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Performance of STATCOM-ES in Mitigating SSR

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ABSTRACT

One of the advanced power applications using energy storage is the integration of energy storage technologies with VSC-based FACTS controllers. With the support of energy storage device, FACTS controllers will have the ability to exchange active power or energy with the ac network in steady state. This paper discusses the impact of Static Synchronous Compensator incorporating energy storage device (STATCOM-ES) on subsynchronous resonance (SSR). It also proposes the design of an auxiliary SSR damping controller (SSDC) for STATCOM-ES to damp the subsynchronous oscillations which the system is undergoing because of a series capacitor in the transmission system. The system under consideration is IEEE FBM which is modified to incorporate STATCOM-ES at the electrical midpoint. The investigation of SSR characteristics when a STATCOM - ES operating in bus voltage regulation mode is carried out by eigenvalue and damping torque analysis. Transient analysis based on the nonlinear model is also performed to validate the results obtained by conventional methods.

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1. INTRODUCTION

Subsynchronous Resonance (SSR) is a power system phenomenon which occurs due to the interaction between mechanical system of turbo-alternator and series compensated transmission line resulting in failure of shaft [1]. The behavior of the system undergoing SSR can be analyzed using linear and nonlinear techniques. With the advent of FACTS controllers, it is possible to have control over the AC transmission system parameters [2].

Static Synchronous Compensator (STATCOM) is a VSC-based shunt FACTS controller whose objectives are the improvement of dynamic voltage regulation and stability of the system. A capacitor supported STATCOM has only one control variable which is the reactive current whereas a battery supported STATCOM has two control variables namely active and reactive current [3]. An auxiliary supplementary controller is required to damp the torsional oscillations. The design of subsynchronous damping controller (SSDC) for FACTS controllers is reported in [4-9]. The efficacy of integrating energy storage devices like a battery, fuel cell, supercapacitor etc., to the dc link of STATCOM in enhancing the performance of STATCOM is demonstrated in [10-12]. The authors have shown that there is improvement in dynamic and transient stability of the system by incorporating energy storage at the dc side of STATCOM. But the effect of STATCOM incorporating energy storage (STATCOM-ES) on SSR characteristics has not been investigated till now. Hence, the design of SSDC for STATCOM-ES to mitigate SSR is not yet reported.

The objective of this paper is to investigate the effect of STATCOM-ES on a power system which is undergoing subsynchronous resonance and design a subsynchronous damping controller to mitigate torsional oscillations. The test system is adapted from IEEE FBM [13]. A twelve pulse, three-level STATCOM with Type 1 controller is connected at the electrical midpoint of the line. The dc link is supported by an energy storage device which maintains the dc voltage constant. The STATCOM-ES controller regulates the voltage of the AC bus to which it is connected. SSR is analyzed using eigenvalue and damping torque techniques. The results obtained by these two techniques are validated by carrying out the transient simulation. An auxiliary SSR damping controller (SSDC) is designed for STATCOM-ES to damp subsynchronous oscillations.

The structure of the paper is as follows: Mathematical model and control of STATCOM-ES are given in Section 2. Section 3 explains the different techniques used to analyze SSR characteristics. Section 4 presents the analysis of the result and conclusions are drawn in section 5.

2. TEST SYSTEM

The test system shown in Figure 1 is IEEE FBM model which is modified by parallel connection of 3 level, 12 pulse STATCOM-ES and a fixed shunt capacitor connected at the electrical midpoint of the line. The mechanical system of the generator consists of six masses. The generator is equipped with static exciter and power sytem stabilizer (PSS). System data is given in Appendix-A.

The input mechanical torque is assumed to be constant. Self and mutual dampings are considered in the multi-mass mechanical system. The generator output power is 0.9pu and magnitude of its terminal voltage is 1pu. The ratings of STATCOM-ES and the fixed shunt capacitor are chosen in order to maintain the midpoint bus voltage at 1.015pu. The energy storage device connected to the dc link of STATCOM has a capability to exchange 0.1pu of real power with the ac power network while supplying near rated reactive power. The series compensation level is fixed at 75% of line reactance.

