A Comparative study of SSR Characteristics of TCSC and SSSC

K. R. Padiyar and Nagesh Prabhu
Department of Electrical Engineering
Indian Institute of Science, Bangalore. INDIA

Abstract - The advent of series FACTS controllers, Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC) has made it possible not only for the fast control of power flow in a transmission line, but also for the mitigation of SubSynchronous Resonance (SSR) in the presence of fixed series capacitors. While the technology of TCSC using thyristor valves is well established, SSSC based on Voltage Source Converter (VSC) with GTO valves is an emerging controller and has several advantages compared to TCSC [1].

This paper presents a comparative study of SSR characteristics of TCSC and SSSC based on the analysis of a system adapted from IEEE first benchmark model (FBM). The analysis is based on D-Q models of the FACTS controllers. It is shown that, while the vernier operation (with constant reactance control) of a TCSC leads to damping of the critical torsional mode, the constant reactive voltage operation of SSSC has the effect of reducing the electrical resonance frequency, which detunes the SSR. However, this leads to the possibility of a higher torsional mode being destabilized when the series effective resistance is low. This paper also presents a simple, yet an effective method of designing SubSynchronous Damping Controller (SSDC) with input from line current magnitude. The results from the linear analysis are validated using transient simulation based on detailed nonlinear system model.
Keywords - FACTS, SSR, TCSC, SSSC, SSDC, damping torque, transient simulation

1 INTRODUCTION

SERIES compensation of long lines using fixed capacitors is an economic solution to the problem of enhancing power transfer and improving system stability. However series compensated transmission lines connected to turbo generators can result in SSR due to negative damping introduced by the electrical network [2]. This can cause self excitation due to torsional interaction (TI) and induction generator effect(IGE). The reduction of damping at torsional frequencies can also result in magnification of shaft torque oscillations caused by transient disturbances. The hybrid series compensation consisting of suitable combination of passive elements and FACTS controllers such as TCSC or SSSC can be used to mitigate SSR.

In this paper, the analysis of SSR of a series compensated system with TCSC and SSSC is presented. The analysis of SSR is carried out based on frequency domain method, eigenvalue technique and transient simulation. The results based on linear analysis are validated using transient simulation based on nonlinear system model.

A comparative study of the SSR characteristics of TCSC and SSSC is presented with the analysis of a system based on IEEE FBM. The transient simulation considers 3 phase, nonlinear model of the system with the detailed model of the FACTS controller, considering switching action of thyristors / GTOs. The linear analysis (based on the D-Q model) considers only the dynamic phasors representing fundamental frequency components in the network, ignoring harmonics introduced by the switching action.

The work presented in this paper is also aimed at establishing the validity of D-Q model in the case of SSSC and the application of SSDC for damping the critical torsional mode. The design of SSDC (with line current as input) is based on the damping torque analysis.

The paper is organized as follows. Section-2 describes the modelling of TCSC and SSSC. Section-3 describes a case study based on IEEE FBM and compares the SSR characteristics of TCSC and SSSC. The design of SSDC and its performance evaluation is presented in section-4. The major conclusions of the paper are given in section-5.

2 MODELLING OF TCSC AND SSSC

2.1 Modelling of TCSC

The schematic of TCSC is shown in Fig. 1. The TCSC is modelled in detail taking into consideration of the switching action of thyristors for transient simulation. The eigenvalue analysis is based on the dynamic phasor model of TCSC given in reference [3], where the TCSC is modelled as a variable capacitor.

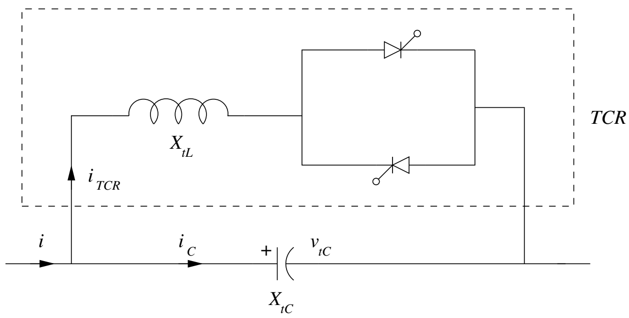

Figure 1: Schematic representation of TCSC

The equations of TCSC in D-Q frame of reference can be given as

$$\frac{dV_{tCQ}}{dt} = (I_Q + b_{Ceff}V_{tCD})\frac{\omega_B}{b_{CtC}} \quad (1)$$

$$\frac{dV_{tCD}}{dt} = (I_D - b_{Ceff}V_{tCQ})\frac{\omega_B}{b_{CtC}} \quad (2)$$

