Summary: In Sweden some long series-compensated 400 kV transmission lines are connected to nuclear power stations. An SSR problem has been noticed and caused repeated triggering of the protections. A study indicated that SSR conditions might appear for some network configurations. Rebuilding of one SC, splitting its total reactance in a fixed part and a Thyristor Controlled Series Capacitor (TCSC) part, was found to eliminate the problem. The paper discusses the problem and the studies performed and also outlines the TCSC that has been realised in Stöde SC station. The TCSC permits that the degree of compensation remains at its earlier level, while the SSR conditions are similar to the case when 30 % of the series capacitor reactance is bypassed.

Keywords: series capacitor, thyristor controlled series capacitor, subsynchronous resonance, frequency scanning, apparent impedance, synchronous voltage reversal

1. INTRODUCTION

The benefits of series compensation were recognized long ago in the history of power transmission technology. From electrical standpoint a virtual reduction of the line length is obtained due to the compensation of line reactance that is accomplished by the series capacitor. The advantages can be illustrated by two generic cases as shown in figure 1.

The impact of series compensation on voltage stability is illustrated in figure 1 a). It shows the voltage as function of the active power transfer in a weak node having no reactive power support when it is fed through a transmission line. A substantial voltage drop is achieved limiting the possible power transfer and voltage collapse occurs at a certain power level. The effect of series compensation is shown and can be summarized as

- reduced voltage drop at the same power transfer
- the voltage collapse point is moved towards much higher levels of power transfer

In figure 1 b) the impact on angle stability is illustrated. In this case the active power flow between two stiff nodes is shown as function of the angle difference between the voltage sources in the line terminals. The power transfer at 90° angle deviation limits the maximum power transfer that can be achieved across the line. For safe operation the angle between the line terminals at normal operating conditions should be limited to 30-40° in order to guarantee sufficient margins in transient conditions. The effects of series compensation are
• reduced angle deviation in normal operating conditions
• increase of maximum power transfer
Both these effects contribute to an increased transient angular stability in the system.

It was recognized in the 70’ies that the introduction of series compensation in lines that are closely connected to thermal generating stations might introduce a negative damping on the mechanical torsional modes in the turbine-generator shaft system. In the electrical system these oscillations occur in the subsynchronous frequency range. Therefore these phenomena are generally referred to as subsynchronous resonance (SSR) effects.

2. SSR CONDITIONS IN THE SWEDISH TRANSMISSION SYSTEM

The Swedish power system is a part of the synchronous Nordic Power System which includes Sweden, Finland, Norway and eastern part of Denmark. The annual energy consumption in Sweden is about 140 TWh and the installed production capacity is about 35 GW.

![Figure 2: The Swedish 400 kV network](image)

The main consumption areas are situated in the southern part of the country. The dominating part of the energy is generated by hydro and nuclear plants (hydro 45%, nuclear 50%). Hydro power plants are situated mostly in the northern part of the country and nuclear power plants in the coastal area of southern Sweden.

Eight 400 kV lines connect the hydro power plants in the north with the large load areas in the south (figure 2). Each line is up to 500 km long and series compensated up to 70%. Two new series capacitors presently are being installed on the 400 kV AC-interconnections between Sweden and Finland.

Two of the eight lines, the ones comprising the series capacitors in Vittersjö and Stöde, are installed in the 400 kV lines directly connected to Forsmark, a major nuclear power plant (figure 3). One of the units, Forsmark 3 has a production capacity about 1150 MW_e.

![Figure 3: The network nearby Forsmark 3](image)

This unit is equipped with an SSR armature current relay that detects if subsynchronous current exceeds a predetermined level for a specified time. The relay has three current levels, the first being an alarm level and the other ones causing generator trip after different time delays.

The series capacitors, Vittersjö and Stöde, both have relay protections which detect subsynchronous current. The relay protection automatically bypasses the series capacitor whenever a certain time-SSR current amplitude criterion is exceeded.

The Stöde SC originally was erected in 1974 using capacitors impregnated with PCB. In the early 1990’ies the installation was completely refurbished with state-of-the-art components including non-PCB capacitors. The station was recommissioned in November 1994.

