0 \frac{X_c}{\sqrt{X_N}}$$

(1)

In this, $X_c$ becomes an SC reactance, $X_N$ would be the reactance of generator and transformer, and $f_0$ has become electrical grid nominal frequency. Of course, $X_c$ could be near 60-70a of $X_N$. From now on, $f_{sr} < f_0$. Sub-synchronous currents result throughout the torque of the rotor as well as the torque of the complementary frequency i.e. $f_r$.

$$f_r = f_0 - f_{sr}$$

(2)

The SSR in the power plant has become a situation where, in the wind turbine generator system, electricity has been provided to the electrical power line from one or more $f_n$ of both parts of the
coupled wind turbine as well as the transmission grid structure. Frequencies with an energy exchange rate are less than the fundamental rated frequency. There are 3 noticeable conditions of SSRs as shown in.
1. The effect of an induction generator (IGE)
2. Interaction between torsional forces (TI)
3. Torque amplification (TA)

IGE would be solely an electrical concept and thus does not involve any mechanical system. The same effect with IGE makes it appear to be significant whenever the level of compensation has been large. IGE happens when there has been a gap between the actual speed and subsynchronous speed. When $N_s$ is less than speeds, the resistance measured first from the armature interface would be negative, leading to negative slip affected by a rise in sub-synchronous current. The preceding concept is nothing more than the negative effect of an induction generator again from the armature terminal, which could cause a significant slip increasing sub-synchronous current. TI aims to build together on the dynamics of mechanical and electrical engineering.

The impactful sub-synchronous action caused a rotor torque that is distinguished to preserve rotor fluctuation as its frequency of armature voltage sub-synchronous configurations has been close or correlated mostly with the electric power setup of the $f_n$. Only at the torsional frequency of the rotor could the torque be enlarged and the shaft fails. TA is indeed an influence that is going to be happening because of some kind of grid fault. A certain disruption of a structure can result in sudden alterations in current, contributing to oscillations. In a non-series-compensated power grid, such a structure disruption will then make a significant contribution to a dc offset which decreases both transients as well as the sub-transient time coefficients of a generator. Alternatively, throughout an SC line, fluctuations of frequencies associated with an $f_1$ including its electricity network were created. A greater torque would then result because the oscillation frequency has been closer to it or associated with one of $f_n$ of the shaft. The presence of TA-related SSR may be due to torsional mechanical perturbations throughout the shaft structure of thermal power plants.

3. Modelling of Thyristor Controlled Series Capacitor

![Figure 1. Modeling of TCSC](image)

Figure 1, TCSC has become a series-controlled FACTS controller offering consistent control power mostly on the AC transmission line. TCSC is often used to control the voltage from across fixed capacitor (FC) in such a series of compensated segments besides means of appropriate adjustment in the firing angle. The figure illustrates the TCSC con Figure. The capacitor has been straight attached to the main section throughout the series as well as the thyristor-controlled inductor has been tied directly to the capacitor. Four TCSC operating configurations were accurate: 1) Block configuration, 2) Bypass configuration, 3) Capacitor boost configuration, 4) Inductive boost configuration. The locking mechanism hasn't ever sent trigger pulses to thyristors, so the TCSC
operates as a fixed series capacitor. In mode operation, these same thyristors are fully functioning, the more flow of current via the thyristors, and thus the TCSC does have a small net inductive reactance. In venires configuration, the thyristors have been conducted out in a way that a controlled amount of inductive current will accumulate via the capacitor, thus further significantly enhancing capacitive/inductive reactance of the device. For normal operation TCSC 50% series compensation is provided for swing operation 90% series compensation is provided to see the performance of TCSC under faulty condition.

The interaction impedance, \( Z_{eq} \), of such a merging of the LC has been conveyed as the impedance of the unassisted FC, below:

\[
X = - j(1/\omega C) \tag{3}
\]

If \( \omega C-(1/\omega L) > 0 \) or, in next statements, \( \omega L > -(1/\omega C) \) the response of a Fixed Capacitor has been below that of the parallel-bonded variable reactor, and then this combination would be a changeable-\( X_L \), however, both of these would be assumed. If \( \omega C-(1/\omega L) = 0 \), the resonance accumulates those implications inside an infinite \( Z \), an incomprehensible and unacceptable scenario.