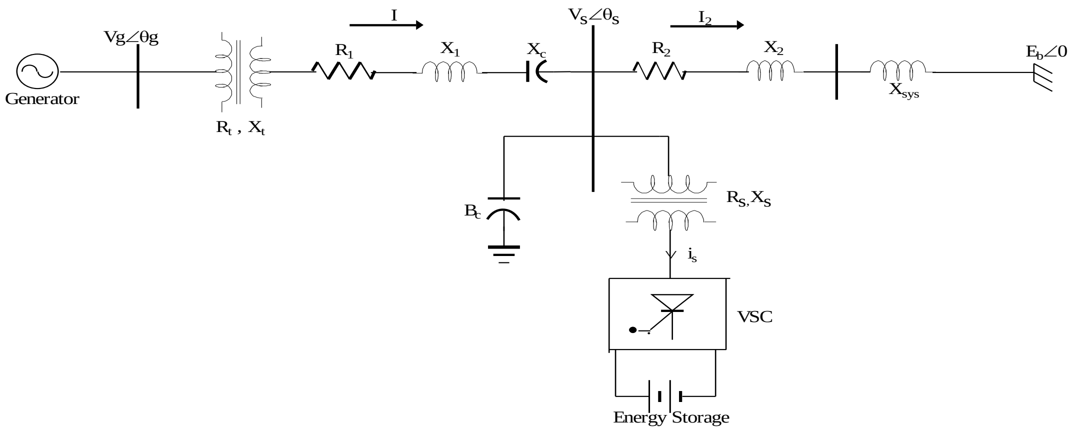


Figure 1. IEEE FBM with STATCOM-ES

2.1. Mathematical Model of STATCOM-ES

A DQ model of 3-level, 12 pulse STATCOM-ES is implemented in MATLAB/SIMULINK. The equations which describe the behavior of STATCOM-ES [14] are given below:

$$\frac{d_{IsD}}{dt} = \frac{-R_S\omega_B}{X_S} I_{sD} - \omega_0 I_{sQ} + \frac{\omega_B}{X_S}[V_{sD} - V_{sD}^i] \quad (1)$$

$$\frac{d_{IsQ}}{dt} = \frac{-R_S\omega_B}{X_S} I_{sQ} + \omega_0 I_{sD} + \frac{\omega_B}{X_S}[V_{sQ} - V_{sQ}^i] \quad (2)$$

where V_s = STATCOM bus voltage, I_s = STATCOM current, V_s^i = STATCOM output voltage, R_s, X_s = resistance and the reactance of transformer, ω_B = base frequency and ω_0 = frequency of the supply. The DQ components of V_s^i are given by

$$V_{sD}^i = K_m V_{dc}\, Sin(\theta + \alpha) \quad (3)$$
$$V_{sQ}^i = K_m\, V_{dc} Cos\,(\theta + \alpha) \quad (4)$$

where V_{dc} = dc link voltage, θ = phase of V_s, α = phase difference between V_s and V_s^i, $K_m = K\cos(\beta)$, β = dead angle and $K = \frac{2\sqrt{6}}{\pi}$ for 12 pulse converter.
The active and reactive currents and powers exchanged by STATCOM-ES in PR variables are given by

$$I_P = I_{sD}\, Sin\, \theta + I_{sQ} Cos\theta \quad (5)$$

$$I_R = -I_{sD}\, cos\, \theta + I_{sQ} Sin\theta \quad (6)$$

$$P^i = I_{sD} V_{sD}^i + I_{sQ}\, V_{sQ}^i \quad (7)$$

$$Q^i = I_{sQ}\, V_{sD}^i - I_{sD}\, V_{sQ}^i \quad (8)$$

2.2. Control of STATCOM-ES

Type 1 controller described in [3] is modified to incorporate active power controller. This controller sets the reference for active current I_{Pref} and real current injection I_P is controlled by the variation of α. Bus voltage controller [4] sets the reference for reactive current I_{Rref} and reactive current injection I_R is controlled by the variation of β. Figure 2 shows the real power and bus voltage controllers of STATCOM where α and β are computed as follows:

