

Analysis and Mitigation of Multimodal SSR using Kalman Filter based SSDC in Non-identical Generators

S. Venkateswarlu¹, M. Janaki^{2*}

¹Research Scholar, School of Electrical Engineering, Vellore Institute of Technology, Vellore, India, Email Id: chvreddy237@gmail.com

²Associate Professor, School of Electrical Engineering, Vellore Institute of Technology, Vellore, India, Email Id: mjanaki74@gmail.com

ABSTRACT

The multimodal non-identical generators having close frequency modes may complicate the design of Subsynchronous Damping Controller (SSDC). In this paper, we propose a multimodal SSDC using Kalman Filter (KF) to damp Subsynchronous Resonance (SSR). The proposed SSDC is incorporated with Static Synchronous Series Capacitor (SSSC). The system is adapted from the IEEE First Benchmark Model (FBM) with two non-identical generators in parallel. One of the generators has a six-mass mechanical system and other has a four-mass mechanical system. The KF based SSDC is designed to adjust the SSSC injected voltage as to suppress the subsynchronous currents flow to generators. The parameters of KF based SSDC are selected to enrich the torsional modes of both generators. The results show that the peak negative damping viewed at both generators is substantially reduced with proposed KF based SSDC and mitigate SSR.

Key words : Static synchronous series capacitor, Non-identical generators, Subsynchronous resonance, Kalman filter, Subsynchronous damping controller.

1. INTRODUCTION

The long transmission lines are most used to transmit power from remote resources. Nonetheless, the power loading of a long transmission line is limited by thermal constraint and stability issues. In power systems, the series capacitor compensation is an affordable solution to increase the power transfer capability of the transmission lines. Adversely, the use of series capacitor compensation can cause SSR problem which can lead to extreme interactions between the mechanical system of the turbine-generator and the electrical network. Thereby, the shaft breakage of the turbine-generator occurs after cumulative SSR events. The hybrid series compensation with the incorporation of FACTS devices is made possible to counteract the SSR by using an SSDC at its

controller. Also, the use of FACTS devices provides the controllability of power flow through transmission lines, and thereby the system stability can be improved [1]-[4].

In the literature there exist various SSDCs with FACTS devices, which are intended to enrich the stability of the system and mitigate the SSR. The SSSC with Band Pass Filter (BPF) based SSDC in one phase and fixed capacitors in other two phases is used to mitigate subsynchronous oscillations and also damp the power swings [5]. The BPF and Band Stop Filter (BSF) based SSDC for STATCOM is used to extract the desired subsynchronous frequency components and the BSF is used to reject the other frequency components [6]. In [7]-[9], the authors proposed Low Pass Filter (LPF) based SSDC to mitigate SSR. The LPF based SSDC is designed for Single Machine connected to Infinite Bus (SMIB) and it is used to extract the fundamental and subsynchronous components from the generator terminal voltage. In [10], the authors proposed BPF based SSDC to suppress the subsynchronous currents following through the generator armature terminal. The Kalman Filter (KF) based SSDC is a highly frequency selective [11].

Recently, the researchers proposed SSDCs for multi-machine system to enhance the torsional damping and to mitigate the multimodal SSR. In [12], [13], the authors reported Generator Terminal Subsynchronous Damping Controller (GTSDC) for multi-machine system using BPFs. The BPFs are used to extract the torsional mode frequencies from the speed deviations of the generator. The disadvantage of GTSDC is could not maintain system stability. The combined scheme of Supplementary Excitation Damping Controller (SEDC) and GTSDC is proposed to mitigate SSR and enhance the system stability [14], [15]. In [16], the authors proposed family of Subsynchronous Dampers (SSDs) for multi-machine system using BPFs to damp the multimodal SSR. The Newton-Raphson (N-R) and Automatic Differentiation methods are utilized to explore the effect of TCSC on power flow is reported in [17].

It is noted that the design of multimodal SSDC in multi-machine system is more complicated due to the widespread close natural frequencies of mechanical system.

