TCSC
Thyristor Controlled Series Compensation
Keeping grids together
Series compensation has been successfully utilized for many years in electric power networks. With series compensation, it is possible to increase the transfer capability of existing power transmission systems at a lower investment cost and with a shorter installation time compared to the building of new, additional lines. This is due to the inherent ability of series capacitors to achieve:

- Increased dynamic stability of power transmission systems
- Improved voltage regulation and reactive power balance
- Improved load sharing between parallel lines

With the advent of thyristor control, the concept of series compensation has been widened and its usefulness has been increased further.
Thyristor-controlled series capacitors (TCSC)

TCSC configurations comprise controlled reactors in parallel with sections of a capacitor bank. This combination allows smooth control of the fundamental frequency capacitive reactance over a wide range. The capacitor bank of each phase is mounted on a platform to enable full insulation to ground. The thyristor valve contains a string of series connected high power thyristors. The inductor is of air-core design. A metal-oxide varistor (MOV) is connected across the capacitor to prevent overvoltage.

TCSC introduce a number of important benefits in the application of series compensation:

- Elimination of subsynchronous resonance risks
- Damping of active power oscillations
- Post-contingency stability improvement
- Dynamic power flow control

**Increased transfer capacity**
The overall result typically appears as increased transfer capacity.

**Applicable in new as well as existing systems**
The benefits of thyristor-controlled series capacitors are by no means attainable only for installations starting from scratch. It is fully possible and practicable also to upgrade existing series capacitors by making all or part of them thyristor-controlled, thereby extending their impact and usefulness in the grid most considerably.
Power flow control

In interconnected power systems, the actual transfer of power from one region to another might take unintended routes depending on impedances of transmission lines connecting the areas. TCSC is a useful means for optimizing power flow between regions for varying loading and network configurations.

It becomes possible to control power flows in order to achieve a number of goals:

- Minimizing system losses
- Reduction of loop flows
- Elimination of line overloads
- Optimizing load sharing between parallel circuits
- Directing power flows along contractual paths.
Damping of power oscillations

Power transmission P over a series compensated line is governed by the expression:

\[ P(t) = \frac{U_1 U_2 \sin \psi}{X_L - X_C(t)} \]

By proper control of the TCSC, the overall transfer reactance is modulated in time in such a way that the power oscillations are damped out.

Oscillations of active power in power transmission systems may arise in corridors between generating areas as a result of poor damping of the interconnection, particularly during heavy power transfer. Such oscillations can be excited by a number of reasons such as line faults, switching of lines or a sudden change of generator output.

The presence of active power oscillations acts to limit the power transmission capacity of interconnections between areas or transmission regions. It is often possible to find remedy by building additional lines or upgrading existing lines, but this costs a lot of money and takes a lot of time, if not rendered impossible altogether by lack of the necessary permits. In some cases, it may also be possible to introduce Power System Stabilizers (PSS) on generators, but this will not always work, particularly not for inter-area power oscillations which tend to be of a low frequency (typically 0.2 Hz to 0.7 Hz).

In either case, TCSC will be an attractive alternative to consider. It offers a cost-effective, robust power oscillation damper, insensitive to its location in the system and non-interacting with local oscillation modes. In a number of cases, it will turn out to be the best practicable solution.

ABB has developed and patented an ingenious control strategy that enhances the TCSC damping performance compared to conventional technology. We call it Phasor Estimation Technique.
An important benefit of TCSC is its ability for quick boosting of its degree of compensation, making it very useful as a tool for improving the post-contingency behaviour of networks. By means of this quality of the TCSC, the degree of compensation of a series capacitor can be increased temporarily following upon a network contingency, thereby adding to the dynamic stability of the network (voltage and angular) precisely when it is needed. By this feature, the series capacitor can be lower rated for steady-state conditions, thereby keeping transmission losses smaller.

For instance, in many applications it is desirable to enable an underlying transmission system to carry a higher amount of power under contingency conditions where a circuit is tripped in higher voltage transmission paths. Series compensation is not needed during normal operation as it would only influence overall system losses in an unfavourable way. In order to meet both objectives, i.e. safeguarding power transmission capability during contingencies and at the same time keeping transmission losses as low as possible during normal operating conditions, TCSC can be advantageously utilized.
Elimation of SSR

SSR scenario
The phenomenon of subsynchronous resonance (SSR) has caused concern in the past in situations where the risk for occurrence of SSR has acted as an impediment to the use of series compensation; cases where the technology would otherwise have offered the best and most economical solution. With the advent of TCSC, no such concerns need to be entertained any longer, and series compensation can be used to its fullest merit.

The SSR risk used to be linked to the utilization of series compensation of transmission lines fed by thermal generation, particularly in cases of high degrees of compensation, where analysis showed that the complementary series resonance frequency of the compensated line(s) co-incided with some poorly damped torsional vibration frequency of the turbine-generator shaft, and could hence induce increased mechanical stresses in the shafts. The TCSC acts to eliminate this risk for co-inciding resonance frequencies by making the series capacitor(s) act inductive in the subsynchronous frequency band, thereby rendering the occurrence of series resonance in the transmission system altogether impossible for subsynchronous frequencies.