$$\alpha = \tan^{-1}\left(\frac{V_{R(ord)}}{V_{P(ord)}}\right) \quad (9)$$

$$\beta = Cos^{-1}\left(\frac{\sqrt{V_{P(ord)}^2 + V_{R(ord)}^2}}{k * V_{dc}}\right) \quad (10)$$

$V_{P(ord)}$ is set by real current controller and $V_{R(ord)}$ is set by reactive current controller and V_C.is the output of auxiliary SSR damping controller which modulates I_{Rref}.

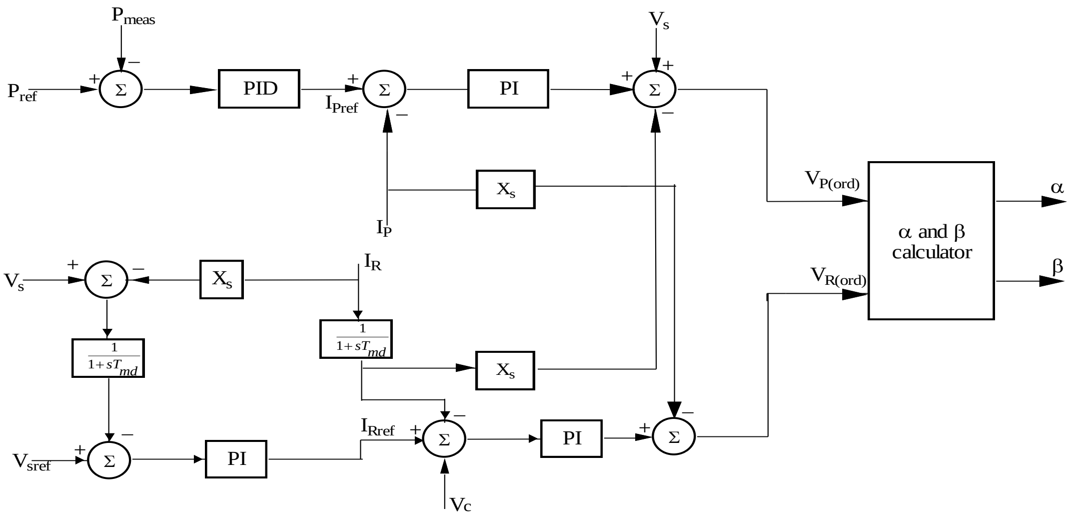


Figure 2. Controller structure of STATCOM-ES

3. ANALYSIS OF SSR

The torsional interactions experienced by the system can be analyzed using linear and nonlinear techniques. In linear analysis, the nonlinear system equations are linearized around an operating point to ascertain the stability of the system. In this paper, damping of mechanical system is considered. The effects of power system stabilizer and exciter are also considered. The investigation of SSR characteristics of system with STATCOM-ES is performed using damping torque method, eigenvalue method and transient simulation. The simulations are carried out using MATLAB/SIMULINK.

a. Damping Torque Analysis

This analysis is carried out in frequency domain and gives approximate results. It is used for the analysis of torsional interactions and determines the stability of torsional modes. The torsional mode is said to be stable if the net damping torque is positive at the torsional mode frequency [1]. A classical model of generator is sufficient to perform this analysis.

b. Eigenvalue Analysis

This analysis is carried out in time domain and gives accurate results compared to damping torque analysis. The generator stator transients are considered by using 2.2 model of synchronous machine [12]. The system equations are linearized around an equilibrium point and eigenvalues of the system are computed. If all the eigenvalues have negative real parts, then the system is considered to be stable.

c. Transient Analysis

This analysis is performed to validate the result obtained by the linear methods. The nonlinearity of the equations is retained while performing transient analysis. A disturbance is applied to the system for a short duration and its behavior is observed.