In this paper, we proposed a KF based SSDC to enrich all the critical torsional modes of both generators and to mitigate the multimodal SSR. The analysis of SSR is done on the modified IEEE FBM with SSSC and KF based SSDC. The KF based SSDC is designed to reduce the negative damping torque at the torsional mode frequencies. The output of KF based SSDC is used to adjust the SSSC injected voltage as to diminish the subsynchronous frequency currents in the line. The results show that the peak negative damping viewed at both generators is considerably reduced with proposed KF based SSDC and mitigate the multimodal SSR.

The other sections are organized as: The Section II depicts the system description with SSSC type-1 controller and the initial operating points. The design of KF based SSDC is described in Section III. The results are illustrated in Section IV. At last, the conclusions are presented in Section V.

2. DESCRIPTION OF SYSTEM AND MODELING

This section presents a brief overview about the system diagram, Type-1 controller of SSSC, and operating points at which the analysis is performed.

2.1 System diagram and methods of SSR analysis

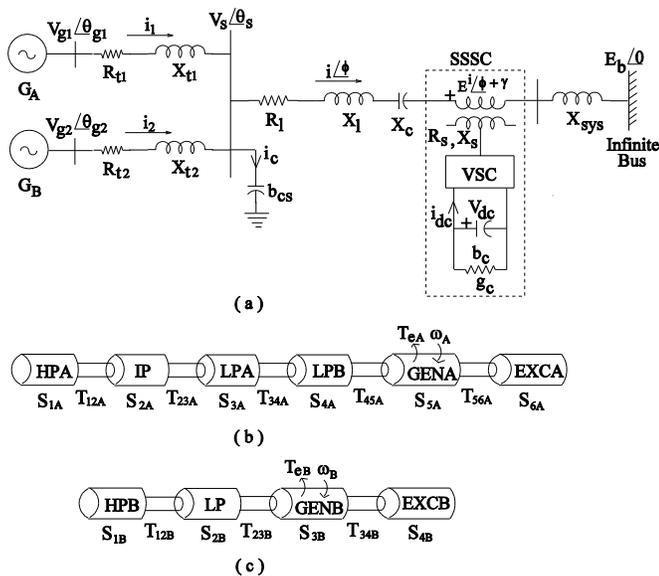


Figure 1: (a) Multi-machine system with SSSC (b) Six-mass mechanical system of generator-A (c) Four-mass mechanical system of generator-B

The pictorial representation of multi-machine system is shown in Figure 1, which is the modified IEEE FBM with the inclusion of four-mass turbine-generator and SSSC.

The study system consists of two non-identical turbine generators with a rating of 892.4 MVA and 600 MVA on the base of 892.4 MVA, 60 Hz. The shaft system of generator-A consists of six-masses namely: HPA, IP, LPA, LPB, GENA and EXCA whose torsional mode frequencies are 15.72 Hz, 20.22 Hz, 25.56 Hz, 32.30 Hz and 47.48 Hz. Similarly, the shaft system of generator-B consists of four-masses namely:

HPB, LP, GENB and EXCB whose torsional mode frequencies are 24.65 Hz, 32.39 Hz and 51.10 Hz.

The magnitude of the SSSC converter output voltage is $|E^i| = M_k V_{dc}$ (1)

Accordingly, the D-Q components of SSSC converter output voltage are given by

$E_D^i = M_k V_{dc} \sin(\phi + \gamma)$ (2)

$E_Q^i = M_k V_{dc} \cos(\phi + \gamma)$ (3)

where M_k is the modulation index and V_{dc} is the dc voltage capacitor.