Shortly after that Stöde was put into service the subsynchronous current relay at Forsmark 3 started to trigger repeatedly and the series capacitors were bypassed several times. A study was made to examine how to prevent the subsynchronous resonance.
3. ANALYSIS

3.1 Shaft system model
The rotor of a thermal generating unit is a complex mechanical system. A rotor system has a large number of torsional vibration modes both above and below the fundamental frequency. An infinite-dimensional model of the rotor system would be required to account for the complete range of torsional oscillations. However, the problem due to interaction between the electrical system and the mechanical system principally occurs in the subsynchronous frequency range. This allows the representation of the rotor system by a simple lumped-mass model for the system interaction studies.

The inertia and spring constants are required to develop the lumped-mass model (figure 4). The natural torsional frequencies and modeshapes, obtained from the lumped-mass model, then are used for developing the constants for the interaction equation.

In order to relate the rotor torsional oscillation frequency, $f_m$, with the frequency of the corresponding electrical oscillation, $f_s$, the following formula is used:

$$f_s = f_0 - f_m$$

where $f_0$ is the synchronous frequency that corresponds to the rotation of the generator rotor. This equation is necessary to assess the torsional interaction phenomenon by the frequency scanning method.

3.2 Frequency scanning method
The frequency scanning method [1] was used in the study. The Swedish 400 and 220 kV network was represented in the study with 215 buses, 265 AC branches and 18 transformers. The transmission lines are represented by $\pi$-equivalents. Each transformer is represented by a resistance and a reactance proportional to frequency $f_s$ between two buses. The series compensation in the eight lines are represented as negative reactances inversely proportional to frequency $f_s$. Forsmark 3 is represented as an induction generator model and all other machines are represented by their short circuit equivalents.

A program has been developed to perform the frequency scanning [2]. This program produces three categories of outputs:

- the impedance $R + jX$ of the system as viewed from behind the generator rotor leakage impedance
- the electrical undamping, which is directly proportional to the quotient $\frac{R}{R^2 + X^2}$
- the subsynchronous currents at specified points in the network

3.3 Results of the simulations
The results showed that the resonance frequency in

![Figure 4: Mode frequencies at Forsmark 3](image)

![Figure 5: Damping with intact network](image)
the network coincides with the electrical frequency corresponding to mode 3 (torsional frequency 21.1 Hz) in Forsmark 3. The total damping at this subsynchronous frequency was close to zero with intact network. This is seen in figure 5 where the electrical network damping is negative with almost the same amplitude as the mechanical damping in the turbine-generator (the latter is drawn with negative sign to allow comparison with the electrical network damping). As soon as a small disturbance occurred oscillations were excited. That would explain the repeated trigger of the relay protection at Forsmark 3.

Further investigations showed that when a 400 kV line nearby Forsmark3, between Forsmark and Odensala, is disconnected undamping will increase so much that self-excited SSR presumably might appear (figure 6).

One way to prevent subsynchronous resonance is to eliminate part of the series compensation in Vittersjö (figure 7). This measure would change the electrical resonance in the network away from the critical frequency. But if more than one third of the reactance in Vittersjö SC is eliminated a new resonance would appear at the critical frequency, now caused by the Stöde SC. This illustrates the problem with two series capacitors with different reactances connected at the same busbar near a power plant. The reactance at Vittersjö at fundamental frequency is 50 Ω and in Stöde 73 Ω.

The reduction of the Vittersjö SC capacitive reactance with one third would change the power flow in one critical bottleneck in the Swedish network and reduce its power transfer capacity. This solution would also increase the power losses in the system.

Another more attractive solution was to install a Thyristor Controlled Series Capacitor (TCSC) that would change the reactance in the subsynchronous frequency range even if the capacitive reactance at fundamental frequency, i.e. 50 Hz, remains constant.

It was decided that a TCSC should be implemented in Stöde. The existing series capacitor would be divided into two segments. One segment, 70% of the originally series capacitor, should remain as a conventional fixed series capacitor and the other segment should be a TCSC.