4. RESULTS AND ANALYSIS

The test system is implemented in MATLAB/SIMULINK. The eigenvalues of the system without and with STATCOM when the series compensation provided by the fixed capacitor X_C=0.375pu (75% of X_L) are shown in Table 1. Without STATCOM, the real part of swing mode is -5.7969 whereas with STATCOM in bus regulation mode and supplying only reactive power, it is -6.5031. Hence, there is an increase in damping of swing mode when STATCOM is connected. The real part of mode 2 is 0.5516 for case-1 and 0.4541 for case-2. This indicates that mode 2 is unstable in both the cases though it is less positive with STATCOM. This necessitates the design of auxiliary SSR damping controller for STATCOM.

Table 1. Torsional and Network modes of IEEE FBM

Modes	Without STATCOM	With STATCOM
N/w (Super)	-4.7863±j624.77	-4.7786±j624.84
N/w (Sub)	-2.4676±j128.35	-2.6232± j128.72
Swing Mode 0	-5.7969±j9.9023	-6.5031±j9.6714
TM1	-0.2382±j99.913	-0.2354±j99.898
TM2	0.5516±j127.42	0.4541±j127.42
TM3	-0.6398±j160.4	-0.6377±j161.73
TM4	-0.3646±j202.85	-0.3642±j202.86
TM5	-1.8504±j298.17	-1.8504±j298.17

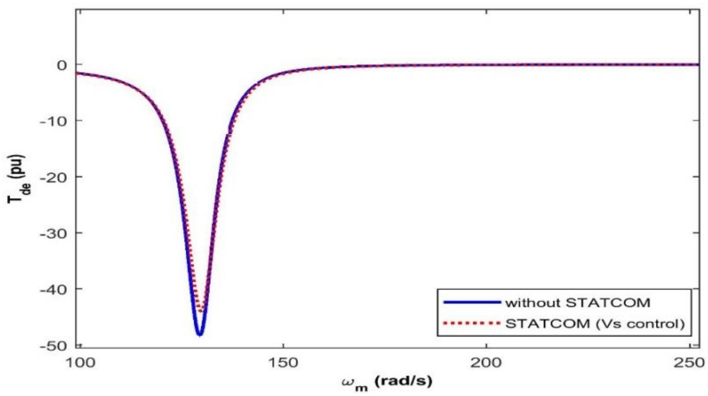


Figure 3. Variation of damping torque with and without STATCOM

The damping torque analysis is also performed for the system without STATCOM and with STATCOM. As seen from Figure 3, the negative peak of damping torque of the system without STATCOM is

47.52pu at 129.6 rad/s whose frequency corresponds to the frequency of torsional mode 2. Hence it is unstable. When STATCOM with voltage control is included into the system, the negative peak of damping torque is reduced to 43.91pu and occurs at 129.8 rad/s. The system is unstable because of the sharp dip near 127 rad/s which again corresponds to frequency of mode 2. There is a good match between eigenvalue analysis and damping torque analysis.

It is required to perform the transient simulation of the system to validate the above results. The analysis is done by applying 10% step decrease in input torque for a duration of 0.5s. Figure 4 shows the time series plot of rotor angle delta and LPA-LPB section torque without STATCOM in the system. The oscillations grow in time which adversely affects the stability of the system.

Figure 5 shows the time series plot of rotor angle and LPA-LPB section torque of the system with STATCOM in bus voltage regulation mode. Though the system remains unstable, there is slight increase in the damping of oscillations as compared to the case where there is no STATCOM.