where,

$$\begin{aligned} b_{CtC}\ (p.u.) &= C_{tC}\ (p.u) = \frac{1}{X_{tC}}\ (p.u.) \\ b_{Ceff}\ (p.u.) &= C_{eff}\ (p.u) \\ L_{tL}\ (p.u.) &= X_{tL}(p.u.) \end{aligned}$$

$$C_{eff}(\sigma) = \left[\frac{1}{C_{tC}} - \frac{4}{\pi}\left\{\frac{1}{2C_{tC}}\frac{1}{1-k_t^{-2}}\left(\frac{\sigma}{2}+\frac{\sin(\sigma)}{2}\right)\right.\right.$$
$$\left.\left. + \frac{\omega_r L_{tL} S k_t}{k_t^2-1}\cos^2(\frac{\sigma}{2})\left(\tan(\frac{\sigma}{2}) - k_t\tan(\frac{k_t\sigma}{2})\right)\right\}\right]^{-1}$$

where
$\omega_r = \sqrt{\frac{1}{C_{tC}L_{tL}}}$, $S = \frac{1}{1-k_t^{-2}}$
$k_t = \sqrt{\frac{X_{tC}}{X_{tL}}}$
The prevailing conduction angle σ can be approximated as

$$\begin{aligned} \sigma &= \sigma^* + 2\phi \\ &\approx \sigma^* + 2arg[-jI\overline{V_{tC}}] \qquad (3) \\ &= \sigma^* + 2arg\left[(I_D V_{tCQ} - I_Q V_{tCD})\right. \\ &\qquad \left. -j(I_Q V_{tCQ} + I_D V_{tCD})\right] \qquad (4) \end{aligned}$$

where $\sigma^* = \pi - 2\alpha^*$ is the conduction angle reference and $\overline{(.)}$ denotes the complex conjugate.

To simplify the analysis, only constant firing angle control is considered. In steady state, this is equivalent to the constant reactance control.

2.2 *Modelling of SSSC*

The Fig. 2 shows the schematic representation of SSSC.

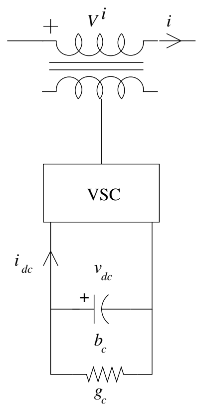

Figure 2: SSSC as a series FACTS controller

Here, the SSSC is realized by a combination of 12 pulse and three level configuration [4]. The three level converter topology greatly reduces the harmonic distortion on the ac side [5, 6, 7, 8, 9]. The detailed three phase model of SSSC is developed by modelling the converter operation by switching functions [4, 10].

When switching functions are approximated by their fundamental frequency components, neglecting harmonics, SSSC can be modelled by transforming the three phase voltages and currents to D-Q variables using Kron's transformation [11]. The SSSC can be represented functionally as shown in Fig. 3.

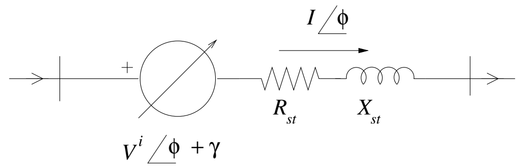

Figure 3: SSSC as a series FACTS controller

In Fig. 3, R_{st} and X_{st} are the resistance and reactance of the interfacing transformer of VSC. The magnitude control of converter output voltage V^i is achieved by modulating the conduction period affected by dead angle of converter while dc voltage is maintained constant.

The converter output voltage can be represented in D-Q frame of reference as:

$$V^i = \sqrt{{V_D^i}^2 + {V_Q^i}^2} \qquad (5)$$

$$V_D^i = k_m V_{dc}\sin(\phi+\gamma) \qquad (6)$$

$$V_Q^i = k_m V_{dc}\cos(\phi+\gamma) \qquad (7)$$

where $k_m = k\ \cos\beta_{se}$; $k = \frac{2\sqrt{6}}{\pi}$ for a 12 pulse converter.

From control point of view it is convenient to define the active voltage ($V_{P(se)}$) and reactive ($V_{R(se)}$) voltage injected by SSSC in terms of variables in D-Q frame (V_D^i and V_Q^i) as follows.

$$V_{R(se)} = V_D^i\cos\phi - V_Q^i\sin\phi \qquad (8)$$

$$V_{P(se)} = V_D^i\sin\phi + V_Q^i\cos\phi \qquad (9)$$

Here, positive $V_{R(se)}$ implies that SSSC injects inductive voltage and positive $V_{P(se)}$ implies that it draws real power to meet losses.