The real and reactive voltages of SSSC are obtained from the DQ quantities as

$E_P = E_D^i \sin(\phi) + E_Q^i \cos(\phi)$ (4)

$E_R = E_D^i \cos(\phi) - E_Q^i \sin(\phi)$ (5)

Figure 2 shows the type-1 controller for SSSC [10], [18]. In Figure 2, the phase angle γ and dead angle β_{se} are calculated using the reference values $E_{P(se)(ref)}$ and $E_{R(se)(ref)}$ as

$\gamma = \tan^{-1} \left[\frac{E_{R(se)(ref)}}{E_{P(se)(ref)}} \right]$ (6)

$\beta_{se} = \cos^{-1} \left[\frac{\sqrt{E_{P(se)(ref)}^2 + E_{R(se)(ref)}^2}}{P \rho V_{dc}} \right]$ (7)

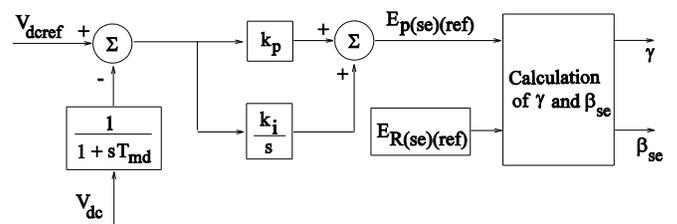


Figure 2: Type-1 controller of SSSC [2], [10]

The differential and algebraic equations of the combined system are used to develop the liner (DQ) model in MATLAB-Simulink. The 2.2 model of two generators are developed for eigenvalue analysis and transient simulation [1]. Whereas, the two non-identical turbine-generators are represented as classical models in damping torque estimation. We perform damping torque, eigenvalue analysis and transient simulation to analyze SSR and to validate the performance of the KF based SSDC connected to SSSC.

2.2 Initial and operating points

The initial operating points and assumptions which are used in the analysis are given below.

- (1) The output power of generator-A and generator-B is set to 0.65 p.u and 0.5 p.u respectively.
- (2) The mechanical power input of the generators G_A and G_B is assumed to be constant.

(3) The hybrid series compensation is provided with $X_c = 0.35$ p.u. and $X_{sssc} = -0.2$ p.u.

3. SCHEME OF KALMAN FILTER BASED SSSC

The proposed multimodal SSSC consists of KF and gains (k_1 to k_{14}) as to reduce the peak negative damping and to enrich all critical torsional modes. The pictorial representation of KF based SSSC is shown in Figure 3. The KF is used to extricate the components pertaining to the subsynchronous frequency from the line to obtain subsynchronous voltages in DQ.

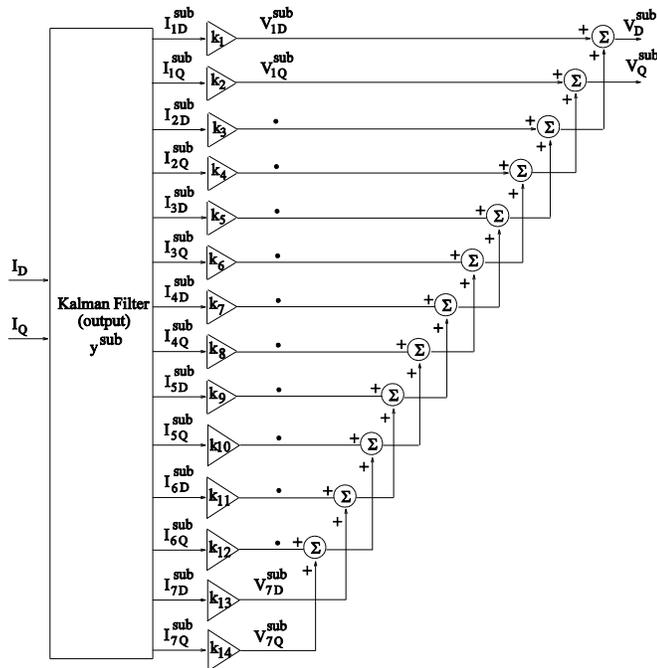


Figure 3: Pictorial representation of proposed KF based SSSC

The output of proposed KF based SSSC is converted to in-phase and quadrature components (real voltage $V_{p\text{sub}}$ and reactive voltage $V_{r\text{sub}}$) and added to type-1 controller of SSSC is shown in Figure 4. The SSSC can inject the reactive voltage in series with the line to suppress the subsynchronous currents following through the generator armature terminal.