This inductive character of the TCSC is made possible by the use of a thyristor-controlled inductor in parallel with (part of) the series capacitor. The system is governed by an elegant, patented control scheme called SVR (Synchronous Voltage Reversal, see page 9).

Subsynchronous resonance: shaft torsional vibrations sustained due to resonant behaviour of the electric system.

SSR mitigation: with TCSC, torsional vibrations die out due to elimination of the resonant behaviour for SSR frequencies in the electric system.
In a TCSC, the whole capacitor bank or alternatively, a section of it, is provided with a parallel thyristor controlled inductor which circulates current pulses that add in phase with the line current so as to boost the capacitive voltage beyond the level that would be obtained by the line current alone. Each thyristor is triggered once per cycle and has a conduction interval that is shorter than half a cycle of the rated mains frequency. By controlling the additional voltage to be proportional to the line current, the TCSC will be seen by the transmission system as having a virtually increased reactance beyond the physical reactance of the capacitor.

The thyristor valve is integrated in the capacitor overvoltage protection scheme. It replaces the Fast Protective Device and allows a reduction of the rating of the protective parallel varistor.

Thyristor-controlled segment of a series capacitor.

TCSC in steady-state, a) circuit b) waveforms.
The control algorithm, SVR, has been developed by means of which the TCSC exhibits an inductive virtual impedance in the complete frequency range of concern for SSR. As a consequence of this property of the series capacitor, SSR is efficiently ruled out.

The SVR approach to controlled series compensation offers a number of benefits to the user:

- No resonance risk throughout the SSR frequency range.
- Robust performance of the TCSC, without any need for specific tuning to meet varying network configurations and various rotating machine modes.
- Additionally variable voltage boost can be utilized for system related control purposes, such as power oscillation damping.
Power Grid Corporation of India Ltd (PGCIL) has purchased two Thyristor Controlled Series Capacitors (TCSC) from ABB.

The banks were installed on the Rourkela-Raipur double circuit 400 kV power transmission interconnector between the Eastern and Western regions of the grid. The length of the interconnector amounts to 412 km. The main purpose of this major AC interconnector is to enable export of surplus energy from the Eastern to the Western regions of India during normal operating conditions, and also during contingencies. The TCSC are located at the Raipur end of the lines.

The TCSC enable damping of interarea power oscillations between the regions, which would otherwise have constituted a limitation on power transfer over the interconnector. Dynamic simulations performed during the design stage, and subsequently confirmed at the commissioning and testing stage, have proved the effectiveness of the Raipur TCSC as power oscillation dampers.

Main technical data (per one TCSC)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed Segment</th>
<th>TCSC Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal system voltage</td>
<td>400 kV</td>
<td>400 kV</td>
</tr>
<tr>
<td>Rated line current</td>
<td>1550 A</td>
<td>1550 A</td>
</tr>
<tr>
<td>Line current overload, 30 minutes</td>
<td>2093 A</td>
<td>2093 A</td>
</tr>
<tr>
<td>Line current overload, 10 minutes</td>
<td>2325 A</td>
<td>2325 A</td>
</tr>
<tr>
<td>Physical capacitor reactance</td>
<td>54.7 Ω</td>
<td>6.83 Ω</td>
</tr>
<tr>
<td>Rated capacitor reactive power</td>
<td>394 Mvar</td>
<td>71 Mvar</td>
</tr>
<tr>
<td>Degree of compensation</td>
<td>40%</td>
<td>5% - 15%</td>
</tr>
</tbody>
</table>
A Swedish case
In Sweden, electric power generation is based chiefly on hydro power in the north and nuclear power in the middle and south of the country. Power transmission is performed on 400 kV over interconnecting lines of considerable lengths. To improve power transmission capacity of these lines and thereby keep their needed number to a minimum, series compensation is used throughout.

The Forsmark nuclear power plant situated in mid-Sweden is interconnected with the north of the country by means of a number of 400 kV lines of varying lengths, all series compensated. However, one of the generator units at Forsmark, rated at 1300 MW, is subject to SSR risk in conjunction with certain conditions in the power grid. To counteract this, one of the series capacitors, located at Stöde, previously used to be bypassed upon SSR indication, which meant loss of power transmission capability of the system. In case of failure of the series capacitor SSR protection, the generator was tripped, with subsequent loss of generation. Such measures, however, have now become unacceptable, as demands on availability of power have steadily grown.

Part of the existing series capacitor at Stöde (30 % of its totally installed reactance) has consequently been rebuilt into a TCSC. The series capacitor thus equipped was commissioned in 1997.

Increased availability of power
With the TCSC in operation, the SSR risk is eliminated for all possible system operating conditions. The benefits are increased availability of power from Forsmark as well as a preserved high level of power transmission over the system, thanks to series compensation.

Technical data, Stöde TCSC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>System voltage</td>
<td>400 kV</td>
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<tr>
<td>Rated continuous current</td>
<td>1500 A</td>
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<tr>
<td>Rated overall power</td>
<td>493 Mvar</td>
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<tr>
<td>Degree of compensation</td>
<td></td>
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<tr>
<td>Total</td>
<td>70 %</td>
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<tr>
<td>Thyristor controlled</td>
<td>21 %</td>
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<tr>
<td>TCSC control mode</td>
<td>SVR</td>
</tr>
</tbody>
</table>

Swedish National Grid TCSC at Stöde.
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