The dc side capacitor is described by the dynamical equation as,

$$\frac{dV_{dc}}{dt} = -\frac{g_c\omega_b}{bc}V_{dc} - i_{dc}\frac{\omega_b}{bc} \qquad (10)$$

where $i_{dc} = -[k_m sin(\phi+\gamma)I_D + k_m cos(\phi+\gamma)I_Q]$, I_D and I_Q are the D-Q components of the line current.

2.3 *Type-1 controller*

In this type of controller, both magnitude (modulation index k_m) and phase angle of converter output voltage (γ) are controlled. The capacitor voltage is maintained at a constant voltage by controlling the active component of the injected voltage $V_{P(se)}$. The real voltage reference $V_{P(se)(ord)}$ is obtained as the output of DC voltage controller. The reactive voltage reference $V_{R(se)(ord)}$ may be kept constant or obtained from a power scheduling controller. However, for the SSR analysis constant reactive voltage control is considered.

It should be noted that harmonic content of the SSSC injected voltage would vary depending upon the operating point since magnitude control will also govern the switching. The capacitor voltage reference can be varied (depending on reactive voltage reference) so as to give optimum harmonic performance. In three level 12-pulse converter, dc voltage reference may be adjusted by a slow controller to get optimum harmonic performance at $\beta_{se} = 7.5^o$ in steady state.

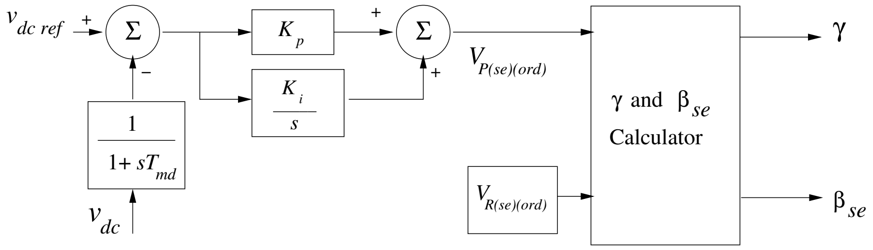

Figure 4: Type-1 controller for SSSC

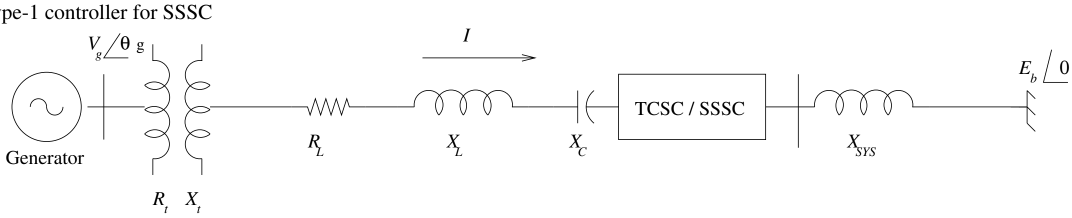

Figure 5: Modified IEEE First Benchmark Model with SSSC

The structure of type-1 controller for SSSC is given in Fig. 4. In Fig. 4, γ and β_{se} are calculated as

$$\gamma = tan^{-1}\left[\frac{V_{R(se)(ord)}}{V_{P(se)(ord))}}\right] \tag{11}$$

$$\beta_{se} = \cos^{-1}\left[\frac{\sqrt{V^2_{P(se)(ord)} + V^2_{R(se)(ord)}}}{kV_{dc}}\right] \tag{12}$$

3 A CASE STUDY

The system considered is a modified IEEE FBM [12] which is represented schematically in Fig. 5. It consists of a generator, turbine, and series compensated long transmission line in series with the TCSC or SSSC.

The modelling aspects of the electromechanical system comprising the generator, the mass-spring mechanical system, the excitation system, power system stabilizer (PSS) with torsional filter, the transmission line containing the series capacitor are discussed in [2].

The analysis is carried out on the IEEE FBM based on the following initial operating condition and assumptions.

1. The generator delivers 0.9 p.u. power to the transmission system.

2. The input mechanical power to the turbine is assumed constant.

3. The total series compensation level is set at 0.6 p.u.(60% of the transmission line reactance).

The following cases are considered for the analysis.
Case-1: Without TCSC/SSSC (compensation only by fixed capacitor, $X_c = 0.60$)
Case-2: With TCSC (X_c=0.40, $X_{TCSC} = 0.20$ with vernier ratio=X_{TCSC}/X_{tc}=1.25)
Case-3: Without TCSC/SSSC,$X_c = 0.40$
Case-4: With SSSC (X_c=0.40,$X_{SSSC} = 0.20$ with constant reactive voltage control).

3.1 Damping torque analysis[2, 13]

The damping torque due to electrical network neglecting IGE is evaluated in the range of frequency of 1-300 rad/sec.