As a temporary solution the series capacitor in Vittersjö was totally bypassed.
4. THYRISTOR CONTROLLED SERIES CAPACITOR

4.1 General considerations

The main circuit of the TCSC and the typical appearance of the steady-state waveforms is illustrated in figure 8.

![Figure 8: a) TCSC main circuit b) TCSC waveforms](image)

The impact of the TCSC with respect to subsynchronous resonance (SSR) has been discussed in [3]. A conceptual approach for the control system design also has been outlined in that paper. The TCSC apparent impedance for subsynchronous frequencies is determined by the dynamical behaviour of the algorithms that control the thyristor triggering. In [3] the concept of “Synchronous Voltage Reversal” (SVR) has been described. This is one systematic method of obtaining a well-defined apparent impedance of the TCSC.

In short the SVR method is implemented in a layered control structure according to figure 9.

![Figure 9: Outline of TCSC control system](image)

The following functional blocks can be recognised:

- an inner control loop that takes a pulse train as input and that calculates the thyristor triggering instant so that the capacitor voltage zero-crossing occurs with a constant time delay with respect to the input pulses. The loop uses instantaneous values of measured line current and capacitor voltage as inputs for calculating the triggering instant.
- a Phase Locked Loop (PLL) that extracts phase information from the line current
- a measuring system that detects the phasors that correspond to line current and capacitor voltage and that evaluates the apparent reactance of the TCSC at fundamental frequency
- a reactance or boost controller that controls the TCSC apparent reactance at fundamental frequency by phase shifting the pulse train to the inner loop relative the phase of the line current
- a reactance reference generator that provides the reference for the boost controllers
- a sequencing system that manages start, stop and protective actions

It has been shown that the apparent impedance ideally is inductive in the subsynchronous frequency range when the dynamical response of the PLL and the boost controller is slow. The characteristics is independent of the boost level and the line current amplitude.

The only purpose of the Stöde installation was to improve the SSR conditions for the generator in the Forsmark 3 unit. Therefore the control system operates with constant boost reference, i.e. the apparent reactance at fundamental frequency is controlled so that the quotient $\frac{X_{TCSC,apparent}(50\,Hz)}{X_{C,phy}(50\,Hz)}$ remains constant.

4.2 TCSC design

It was mentioned above that the inner loop in the control system provides an inductive apparent reactance for the TCSC. Thus if the series capacitor would be fully controlled the electrical resonance of the line could be moved out of the subsynchronous frequency range where the mechanical modes are located. For economical reasons, however, only part of the series capacitor bank is thyristor controlled. It was a requirement that, in case of a failure occurred on the TCSC equipment, it should be possible to operate the line with a reduced degree of compensation with the TCSC part bypassed. Calculations showed that if 30 % of the total series capacitor reactance was thyristor controlled this requirement would be fulfilled.

The selected boost reference value for the TCSC part is 1.20. This value is a reasonable compromise between the following considerations:

- capacitor bank rating increases with increasing boost level as the current circulating through the
thyristor branch adds to the line current when passing through the capacitor bank

- thyristor current is proportional to the boost level
- the harmonic voltage inserted in series with the line grows with increasing boost level
- the thyristor turn-on appears close to voltage zero-crossing when boost level is low. This means that if the line current in modulated, as is the case during SSR conditions, the TCSC firing will sometimes occur with reverse blocking conditions. Thus a certain boost level will be required in order to establish a safe apparent impedance characteristics.

With the selected design parameters the Stöde TCSC got the following characteristics:

<table>
<thead>
<tr>
<th>Physical capacitor reactance</th>
<th>18.25 Ω/ph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent TCSC reactance in steady state</td>
<td>21.9 Ω/ph</td>
</tr>
<tr>
<td>Rated current</td>
<td>1500 A rms cont</td>
</tr>
<tr>
<td>Short time current</td>
<td>2025 A rms 30 min 2250 A rms 10 min</td>
</tr>
</tbody>
</table>

4.3 System characteristics with TCSC

The boost controller makes the apparent impedance of the TCSC capacitive at frequencies close to 50 Hz. When the gain in the controller is increased its bandwidth increases and the TCSC apparent impedance becomes capacitive at frequencies farther and farther from 50 Hz. By adjusting the gain and bandwidth in the boost controller and the PLL and use of some correction filters the impedance characteristics in figure 10 was obtained.