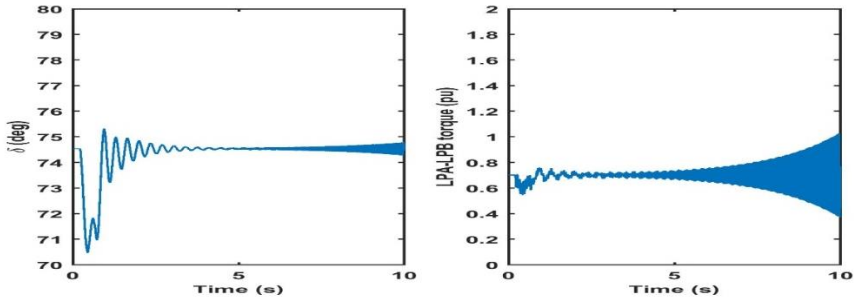


Figure 4. Time series plot of rotor angle and LPA-LPB section torque without STATCOM

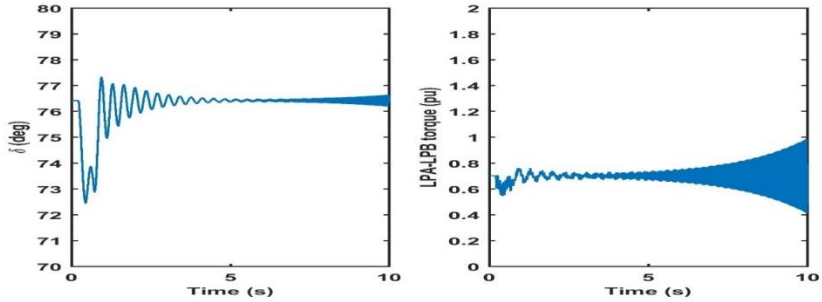


Figure 5. Time series plot of rotor angle and LPA-LPB section torque with STATCOM

4.1. Implementation of Subsynchronous Damping Controller (SSDC)

SSDC is an auxiliary controller used to damp subsynchronous oscillations. The design procedure is based on damping torque analysis and is given in [4]. The input to this controller is Thevenin's voltage derived from V_s and I_s. The output of this controller modulates I_{Rref} so as to increase the damping of torsional modes. X_{th} is the Thevenin's reactance which is 0.1pu.The block diagram is shown in Figure 6. The transfer function of SSDC $T_2(s)$ is of second order which is of the form

$$T_2(s) = \frac{(as+b)}{(s^2+cs+d)} \quad (11)$$

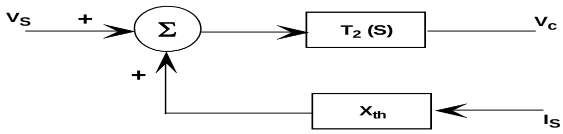


Figure 6. Block diagram of SSDC controller

The controller needs to provide positive damping at critical frequencies and should not affect synchronizing torque. Since mode 2 is unstable, the controller should be designed so as to provide positive damping over a range of 110-135Hz. The design is carried out using SISO tool provided in MATLAB. The transfer function $T_2(s)$ is fitted with curve and is given by

$$T_2(s) = \frac{(-1250.87s + 41574)}{(s^2 + 70.964s + 24097)}$$

Table 2 shows the eigenvalues of the system with SSDC when (a) STATCOM-ES is not exchanging real power (P_{REF}=0pu) (b) STATCOM-ES is absorbing real power (P_{REF}=0.1pu) and (c) STATCOM-ES is injecting real power (P_{REF}= -0.1pu).

In all the three cases, the unstable torsional mode 2 has become stable. There is an improvement in the damping of mode 3 and mode 4 whereas mode 1 damping is slightly decreased when compared to the case without SSDC. In all the three cases, the frequency of subsynchronous network mode which is around 137.5 rad/s does not coincide with any of the frequencies of torsional modes and hence the system is stable. The damping of torsional modes is marginally better when STATCOM-ES draws active power. It is not surprising as the STATCOM-ES emulates a small negative conductance during injection of real power and a small positive conductance during absorption of real power. The damping of network modes is improved when STATCOM-ES injects real power with the ac system.