Fig. 6 shows variation of damping torque for cases-1 and 2. It is to be noted that,with case-1, the damping torque is maximum negative at a frequency of around 127 rad/sec which matches with the frequency of torsional mode-2 and adverse torsional interactions are expected. When TCSC operating with vernier control, The peak negative damping is significantly reduced and occurs at about 130 rad/sec. This example illustrates the fact that, the vernier operation of TCSC (constant reactance control) is adequate to damp the Subsynchronous Oscillations (SSO) in most of the cases [14].

The variation of damping torque with cases 3 and 4 is shown in Fig. 7. In case-3, the maximum undamping occurs at about 173 rad/sec and does not coincide with any of the torsional mode and the system is stable. However, the inclusion of additional compensation of 20% by SSSC (case-4 with constant reactive voltage control of SSSC) causes the electrical resonant frequency (ω_{er}) to increase and the frequency of subsynchronous network mode ($\omega_0 - \omega_{er}$) is reduced (158 rad/sec) as indicated in Fig 7. This network mode is very close to the frequency of torsional mode-3.

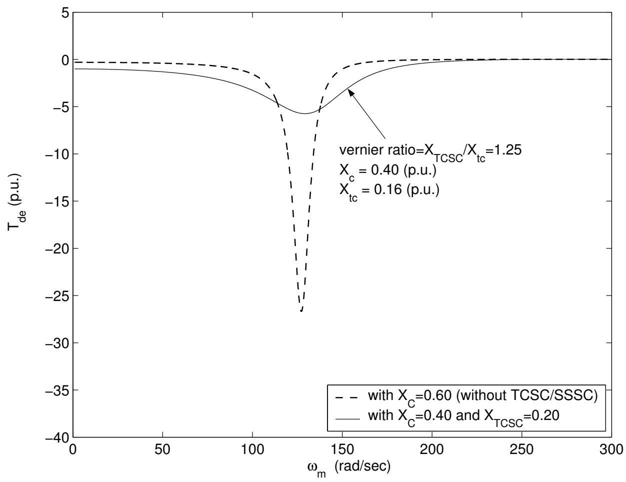

Figure 6: Variation of damping torque with and without TCSC

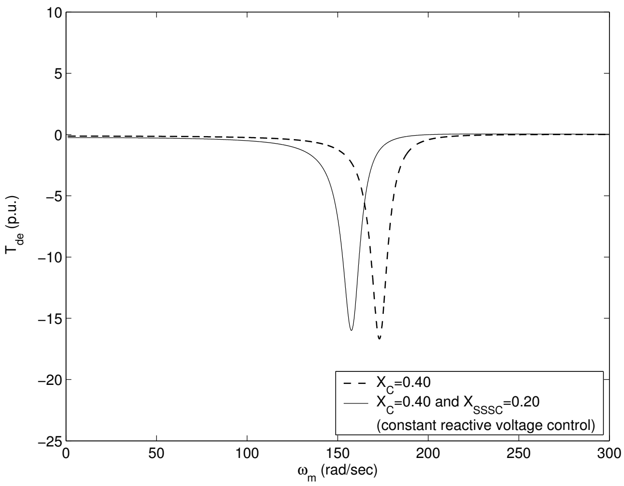

Figure 7: Variation of damping torque with and without SSSC

3.2 *Eigenvalue analysis*

In this analysis, the turbine-generator mechanical damping is considered and generator is modelled with 2.2 model [11]. The mechanical system of FBM is modelled as a multi-mass, mass spring damper system[2, 11]. The overall system is linearized about an operating point and the eigenvalues of the system matrix [A] are given in Table 1 for cases-1 and 2.

Mode	With fixed capacitor X_c=0.60 (case-1)	With fixed capacitor X_c=0.40 and X_{TCSC}=0.20 (case-2)
0	$-1.790 \pm j\ \ 6.281$	$-1.684 \pm j\ \ 6.300$
1	$-0.184 \pm j\ 99.137$	$-0.0774 \pm j\ 98.972$
2	$0.190 \pm j\ 127.000$	$-0.0315 \pm j\ 127.010$
3	$-0.644 \pm j\ 160.440$	$-0.5812 \pm j\ 160.460$
4	$-0.367 \pm j\ 202.830$	$-0.3526 \pm j\ 202.820$
5	$-1.850 \pm j\ 298.170$	$-1.8504 \pm j\ 298.170$
Network mode subsynchronous, $(\omega_0 - \omega_{er})$		
	$-4.222 \pm j\ 127.640$	$-27.163 \pm j\ 133.290$
Network mode supersynchronous, $(\omega_0 + \omega_{er})$		
	$-5.740 \pm j\ 626.740$	$-28.101 \pm j\ 584.010$