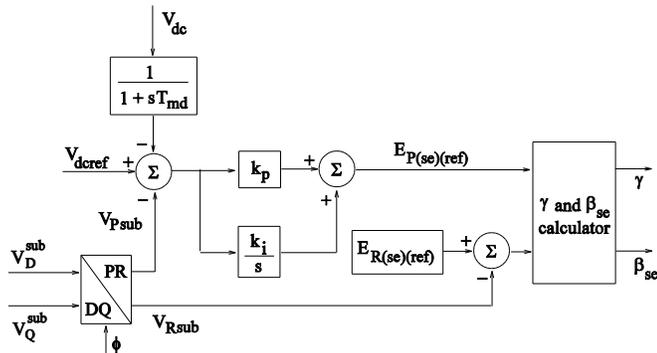


Figure 4: Type-1 controller for SSSC with estimated subsynchronous components from proposed KF based SSSC

4. RESULTS AND DISCUSSION

This section presents the analysis of SSR without and with proposed KF based SSSC in the system shown in Figure 1.

4.1 Damping torque analysis

In this technique, the two non-identical generators are represented as classical model. The dynamics pertaining to the mechanical system is neglected. The electrical damping torque is calculated from the internal bus of the generators G_A and G_B to infinite bus. The damping torque of the generators G_A and G_B for $X_c = 0.35$ p.u. and $X_{sssc} = -0.2$ p.u. without and with proposed KF based SSSC is shown in Figure 5.

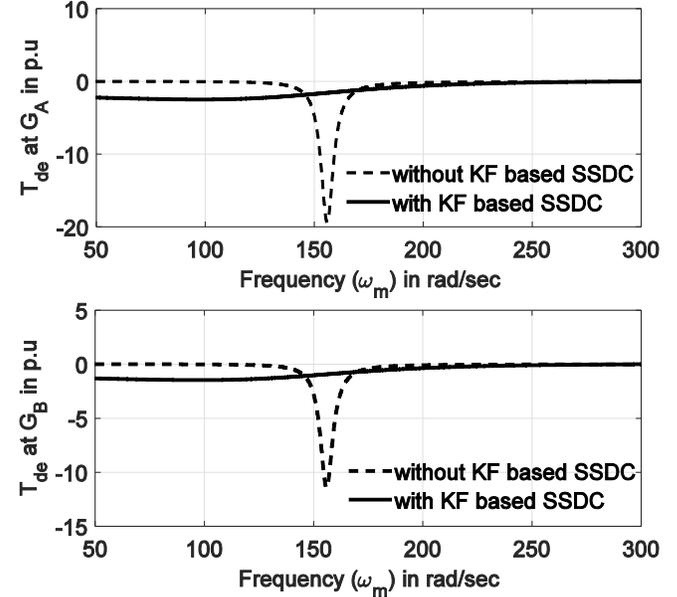


Figure 5: Damping torque of the generators G_A and G_B without and with proposed KF based SSSC on SSSC for $X_c = 0.35$ p.u. and $X_{sssc} = -0.2$ p.u.

From Figure 5, we observe that without KF based SSSC the peak negative damping occurs at about 155 rad/sec. Hence, the corresponding torsional modes are expected to be unstable. On the other hand, the peak negative damping is noticeably reduced with the proposed KF based SSSC in the entire range of critical torsional modes from 0 to 300 rad/sec.

4.2 Eigenvalue analysis

We perform eigenvalue analysis with the detailed synchronous generator 2.2 model. The eigenvalues of the system without and with proposed KF based SSSC on SSSC are tabulated in Table 1 and Table 2 respectively.

We estimated the participation of shaft torque and speed deviation in the torsional modes of two generators (G_A and G_B) with KF based SSSC. Table 3 shows the participation factors of various states of two generators. The participation factor is used to identify the mode belonging to the generators with close frequency modes. The highest participation of state variables are marked in bold. Also, the identified modes are shown in the last row of Table 3.