Table 2. Torsional and Network modes of IEEE FBM with STATCOM-ES and SSDC

Modes	STATCOM-ES P_{REF}=0pu	STATCOM-ES P_{REF}=0.1pu	STATCOM-ES P_{REF}= -0.1pu
N/w (Super)	-4.8943±j624.7	-4.8113±j624.7	-4.9688±j624.72
N/w (Sub)	-0.8375±j137.56	-0.7832±j137.6	-0.8779±j137.54
Swing Mode 0	-6.448±j9.5453	-6.4603±j9.525	-6.4331±j9.568
TM1	-0.1959±j99.804	-0.1961±j99.808	-0.1959±j99.801
TM2	-0.0219±j127.24	-0.0225±j127.24	-0.0216±j127.24
TM3	-0.7271±j160.36	-0.7285±j160.36	-0.7259±j160.36
TM4	-0.3833±j202.86	-0.3833±j202.86	-0.3832±j202.86
TM5	-1.8504±j298.17	-1.8504±j298.17	-1.8504±j298.17

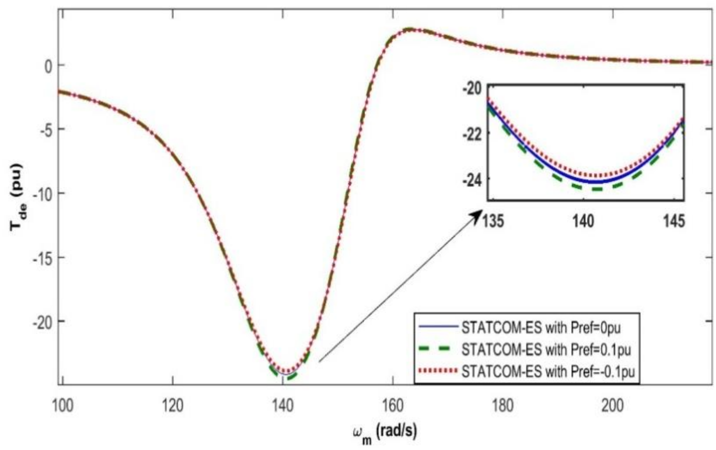
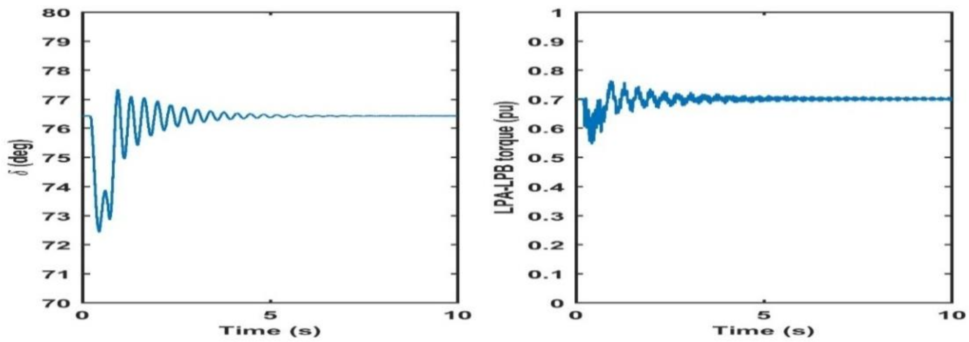


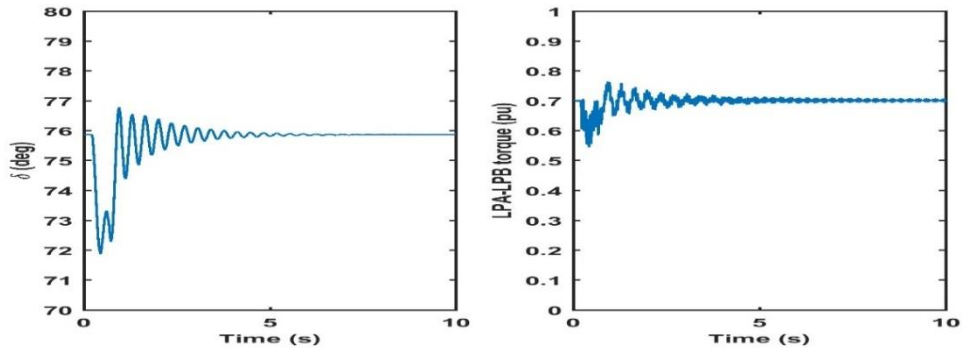
Figure 7. Variation of damping torque with STATCOM-ES and SSDC