If, \( \omega C-(1/\omega L) < 0 \), the, LC integration intends to make accessible this same inductance at the top of the fixed inductor value. The whole scenario has been compatible with TCSC inductive operation mode. Because as \( X_L \) of the uncertain inductor has been enhanced throughout the TCSC changeable-capacity configuration, the equivalent capacitive reactivity has repeatedly failed. The least consequent \( X_C \) has been obtained besides strongly heavy \( X_L \) or if the variable inductor has been open circuit wherein the equals to that of the FC of its own.

\[ X_{TCSC} = \frac{(X_L \times X_C)}{(X_L - X_C)} \tag{4} \]

Overall line reactance including TCSC is:

\[ X = X_L - X_{TCSC} \]

\[ Q_{TCSC} = (I_C \times I_C \times X_C) - (I_{TCR} \times I_{TCR} \times X_L) \tag{5} \]

The discrepancy of \( Q \) stipulates with load dissimilarities is acquired as If \( Q_{d_{min}} \) is the minimum \( Q \) demand, \( Q_{d_{max}} \) \( Q_{d_{max}} \) us the maximum reactive power demand, then,

\[ Q_{d_{TCSC}} = Q_{d_{max}} - Q_{d_{min}} \tag{6} \]
$$Q_{\text{ref}} = Q_i = 1 \text{pu}$$

$$V = V_{\text{ref}} = 1.0 \text{pu}$$

$$Q_c = Q_{d, \text{max}} - Q_{\text{ref}}$$

$$Q_{\text{scr}} (\alpha) = Q_{\text{ref}} - Q_{d, \text{min}}$$

$$Q_{\text{csc}} = Q_c - Q_{\text{scr}} (\alpha)$$

Hence,

$$X_L = (I_c * I_c * X_c * Q_{\text{csc}}) / I_{\text{scr}} * I_{\text{scr}}$$

4. Simulation and Results

Figure 3 shows the series compensated for overhead transmission lines by TCSC. The overall length of the transmission network has been 100km and the series capacitor has been placed in the center of the transmission network at 50km from bus A. 90 percent of an SC has been presented to enhance the power transfer ability of the transmission line. The worst possible condition is known when the power levels are rising from 100MW to 500MW at 90 percent of the series compensation. TCSC has been used to enhance transfer capability as it both enhances power transfer as well as the ability to overcome the impact of sub-synchronous resonance.

TCSC operates in closed-loop current control mode. This same TCSC pulse has been connected to the circuit with firing that is shown in Figure 4. Then it goes to an impedance computation which validated the criteria and provides a command to the circuit breaker and the resistive damping of the SSR is done. When the capacitive response is equal to the line response, sub-synchronous resonance oscillation has occurred. The SSR has an impact on the operation of the wind turbine. There are two effects of SSR: 1. Effect of induction, 2. Torsional interactions. For the induction effect, 90 percent of a series has been compensated for the transfer of 100MW of power through the transmission network. TCSC operates in induction without any of the current control modes; by which TCSC bypasses all unstable parameters. In the torsional interaction effect, 90 percent of a series has been compensated for the transmitting of 500MW of power through the transmission line. When the TCSC is bypassed, the mechanical torque increases, making the system unbalanced and causing damage to the shaft. When line $X_L$ is equal to $X_C$, it will nullify each other. Resistant damping helps to damp this same SSR with the use of the TCSC.

Figure 3. Simulation model of the system
In that same regard, it is assumed that the TCSC has been directly implicated within $X_C$ of the power system and, as a result, controls the power outage.