From the Table 1, we observe that, without KF based SSSC the frequency of NM_{Sub} (subsynchronous network mode) is close to frequency of TM_{1GB} (torsional mode-1 of generator G_B). Hence, the torsional mode-1 of generator G_B is unstable.

On the other hand, all the eigenvalues having negative real parts with proposed KF based SSSC as shown in Table 2. It indicates that the system is stable. Also, the damping of all the critical torsional modes are improved with proposed KF based SSSC as compared to without KF based SSSC.

Table 1: Eigenvalues of the system without KF based SSSC on SSSC

Mode	SSSC without KF based SSSC
	$X_c = 0.35$ p.u and $X_{sssc} = -0.2$ p.u
TM_{0GA}	$-0.48223 \pm j 5.19010$
TM_{1GA}	$-0.24581 \pm j 99.2490$
TM_{2GA}	$-0.07405 \pm j 127.040$
TM_{3GA}	$-0.60776 \pm j 160.450$
TM_{4GA}	$-0.36285 \pm j 202.970$
TM_{5GA}	$-1.85040 \pm j 298.170$
TM_{0GB}	$-8.59720 \pm j 8.61320$
TM_{1GB}	$0.57681 \pm j 155.020$
TM_{2GB}	$-0.04421 \pm j 203.460$
TM_{3GB}	$-0.03364 \pm j 321.180$
NM_{Sub}	$-3.30550 \pm j 155.130$
NM_{Sup}	$-3.05380 \pm j 565.910$

Table 2: Eigenvalues of the system with proposed KF based SSSC on SSSC

Mode	SSSC with KF based SSSC
	$X_c = 0.35$ p.u and $X_{sssc} = -0.2$ p.u
TM_{0GA}	$-0.75461 \pm j 3.71330$
TM_{1GA}	$-0.26895 \pm j 99.1140$
TM_{2GA}	$-0.07630 \pm j 127.030$
TM_{3GA}	$-0.64952 \pm j 160.630$
TM_{4GA}	$-0.36200 \pm j 203.000$
TM_{5GA}	$-1.85040 \pm j 298.170$
TM_{0GB}	$-9.12640 \pm j 10.2290$
TM_{1GB}	$-0.05909 \pm j 155.110$
TM_{2GB}	$-0.04324 \pm j 203.460$
TM_{3GB}	$-0.03368 \pm j 321.180$
NM_{Sub}	$-77.6170 \pm j 129.670$
NM_{Sup}	$-53.1320 \pm j 538.590$

4.3 Transient simulation

The transient analysis is performed for large disturbances (of 10% lessening in mechanical power) with non-linear models. The step response of two generators G_A and G_B without KF based SSSC for the compensation $X_c = 0.35$ p.u is shown in Figure 6 and Figure 7 respectively.

From Figure 6 and Figure 7, we observe that, the magnitude of the oscillatory response of generator G_B rises faster than generator G_A . It indicates that, with 10% lessening in mechanical power, the system is unstable.

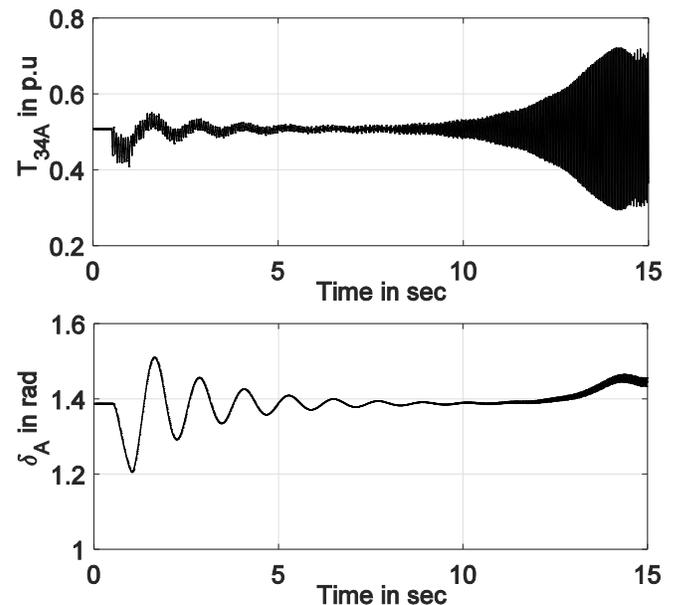


Figure 6: Sectional torque and rotor angle of generator G_A without KF based SSSC for the compensation $X_c = 0.35$ p.u.