The plot of damping torque T_{de} with torsional mode frequency for all the three cases is as shown in Figure 7. The negative peak damping is reduced to near about -24pu, and it occurs near 141 rad/s. It does not overlap with any of the torsional mode frequencies. Hence the system is stable. The negative peak damping when STATCOM-ES is injecting real power is slightly less as compared to the case where there is absorption of real power. SSDC also provides positive damping for the critical range of frequencies and hence damping of mode 3 and mode 4 has increased. Thus, the results obtained by tdamping torque method are validated by eigenvalue analysis.

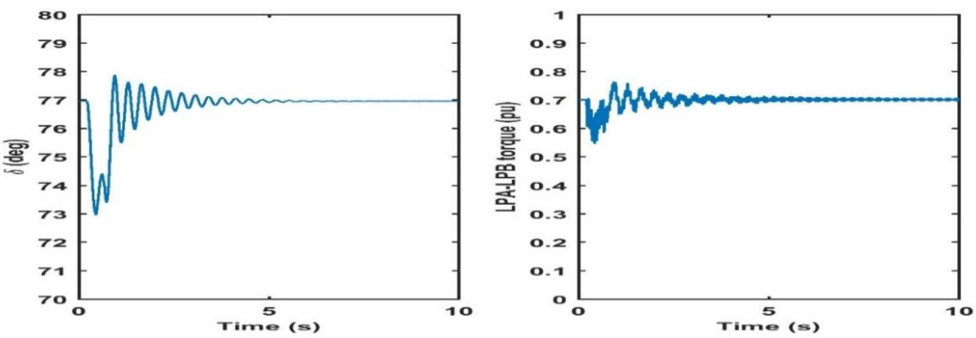
The transient response of the system for the three cases with SSDC is shown in Figure 8. The rotor angle and LPA-LPB section torque oscillations die out as time progresses indicating a stable system in all the three cases when STATCOM-ES incorporates SSDC. The results obtained by the transient simulation are in agreement with the linear methods.



(a) Pref= 0pu



(b) Pref= 0.1pu



(c) Pref= -0.1pu

Figure 8. Time series plot of rotor angle and LPA-LPB section torque with STATCOM-ES and SSDC

5. CONCLUSION

The aim of this paper is to analyze the effect of STATCOM-ES on SSR in a hybrid compensated system. The fixed compensation is given by series capacitor and a shunt capacitor. It is shown that the presence of STATCOM-ES does not significantly affect the SSR characteristics of the system. It is found that STATCOM-ES in voltage control mode slightly reduces the peak negative damping torque. But still it needs an auxiliary SSR damping controller to damp the oscillations of critical torsional modes. The design of SSDC for STATCOM-ES is based on damping torque analysis. The parameters of SSDC are obtained using curve fitting technique. It is shown that unstable torsional mode becomes stable as SSDC provides positive damping at this critical frequency. In addition to mitigating SSR, STATCOM-ES with SSDC is capable of absorbing or injecting real power to the ac system.

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Appendix-A

Shunt capacitor: Bc = 0.25213pu
Exciter: Ka=200; Ta=0.05; Tmd=0.002
PSS parameters: Ks= 4; Tw=10; T1=0.1; T2=0.01; Wn=22; eta=0.5
STATCOM rating: MVA=150; Rs=0.01pu; Xs=0.15; V_{dc}=0.7pu