Table 1: Torsional mode eigenvalues of the system with and without TCSC

Table 1 shows that, with case-1, mode 2 is unstable at the operating point considered. The inclusion of TCSC operated with the vernier ratio 1.25 stabilizes the unstable torsional mode-2. Although the damping of mode-1 is reduced, the system is stable. The damping of mode 3 and 4 are marginally reduced. Mode-5 is not affected as its modal inertia is very high. These results are in agreement with the damping torque analysis. The damping of subsynchronous network mode is increased with marginal increase in the frequency. It is observed that, the vernier operation of TCSC is adequate for the mitigation of SSR.

Table 2 shows the eigenvalues for case-3 and case-4. The system is stable at these operating points. It is to be noted that when the fixed capacitor provides 40% compensation (Case-3, $X_C = 0.40$), the frequency of subsynchronous network mode is $\omega_{sub} = (\omega_0 - \omega_{er}) = 172.8$ rad/sec is in agreement with damping torque results. The effect of providing additional series compensation by SSSC (case-4) is to increase the electrical resonance frequency (ω_{er}) and decrease the frequency of subsynchronous network mode to 158.4 rad/sec.

Mode	With fixed capacitor X_c=0.40 (case-3)	With fixed capacitor X_c=0.40 and X_{SSSC}=0.20 (case-4)
0	$-1.054 \pm j\ \ 5.786$	$-1.348 \pm j\ \ 5.901$
1	$-0.268 \pm j\ 98.853$	$-0.235 \pm j\ 98.908$
2	$-0.075 \pm j\ 127.020$	$-0.070 \pm j\ 127.030$
3	$-0.562 \pm j\ 160.780$	$-0.128 \pm j\ 160.200$
4	$-0.352 \pm j\ 202.720$	$-0.372 \pm j\ 202.800$
5	$-1.850 \pm j\ 298.170$	$-1.850 \pm j\ 298.170$
Network mode subsynchronous, $(\omega_0 - \omega_{er})$		
	$-4.773 \pm j\ 172.800$	$-5.046 \pm j\ 158.400$
Network mode supersynchronous, $(\omega_0 + \omega_{er})$		
	$-5.714 \pm j\ 580.890$	$-4.884 \pm j\ 566.990$

Table 2: Torsional mode eigenvalues of the system without and with SSSC (constant reactive voltage control)

It has been suggested that SSSC with an energy source on the dc side can be used to compensate the line resistance drop also [15]. However, this can cause destabilization of the critical torsional mode-3 (see column 1 of Table 3 for eigenvalues) when the line resistance R_L is reduced to 0.02 from 0.04 p.u.

Mode	Without SSDC	With SSDC
0	$-1.311 \pm j\ \ 5.936$	$-1.312 \pm j\ \ 5.935$
1	$-0.239 \pm j\ 98.914$	$-0.247 \pm j\ 98.917$
2	$-0.072 \pm j\ 127.030$	$-0.075 \pm j\ 127.030$
3	$0.259 \pm j\ 159.590$	$-0.503 \pm j\ 160.070$
4	$-0.376 \pm j\ 202.790$	$-0.374 \pm j\ 202.790$
5	$-1.850 \pm j\ 298.170$	$-1.850 \pm j\ 298.170$
Network mode subsynchronous, $(\omega_0 - \omega_{er})$		
	$-2.478 \pm j\ 159.020$	$-1.969 \pm j\ 153.750$
Network mode supersynchronous, $(\omega_0 + \omega_{er})$		
	$-2.330 \pm j\ 567.050$	$-2.458 \pm j\ 567.280$

Table 3: Torsional mode eigenvalues of the system with SSSC and SSDC (case-4 with line resistance R_L=0.02)

3.3 *Transient simulation*

The eigenvalue analysis uses linearized equations in D-Q variables where the switching functions are approximated by their fundamental components (converter switchings are neglected). To validate the results obtained from damping torque and eigenvalue analysis, the transient simulation is carried out for small disturbance using detailed model of TCSC/SSSC which considers the switching of thyristors/three phase converter.

The transient simulation of the combined system with detailed three phase model of TCSC/SSSC has been carried out using MATLAB-SIMULINK[16].

The simulation results for 10% decrease in the input mechanical torque applied at 0.5 sec and removed at 1 sec are shown in Figs. 8 and 9 for case-1 and case-2 respectively.