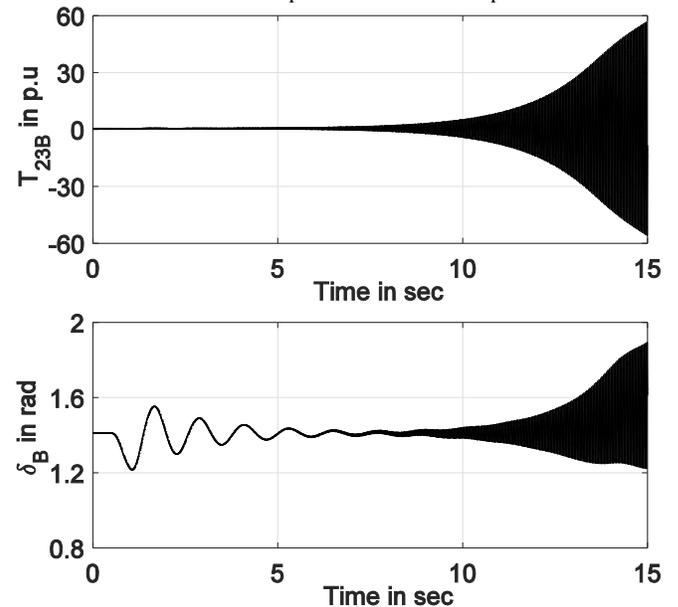


Figure 7: Sectional torque and rotor angle of generator G_B without KF based SSSC for the compensation $X_c = 0.35$ p.u.

Similarly, the step response of two generators G_A and G_B with proposed KF based SSSC for the compensation $X_c = 0.35$ p.u is obtained. We observe that, initially the magnitude of the oscillatory response of both generators G_A and G_B rises until $t = 4$ sec as shown in Figure 8 and Figure 9,. When the proposed KF based SSSC is activated at $t = 4$ sec the oscillatory response dies out along time. It indicates that system is stable.

Table 3: Participation of shaft torque and speed deviation in the torsional modes of generators G_A and G_B with KF based SSDC