5. Mitigation of SSR with TCSC

5.1 TCSC effectiveness for damping during IG effect

Power transfer has been boosted from 100MW to 500MW at 90 percent of series compensation. Following signals are recorded to demonstrate the damping effectiveness of TCSC as during IG impacts:

- The rotor speed of the generator ($\omega_r$)
- The terminal voltage of the generator ($V_t$)
- Electromagnetic torque ($T_e$)

Figure 6 shows that without a close current control loop, Fault has at first existed at 0.4sec and the electromagnetic torque has been continuously increasing to its infinite value. Similarly, the rotor speed and the terminal voltage increase to a very high magnitude. TCSC is not controlled in closed-loop mode. Using closed-loop current control, three factors are presented as shown in the Figure. 5, 6, and 7 in that the value of the electromagnetic torque expanded infinitely over time but controlled by the TCSC in a closed-loop when the steady-state value has been progressively improved.
Figure 6. (a) Without TCSC (b) With TCSC Damping of SSO in the generator terminal voltage

Figure 7. (a) Without TCSC (b) With TCSC Damp of SSO in electromagnetic torque

5.2 TCSC’s damping effectiveness during the TI impact

Using TI File had been two methods taking into account one would be wind turbine mass, the other one is shaft means train mass. In that power transfer capacity has up to 500MW. And for series compensation, 90 percent has been compensated. In TCSC simulation bypassing the TCSC and
bypassing the rotor speed as well as the mechanical torque. Seeing as the TCSC bypass, the mechanical torque oscillation has been rising and becoming unstable. In the same way, the rotor speed is increasing very high, making the system unstable. Figures 8 and 9 show the quantification of three variables, including TCSC.

1. TCSC reactance ($X_{TCSC}$)
2. Generator rotor speed ($\omega_r$)
3. Mechanical torque

TCSC controls the current control mode of a closed-loop. The findings have been seen in Figure 9. Mechanical torque stable very short time likewise rotor speed and susceptibility was its Constance value as can be seen in Figure 8, so the terminal voltage generator is the stability owing to SSO damping.

Figure 8. (a) Without TCSC and (b) with TCSC Damp of SSO in the rotor speed
The signals examined are the speed of the generator rotor ($\omega_r$) as well as the TCSC reactance ($X_{TCSC}$). The figure shows that TCSC closed-loop current control successfully dampens the SSO owing to the TI impact. Thus, the TCSC as well offers resistance damping with SSO.

6. Conclusion

In this investigation, a basic agenda of this article is that TCSC, already introduce in the system, has been intended for power transfer only. But it’s the same TCSC can also be used to damp the SSR. If the outcome acknowledges a current control loop attributable to closed-loop current control both in the TA and the IGE of a TCSC, the SSO appears to be effective in damping, even though the mechanism causes a serious fault.

Appendix

A. Generator Data:

| Parameter                                | Rating      |
|------------------------------------------|-------------|
| Power Rating (P)                         | 1000HP      |
| The line to Line resistance ($V_{LL}$)   | 26KV        |
| Stator resistance ($R_s$)                | 0.015p.u.   |
| (Line stator reactance) $X_{ls}$         | 0.091p.u.   |
| (Rotor resistance) $R_{r1}$              | 0.0507p.u.  |
| (Rotor resistance) $R_{r2}$              | 0.0095p.u.  |
| (Line reactance)$X_{L1}$                 | 0.0p.u.     |
| (Line reactance)$X_{L2}$                 | 0.0539p.u.  |
| (Mutual reactance)$X_{m12}$              | 0.1418      |
| $H_G$                                    | 0.5         |

B. Torsional system data

| Parameter | Rating   |
|-----------|----------|
| Power     | 100MW    |
| $H_T$     | 12.5p.u. |
| $H_G$     | 0.5pu    |
| $K_{GT}$  | 0.15pu   |
C. TCSC data

| Parameters                  | Rating          |
|-----------------------------|-----------------|
| Series compensation         | 90%, 65% and 50%|
| TCSC current controller     |                 |
| Proportional controller (K_p)| 0.0             |
| Integrator controller (K_i) | 200             |

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