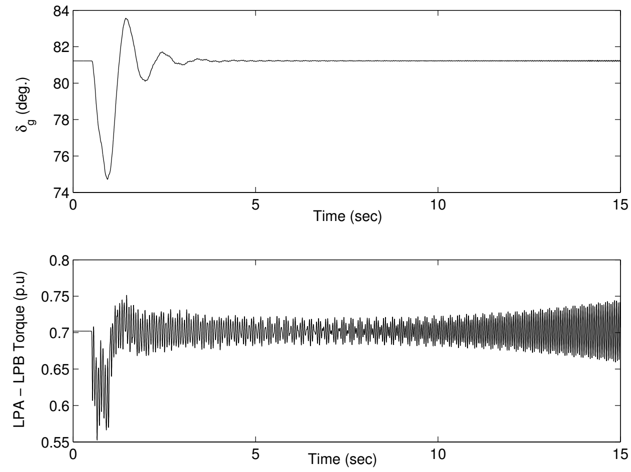

Figure 8: Variation of rotor angle and LPA-LPB section torque for pulse change in input mechanical torque (without TCSC/SSSC case-1).

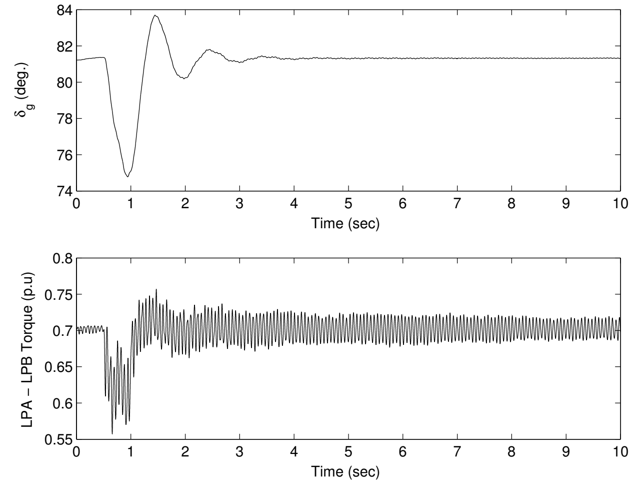

Figure 9: Variation of rotor angle and LPA-LPB section torque for pulse change in input mechanical torque (3ph switching model of TCSC) case-2.

It is observed that, the system is unstable for case-1 as the LPA-LPB shaft torque oscillations grow with time. The decrement factor of critical mode-2 of FBM computed from the FFT analysis of LPA-LPB shaft torque is 0.182 and is comparable with the real part of eigenvalue (0.190) obtained with case-1 (refer Table-1). In case-2 with TCSC operated in vernier mode control, the system is found to be stable and the decrement factor of dominant mode-1 of FBM computed from the FFT analysis of LPA-LPB shaft torque is -0.0828 and is comparable with the real part of eigenvalue (-0.0774) obtained with case-2 (refer Table-1). This indicates the D-Q model is quite accurate for the analysis of SSR with TCSC.

The simulation results with D-Q and 3 phase model of three level SSSC are shown in Fig. 10 and Fig. 11 respectively for case-4 with line resistance 0.04 p.u.

It is observed that, there is excellent match between the simulation results obtained with D-Q and 3 phase models of type-1 SSSC. Also, the LPA-LPB shaft torque oscillation decay with time indicating the system is stable with line resistance of 0.04 p.u.

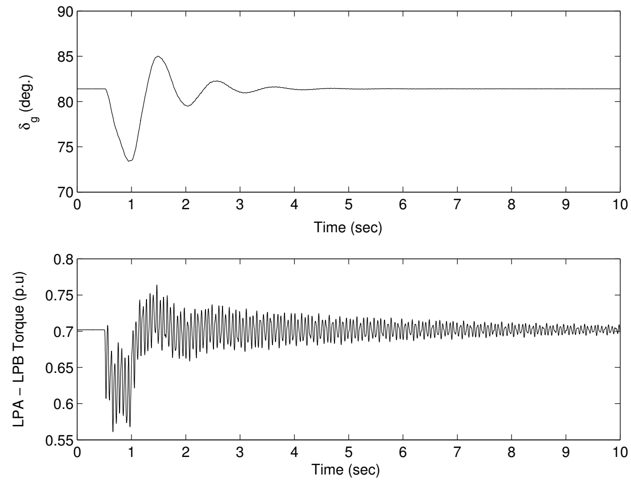

Figure 10: Variation of rotor angle and LPA-LPB section torque for pulse change in input mechanical torque (D-Q model of three level VSC based SSSC (Constant reactive voltage control) case-4).

