Inductive Vernier Operation of Thyristor Controlled Series Compensator for Damping of Large Power Swings

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Abstract: The Thyristor Controlled Series Compensation (TCSC) is a variable reactance series compensation device with both inductive and capacitive capability. The capacitive region of TCSC can be used for increasing power transfer capability, while the inductive capability can be used to depress fault currents. This paper addresses the issue of enhancing power swing damping subsequent to large disturbances, by use of inductive capability in addition to capacitive capability. Since the movement from capacitive to inductive region and back results in relatively large transients, an investigation using detailed simulation (including network transients) is also carried out.

Keywords: FACTS, series compensation, TCSC

1 Introduction

The advent of fast acting FACTS devices allows for fast and vernier control of series compensation using Thyristor Controlled Series Capacitor (TCSC) [1, 2, 3, 4, 5] and SSSC (Static Synchronous Series Compensator). TCSC is a variable impedance device based on thyristors. TCSC is made up of one or more modules of a Fixed Capacitor in parallel with a TCR (see Fig.1). To reduce costs, a TCSC can be combined with fixed series compensation. The effective impedance of TCSC can be varied by controlling the firing angle $\alpha$ of the thyristor in the same way as for a FC-TCR SVC. However the voltage across the TCR is not sinusoidal even if the line current is assumed to be sinusoidal. The expression for the equivalent (capacitive) reactance of a TCSC is given by [1],

$$\begin{align*}
X_c &= X_{FC} - (X_{FC} - X_{90})(\frac{2(\pi - \alpha) + \sin2(\pi - \alpha))}{\pi} \\
&+ \frac{4X_{90}^2 \cos^2(\pi - \alpha)(k_\omega \tan\alpha - \tan(\pi - \alpha))}{X_L} (1)
\end{align*}$$

where, $X_{90} = \frac{X_{FC}X_L}{X_{FC} - X_L}$, $k_\omega = \frac{\omega}{\omega_n}$ and $\omega_n = \omega\sqrt{\frac{X_{FC}}{X_L}}$.

$\omega$ is the fundamental radian frequency.

$X_L$ is the value of the TCR reactance.

$X_{FC}$ is the reactance of fixed capacitor in parallel with TCR.

$k_\omega$ can be chosen so that only one resonance peak is present.

The steady state impedance characteristic is shown in Fig.1.

![TCSC Diagram](image)

**Figure 1: TCSC**

![Possible Operational Modes](image)

**Fig.2. The possible operational modes of the TCSC are:**

1. Capacitive Vernier Mode : $180^\circ > \alpha > \alpha_{res}$
2. Blocked Mode : $\alpha = 180^\circ$ (thyristors do not conduct)
3. Bypass Mode : $\alpha = 90^\circ$ (thyristors conduct continuously)
4. Inductive Vernier Mode: $90^\circ < \alpha < \alpha_{res}$

The parallel resonance (at $\alpha_{res}$) region is to be avoided as it corresponds to high impedance, voltage and internal circulating current.

A TCSC controller (Fig.3) can be a relatively slow power
scheduling controller along with an auxiliary controller to damp power swings (PSDC).

While the use capacitive region of TCSC for increasing

power transfer capability is obvious, inductive capability may be used to depress fault currents. This paper addresses the issue of enhancing power swing damping to large disturbances, by use of inductive capability in addition to capacitive capability. Since the movement from capacitive to inductive region and back results in relatively large transients, an investigation using detailed simulation (by modelling network dynamics) is also carried out.

2 Motivation: Damping of Large Power Swings

In this section, we consider two motivating examples to show that enhanced TCSC limits by use of the inductive vernier region can improve the damping substantially. The disturbances considered are large enough to make the TCSC hit its reactance limits but not large enough to cause monotonic increase of rotor angle (loss of synchronism) in the first swing. The damping controller uses the approximate "Thevenin Angle" signal as described in [6, 7] and is shown in Fig. 4. The reactance modulation is approximately proportional to the derivative of the signal (phase lead of 90° at the swing frequency). Alternatively, the speed signal of a generator can be synthesized or measured and used as a feedback signal without need of phase lead.

Fig. 5 shows the behaviour of a single machine infinite bus (SMIB) system to large and small disturbances. The data is as follows:

Generator 1.0 model: \( f = 60Hz T_d' = 6.0; x_d = 1.6; x_q = 1.55; x_{d} = 0.32; H = 5; \)

Static Exciter: \( k_A = 200.0; T_A = 0.05; Ef_{max} = 6; Ef_{min} = -6 \)

Line reactance: \( X_e = 0.4, \) Infinite bus voltage: \( E_b = 1.0, P_g = 0.5; V_g = 1.0 \)

It is seen that the system is oscillatory unstable for large disturbances even though it is stable for small disturbances. Moreover, presence of TCSC damping controller with inductive capability can damp oscillations effectively. The following can be inferred from these observations:

1. It can be inadequate to view oscillatory instability as only a small signal stability phenomena. Nonlinear effects may significantly alter damping.