SSSC with KF based SSDC ($X_c = 0.35$ p.u and $X_{sssc} = -0.2$ p.u)								
State variables	Eigenvalues							
	-0.26895	-0.07630	-0.64952	-0.36200	-1.85040	-0.05909	-0.04324	-0.03368
	$\pm j$	$\pm j$	$\pm j$	$\pm j$	$\pm j$	$\pm j$	$\pm j$	$\pm j$
	99.1140	127.030	160.630	203.000	298.170	155.110	203.460	321.180
G_A	Participation factors of generator G_A							
T_{12A}	$1.87e^{-02}$	$6.13e^{-03}$	$1.60e^{-01}$	$2.37e^{-02}$	$2.91e^{-01}$	$1.93e^{-04}$	$4.79e^{-04}$	$1.65e^{-11}$
T_{23A}	$5.26e^{-02}$	$1.33e^{-02}$	$2.18e^{-01}$	$1.09e^{-02}$	$2.04e^{-01}$	$2.90e^{-04}$	$2.17e^{-04}$	$2.76e^{-11}$
T_{34A}	$2.75e^{-01}$	$2.39e^{-02}$	$1.88e^{-02}$	$1.76e^{-01}$	$4.44e^{-03}$	$6.12e^{-07}$	$3.61e^{-03}$	$2.63e^{-10}$
T_{45A}	$1.21e^{-01}$	$5.67e^{-05}$	$9.18e^{-02}$	$2.81e^{-01}$	$2.19e^{-04}$	$1.53e^{-04}$	$5.92e^{-03}$	$9.44e^{-09}$
T_{56A}	$2.98e^{-02}$	$4.56e^{-01}$	$9.53e^{-03}$	$4.28e^{-03}$	$3.92e^{-07}$	$6.16e^{-06}$	$9.25e^{-05}$	$3.61e^{-10}$
S_{1A}	$7.47e^{-02}$	$1.49e^{-02}$	$2.43e^{-01}$	$2.25e^{-02}$	$1.28e^{-01}$	$3.15e^{-04}$	$4.53e^{-04}$	$6.28e^{-12}$
S_{2A}	$7.02e^{-02}$	$8.62e^{-03}$	$4.74e^{-02}$	$1.06e^{-04}$	$3.46e^{-01}$	$7.85e^{-05}$	$2.59e^{-06}$	$2.81e^{-11}$
S_{3A}	$1.32e^{-01}$	$2.56e^{-03}$	$1.20e^{-01}$	$7.08e^{-02}$	$2.45e^{-02}$	$8.73e^{-05}$	$1.43e^{-03}$	$4.65e^{-11}$
S_{4A}	$1.57e^{-02}$	$1.83e^{-02}$	$2.01e^{-02}$	$2.90e^{-01}$	$8.78e^{-04}$	$1.01e^{-04}$	$6.02e^{-03}$	$1.81e^{-09}$
S_{5A}	$1.62e^{-01}$	$1.60e^{-02}$	$6.35e^{-02}$	$1.12e^{-01}$	$3.88e^{-05}$	$3.03e^{-05}$	$2.44e^{-03}$	$4.39e^{-08}$
S_{6A}	$4.71e^{-02}$	$4.40e^{-01}$	$5.74e^{-03}$	$1.61e^{-03}$	$6.86e^{-08}$	$3.98e^{-06}$	$3.47e^{-05}$	$5.45e^{-11}$
G_B	Participation factors of generator G_B							
T_{12B}	$3.20e^{-06}$	$1.05e^{-06}$	$1.48e^{-04}$	$8.25e^{-03}$	$1.91e^{-12}$	$1.12e^{-01}$	$3.85e^{-01}$	$1.59e^{-05}$
T_{23B}	$4.65e^{-05}$	$9.14e^{-06}$	$3.85e^{-04}$	$2.16e^{-03}$	$9.59e^{-11}$	$3.85e^{-01}$	$1.11e^{-01}$	$1.30e^{-03}$
T_{34B}	$6.12e^{-10}$	$3.96e^{-09}$	$1.20e^{-06}$	$7.47e^{-06}$	$1.47e^{-10}$	$8.98e^{-04}$	$4.25e^{-04}$	$4.99e^{-01}$
S_{1B}	$1.05e^{-05}$	$2.11e^{-06}$	$1.86e^{-04}$	$6.47e^{-03}$	$6.94e^{-13}$	$1.51e^{-01}$	$3.01e^{-01}$	$4.97e^{-06}$
S_{2B}	$3.17e^{-05}$	$3.29e^{-06}$	$4.69e^{-05}$	$3.06e^{-03}$	$1.33e^{-11}$	$6.11e^{-02}$	$1.48e^{-01}$	$1.49e^{-04}$
S_{3B}	$6.63e^{-07}$	$2.26e^{-06}$	$3.39e^{-04}$	$8.40e^{-04}$	$3.65e^{-10}$	$2.84e^{-01}$	$4.73e^{-02}$	$5.99e^{-03}$
S_{4B}	$6.37e^{-09}$	$2.51e^{-08}$	$4.76e^{-06}$	$1.85e^{-05}$	$1.69e^{-10}$	$3.82e^{-03}$	$1.05e^{-03}$	$4.94e^{-01}$
Identified mode	TM_{1GA}	TM_{2GA}	TM_{3GA}	TM_{4GA}	TM_{5GA}	TM_{1GB}	TM_{2GB}	TM_{3GB}