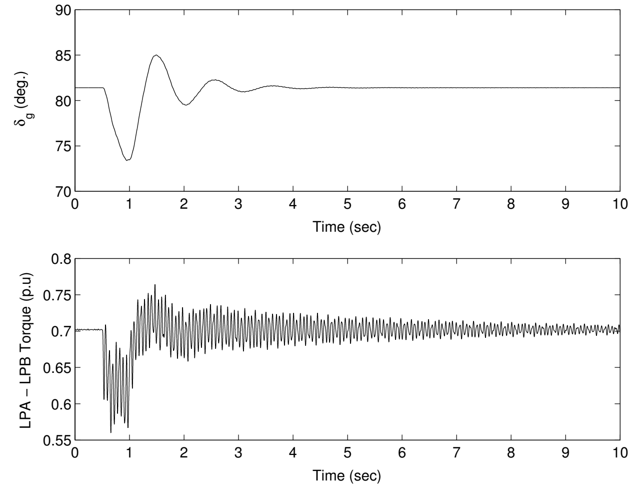

Figure 11: Variation of rotor angle and LPA-LPB section torque for pulse change in input mechanical torque (3 phase model of three level VSC based SSSC (Constant reactive voltage control)case-4).

3.4 Discussion

When the fixed capacitor provides 40% compensation (Case-3, $X_C = 0.40$), the resonance occurs at $\omega_{er} = 203.78$ rad/sec where $X_C = X_L$. When the additional compensation of 20% is provided by SSSC (Case-4), it is found that SSSC offers a constant reactance (X_{se}) and the resonance occurs at a higher frequency of $\omega_{er} = 218.05$ rad/sec where $(X_C + X_{se}) = X_L$ and this is consistent with the subsynchronous network mode frequency $(\omega_0 - \omega_{er} = 377 - 218.05 = 158.95)$ of about 158 rad/sec as obtained with damping torque analysis for case-4. This indicates that, the SSSC is not strictly SSR neutral. However, this increase in frequency is not significant as compared to that obtained with the fixed capacitor (case-1) with X_c=0.6 ($\omega_{er} = 250$ rad/sec in this case).

The effect of hybrid compensation with SSSC (case-4), is to reduce the electrical resonance frequency of the network and also provide some damping. However, this damping is not adequate and there is a danger of adverse torsional interactions at higher frequency (mode-3), when the effective series resistance in the line is reduced (from 0.04 to 0.02 p.u.). To stabilize the system in this case, a

SSDC is required. A method based on damping torque is presented in next section for the design of SSDC.

4 DESIGN OF SSDC FOR SSSC

The damping of torsional modes can be achieved by SSDC. Here, the SSDC with line current signal (locally available) as input modulates the reactive voltage reference to damp the unstable torsional mode (see Fig. 12).

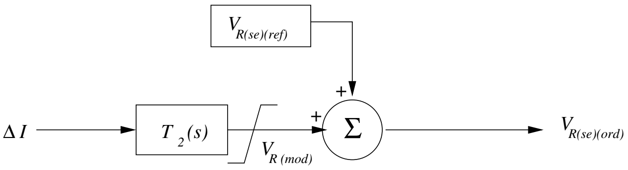

Figure 12: Schematic of SSDC for SSSC

4.1 Design of SSDC based on parameter optimization of the Transfer function $T_2(s)$

The structure of the transfer function is assumed as,

$$T_2(s) = \frac{as+b}{s^2+cs+d} \tag{13}$$

The effect of hybrid series compensation (SSSC with fixed series capacitor) is to introduce negative damping in the critical range of frequencies around the critical torsional mode. The objective of SSDC is to introduce positive damping in this range such that the net damping is positive. Thus, the parameters of the SSDC can be selected such that the difference between the desired (net) damping torque $(T_{de(des)})$ and the actual damping torque (T_{de}) is minimized. The choice of $(T_{de(des)})$ has to be done carefully. Too high a value can result in the network mode becoming unstable.

The objective for optimizing of the parameters 'r' (a, b, c and d) of the transfer function $T_2(s)$ can be stated as,

$$\text{Minimize } f(r) = \sum_{\omega_{min}}^{\omega_{max}} (T_{de(des)}(\omega) - T_{de}(\omega))^2$$

$$\text{subjected to, } \begin{cases} c > 0, \quad c^2 - 4d < 0 \\ \omega_{min} \le \omega \le \omega_{max} \end{cases}$$

The constraints ensure that the poles of the transfer function $T_2(s)$ are complex and have negative real parts.

It order that, the SSDC contributes to the positive damping the $T_{de(des)}$ is chosen to be positive and having a value of 1 (p.u.) for $\omega_{min} \le \omega \le \omega_{max}$. ω_{min} and ω_{max} are chosen as 120 and 180 rad/ sec. The initial values of the transfer function parameters are assumed to be zero. The upper and lower bounds on 'r'' are selected so as to ensure the stability of the system with SSDC.