The apparent impedance is inductive at the frequencies that corresponds to the critical torsional modes in the Forsmark 3 generator.

The calculated apparent impedance was checked in a real-time Transient Network Analyser (TNA) study that was performed at Royal Institute of Technology in Stockholm. The measured apparent impedance from the TNA also is indicated in figure 10.

It is important to realise that the characteristics of the TCSC is given by controllers and filters that operate in a rotating coordinate system that is synchronised with the line current. Therefore its characteristics with respect to the torsional vibrations in the rotor system are unchanged even if the shaft speed (the generator stator frequency) varies. This is unlike the situation when SSR is cured by passive filters that are tuned on the frequency on the stator side.

Further the electrical damping for the Forsmark 3 generator was evaluated, using the calculated (and measured TCSC) apparent impedance values in the complete Nordel system. The result is shown in figures 11 and 12, which shall be compared with figures 5 and 6.

![Figure 10: TCSC apparent impedance vs electrical frequency](image)

![Figure 11. Damping with TCSC implemented, intact network](image)
It can be seen that the use of TCSC makes it possible to leave the degree of compensation unchanged and at the same time get SSR conditions that are close to the situation when the TCSC is bypassed. Even with a line nearby Forsmark disconnected, the total damping in the system remains positive (figure 12).

4.4 System realisation

The single-line diagram of the Stöde installation is shown in figure 13.

The Stöde SC has been rebuilt as follows:

- the existing capacitors were rearranged to form the fixed part of the TCSC. The reactance was reduced from 73 Ω/phase to 51.1 Ω/phase. The protection scheme, the spark gap and the MOV were adjusted accordingly.
- three new platforms were erected and equipped with capacitor banks using the removed cans from the existing SC together with some newly manufactured units. The isolation distances between the new and the existing platforms were chosen so that work on the new platforms could be performed with the existing capacitors energised.
- the associated equipment like the TCSC inductors and the bypass breakers were erected beside the new platforms.
- the TCSC valves were placed on the platform and the installation of the control equipment and the cooling equipment was done.
- commissioning and testing of the new equipment was made with the reduced fixed series capacitor still in service.
- the line was de-energised during a short time for the installation of the new disconnector arrangement.
A compact design is obtained as spark gaps are not required and the MOV energy rating can be kept low due to the possibility of fast bypass using the thyristor valve.

5. FIELD VALIDATION

As a preparatory step the Forsmark 3 generator was equipped with additional mechanical sensors on the shaft during the revision period 1996. Then measurements were made in October 1996. At that occasion a low self-excitation of SSR was obtained and measured.

The TCSC control system was developed and tested in a Transient Network Analyser (TNA) at Royal Institute of Technology in Stockholm during the spring 1997. These studies verified the performance of the TCSC for the intended application.

The TCSC was commissioned during the autumn 1997 and tests have been carried out in the system in order to verify its proper behaviour with respect to subsynchronous oscillations at the critical frequencies in Forsmark 3 power station. At the time of writing it is intended to put the TCSC into test operation in the system for a longer period of time. It is also expected that further performance tests will then be carried out. SSR oscillations will be studied for certain transmission line outages that are known to show very low damping of SSR.

Experience shows that the TCSC can be used to excite SSR oscillations for modes having positive damping in a controlled way. Thereby comparative measurements of the damping characteristics can be performed under very similar conditions.

6. CONCLUSION AND OUTLOOK

The studies related to the Stöde TCSC installation reveal that the TCSC technology can be advantageously used to improve the SSR conditions even in a complex system involving several series compensated lines.

It has also been demonstrated that an existing installation may be rebuilt using the existing equipment together with newly manufactured apparatus. The outage time for the line can be minimised when the TCSC part is located on separate new platforms.

To conclude the TCSC technology permits an enhanced use of series compensation to a degree closer to that desired from a system point of view disregarding earlier experienced restrictions due to the risk of SSR.

We intend to report on the operational experience of the Stöde SC in coming papers.

7. REFERENCES