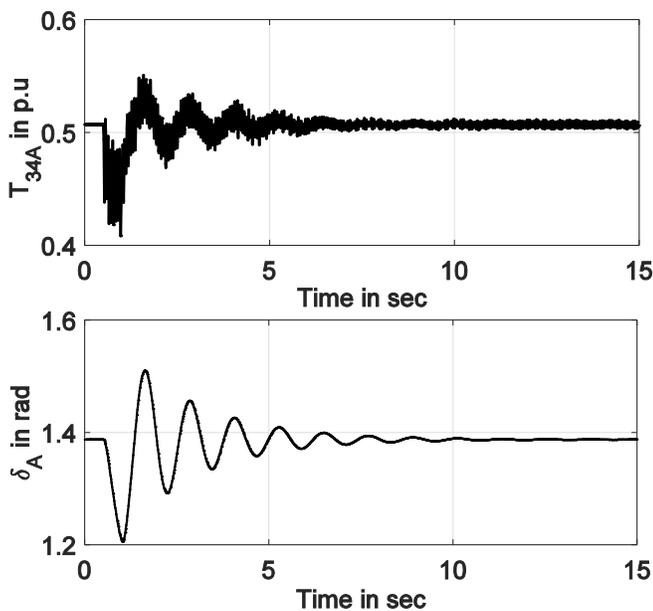


Figure 8: Sectional torque and rotor angle of generator G_A with proposed KF based SSDC for the compensation $X_c = 0.35$ p.u activated at $t = 4$ sec.

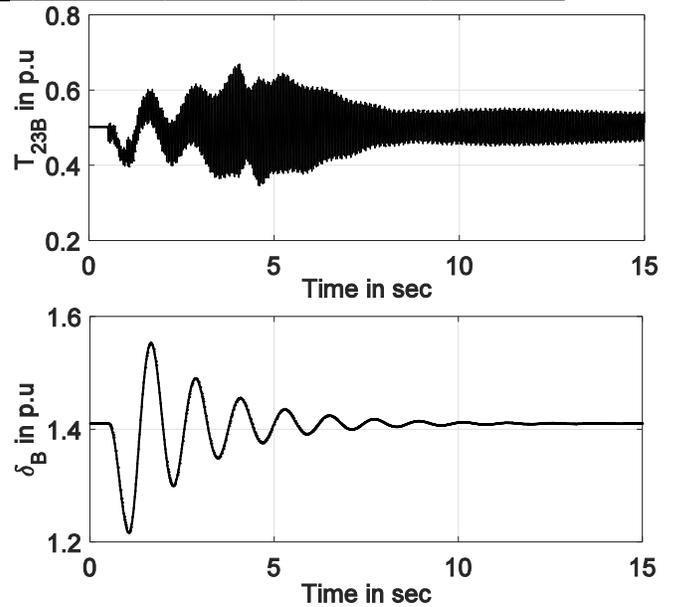


Figure 9: Sectional torque and rotor angle of generator G_B with proposed KF based SSDC for the compensation $X_c = 0.35$ p.u activated at $t = 4$ sec.

4.4 Discussion

We proposed a multimodal SSDC using KF for multi-machine system to enrich all critical torsional mode frequencies. From the results, it is clear that the highest negative damping is noticeably decreased with proposed KF based SSDC in the entire range of critical torsional mode frequencies. The proposed KF based SSDC effectively mitigates multimodal SSR

5. CONCLUSION

We proposed a multimodal SSDC using KF for multi-machine system. The SSR analysis is carried out on the modified IEEE FBM with the inclusion of four-mass turbine-generator and SSSC. The parameters of KF based SSDC are selected to enhance the damping of all critical torsional mode frequencies and to mitigate the multimodal SSR. The SSR analysis is performed through damping torque, eigenvalue and transient simulation methods to validate the proposed KF based SSDC. The results demonstrated that the peak negative damping viewed at both generators is substantially reduced with proposed KF based SSDC and effectively mitigates SSR.

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