The optimization routine 'fmincon' of MATLAB is used for the solution. The designed $T_2(s)$ (SSDC) is obtained as

$$T_2(s) = -\frac{100s + 75}{s^2 + 50s + 26000}$$

4.2 Analysis of SSR with SSSC and SSDC

4.2.1 Damping torque analysis with SSDC

The damping torque with detailed D-Q model of type-1 SSSC and SSDC is shown in Fig. 13. It is seen that, the damping is significantly increased with SSDC and causes the damping of SSR.

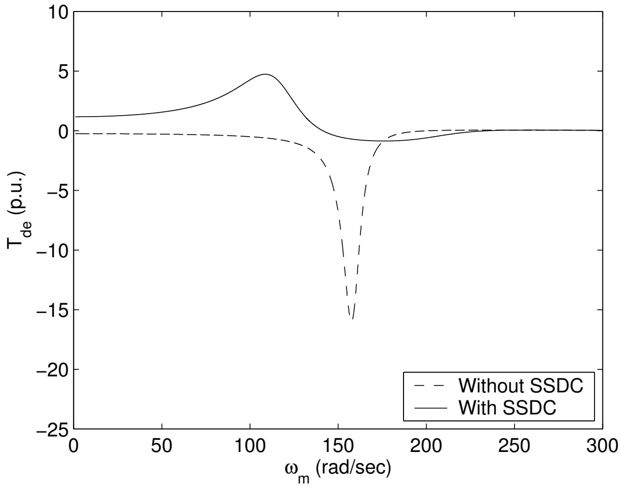

Figure 13: Damping torque with and without SSDC, case-4 (R_L=0.02)

4.2.2 Eigenvalue analysis with SSDC

The eigenvalues of the overall system with D-Q model of type-1 SSSC and SSDC are shown in column-2 of Table 3.

Comparing the eigenvalue results for the system without and with SSDC for case-4 (R_L=0.02) (Table 3), the following observations can be made.

1. The damping of critical mode-3 has significantly improved with SSDC.

2. The damping of swing mode and torsional modes 1 and 2 is increased with SSDC. The damping of mode-4 is practically unaltered. Mode-5 is not affected as its modal inertia is very high.

4.2.3 Transient simulation

The transient simulation of the overall system including SSSC with SSDC has been carried out with 3 phase model using MATLAB-SIMULINK [16].

The simulation results for 10% decrease in the input mechanical torque applied at 0.5 sec and removed at 1 sec with three level VSC based SSSC along with SSDC are shown in Fig. 14 when the line resistance is 0.02 p.u.

The results show that, the SSDC is effective in stabilizing the critical torsional mode and the oscillations decay fast.

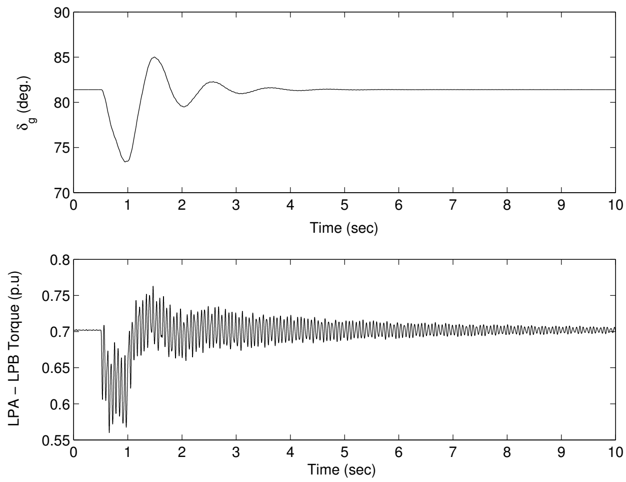

Figure 14: Variation of rotor angle and LPA-LPB section torque for pulse change in input mechanical torque (with detailed three phase model of type-1 SSSC with SSDC, case-4 (R_L=0.02))

5 CONCLUSIONS

In this paper, we have studied the SSR characteristics of a series compensated transmission line with TCSC and SSSC. While constant reactance control is adequate for mitigating SSR in the case of TCSC, a properly designed SSDC is required for damping the critical torsional mode when the effective line resistance is small. A simple yet effective method of design of SSDC to provide positive damping in the critical range of torsional frequencies is presented.

The D-Q model used for SSSC was derived from first principles by neglecting harmonics in the switching functions. The results show that the D-Q model is very accurate in predicting the system performance and the transient simulation based on D-Q model is indistinguishable from the results based on detailed 3 phase model.

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