2. Larger range of TCSC by inclusion of inductive compensation helps in damping.

3. TCSC Damping Controller may over-ride the Power Scheduling Controls for the transient periods; consequently the range of TCSC damping controller
will be decided by its rating. Thus damping capability can be related to TCSC rating and may be considered during the planning stage. In particular, the limits are decided by the voltage across the TCSC and also TCR current during the transient [5]. The lower limits of TCSC can be larger since the voltage across TCSC generally reduces in the inductive region.

![Image of TCSC in SMIB system](image)

Figure 5: TCSC in SMIB system: Note that the system is oscillatory unstable for large disturbances if TCSC is not present.

Similar improvement in damping is observed for a multimachine system Fig.6 when TCSC’s placed at 2 strategic locations to damp 2 swing modes, use their inductive capability.

3 Detailed Simulation

3.1 Synchronisation

In past literature, line current based synchronisation (of firing pulses) has been shown to be superior to capacitor voltage based synchronisation [8]. The voltage across the TCSC undergoes a large shift in phase angle during the transient while the phase of line current is (relatively) less affected. The detailed simulations carried out show that transition from capacitive to inductive region may not be possible with voltage based synchronisation as the system does not stabilize for large step change in firing angle, while current synchronisation is stable (see Fig.7,8). Note that a d-q based Phase Locked Loop (PLL) is used in both synchronisation schemes [9].

![Image of TCSC response](image)

Figure 6: TCSCs in 2 lines of a 10 machine systems: Dotted line shows the response when inductive compensation is possible.

3.2 Reactance Controller

Since reactance is a highly nonlinear function of voltage, investigations are also carried out on the closed loop control of reactance in capacitive and inductive regions to prevent over-voltage due to straying of firing angle close to resonance region. The basic structure of the reactance regulator is shown in Fig.9. There are separate PI controllers for capacitive and inductive region. Note that the reactance controller switches in the appropriate delay angle order depending on whether the order is capacitive or inductive.

Reactance (Capacitive) is defined as:

\[
X_c = \frac{V_{C_q}i_P - V_{C_d}i_Q}{i_P^2 + i_Q^2} = \frac{V_{C_d}}{i_Q}
\]  

Note that the definition can be in terms of the D-Q variables (using synchronously rotating transformation [10]) or d-q variables using a transformation which is synchronised to line current. This agrees with the conventional definition of capacitive reactance (in steady state).

The response of the reactance regulator is shown in Fig.10. During the transition from capacitive and inductive region a large jump in TCR current is seen.

3.3 Detailed Simulation of SMIB system with TCSC

The system under study is shown in Fig.11. The generator modelling and data is given in the appendix. The
TCSC damping controller uses the speed signal of the generator. The TCSC quiescent reactance is kept in the capacitive vernier region so that there is adequate margin for small signal damping (otherwise the TCSC may hunt about the inductive and capacitive regions—note that there is deadband in between the blocked and bypass modes). This is also important from the point of view of immunity from SSR [4] (TCSC in blocked mode is equivalent to a fixed capacitor). The simulation results (for a pulse disturbance in generator torque) show that if only capacitive compensation is used, then the damping is inadequate. The use of both capacitive and inductive compensation can damp the large power swings.

Figure 7: Capacitor Voltage Synchronisation: Large change in Firing Angle

Figure 8: Line Current Synchronisation: Large change in Firing Angle (151-121-161 degrees)

Figure 9: Reactance Controller

Figure 10: Response of Reactance Controller

Figure 11: System Under Study
4 Conclusions

The contributions and conclusions of this paper are summarized below:

1. There is a critical dependence of the damping ability of a TCSC on its limits (and therefore the rating) especially for large swings.

2. In this context, it is inadequate to view oscillatory instability and its mitigation as a purely small signal problem.

3. A closed loop scheme for controlling reactance is proposed for both inductive and capacitive regions.

4. Detailed simulation validates the performance of the controller; the use of inductive region can considerably enhance damping.

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References


\[
-\frac{1}{\omega_B} \psi_d - (1 + s_q)\psi_q - R_ai_d = v_d
\]
\[
-\frac{1}{\omega_B} \psi_q + (1 + s_q)\psi_q - R_ai_q = v_q
\]
where
\[
i_d = \frac{\psi_d - E'_d}{x'_d}
\]
\[
i_q = \frac{\psi_q + E'_q}{x'_q}
\]

It is assumed that the zero sequence angular frequency in rad/s, \(s_q\) is the generator slip, \(i_d\) and \(i_q\) are d and q axes components of armature current, \(v_d\) and \(v_q\) are d and q axes components of machine terminal voltage respectively.

In order to have a common axis of reference with the network \(v_{gd}\) and \(v_{gq}\) are transformed to Kron's reference frame (D-Q axes) using the transformation
\[
\begin{bmatrix}
  v_{gd} \\
  v_{gq}
\end{bmatrix} =
\begin{bmatrix}
  \cos \delta & -\sin \delta \\
  \sin \delta & \cos \delta
\end{bmatrix}
\begin{bmatrix}
  v_{gD} \\
  v_{gQ}
\end{bmatrix}
\]
where \(v_{gD}\) and \(v_{gQ}\) are D and Q axes components of machine terminal voltage respectively. \(\delta\) is the angle between the D-Q (synchronously rotating frame) axes and the d-q axes. \(i_D\), \(i_Q\) and \(i_d\), \(i_q\) are similarly related.

**Rotor**: The equations for rotor windings are
\[
\frac{dE'_d}{dt} = \frac{1}{T'_{d0}} \left[ -E'_d - (x_q - x'_d)i_q \right]
\]
\[
\frac{dE'_q}{dt} = \frac{1}{T'_{q0}} \left[ -E'_q + E_{fd} + (x_d - x'_q)i_d \right]
\]
where \(T'_{d0}\) and \(T'_{q0}\) are the open circuit d and q axes transient time constants and \(E_{fd}\) is the field voltage.

**Swing equation** The electrical torque of the generator is given by,
\[
T_e = \frac{x'_d - x'_q}{x'_d x'_q} \psi_d \psi_q + \frac{\psi_d E'_q}{x'_q} + \frac{\psi_q E'_d}{x'_d}
\]

The swing equation is given by,
\[
s_g = \frac{1}{2H_g} (T_m - T_e)
\]

Note that in the above equation generator and turbine is represented as one mass, this equation needs to be modified when studying torsional dynamics (SSR).

**Excitation System**: Automatic Voltage Regulator (AVR) with single time constant as shown in Fig.13 is considered. Here \(V_g\) is machine terminal voltage, \(V_s\) is output from PSS. State equation for the excitation system is
\[
\dot{E}_{fd} = -\frac{1}{T_E} E_{fd} + \frac{K_E}{T_E} (V_{ref} + V_s - V_g)
\]
\[
V_g = \sqrt{V_{gD}^2 + V_{gQ}^2}
\]

**Equation describing network (refer Fig.11)**: The equation describing the network in the DQ frame can be written as,
\[
\begin{bmatrix}
  V_{gD} \\
  V_{gQ}
\end{bmatrix} = [F1]
\begin{bmatrix}
  i_D \\
  i_Q
\end{bmatrix} + [F2]
\begin{bmatrix}
  \frac{di_D}{dt} \\
  \frac{di_Q}{dt}
\end{bmatrix}
\]
\[
+ \begin{bmatrix}
  V_{CD} \\
  V_{CQ}
\end{bmatrix} + \begin{bmatrix}
  0 \\
  0
\end{bmatrix}
\]
where,
\[
F1 = \begin{bmatrix}
  R_E & X_E \\
  -X_E & R_E
\end{bmatrix}
\]
\[
F2 = \begin{bmatrix}
  X_E & 0 \\
  0 & X_E
\end{bmatrix}
\]

\(R_E\) and \(X_E\) are the line reactance and resistance respectively. The equations governing TCSC capacitor dynamics are:
\[
\dot{V}_{CD} = -\omega_B V_{CQ} + i_{Dc} \omega_B X_C
\]
\[
\dot{V}_{CQ} = \omega_B V_{CD} + i_{Qc} \omega_B X_C
\]
where,
\[
i_{Dc} = i_D - i_{Dter}
\]
\[
i_{Qc} = i_Q - i_{Qter}
\]
\(i_{Dter}\) and \(i_{Qter}\) are the TCR currents which are dependent on the state of the thyristors and reactor dynamics.  

**Data for Detailed Simulation Study**
- \(T_{d0} = 6.66; T_{q0} = 0.44; H = 3.542; f = 50Hz; x_d = 1.7572; x_q = 0.4245; x' = 1.5845; x'_q = 1.04; X_E = 0.4; R_E = 0.04;\) Static Exciter : \(K_A = 400; T_A = 0.025; Efdmax = 6; Efdmin = -6\) Sending End Volt-
- \(age: V_s = 1.0 \angle 20^\circ,\) Receiving End Voltage \(V_s = 1.0 \angle 0^\circ,\)
- TCSC : \(X_{FC} = 0.1, X_L = 0.015\)