

BPF based Estimation and Mitigation of SSR with SSSC



S. Venkateswarlu, M. Janaki

Abstract: *The risk of Subsynchronous Resonance (SSR) may reduce with the hybrid of active and passive series compensations. The hybrid series compensation can be done with Static Synchronous Series Compensator (SSSC) (an active FACTS device) and fixed series capacitor (passive compensation). In this paper, we propose a Band Pass Filter (BPF) based Subsynchronous Damping Controller (SSDC) with SSSC. The aim of the paper is to increase the damping of all critical TMs with minimum number of highly frequency selective BPFs. The BPFs are used to extract the subsynchronous frequency components from electrical network. The extracted subsynchronous frequency components are used to modulate the reference value of SSSC injected voltage. Thereby, the SSSC injecting voltage can suppress the subsynchronous currents flowing in the transmission network. The linear (DQ) model is developed in MATLAB-Simulink using the differential and algebraic equations of the system. The damping torque, eigenvalue and transient simulation methods are performed with the linear model to carry out the analysis of SSR. The eigenvalue analysis is used to select the number of filters. The number of BPFs is selected in view of suppressing the torsional vibrations at all critical frequencies. The outcomes of the paper show that the negative damping is considerably diminished with the proposed SSDC in the entire range of torsional mode frequencies and mitigate SSR.*

Keywords: *Damping torque, eigenvalue, static synchronous series compensator, subsynchronous resonance, subsynchronous damping controller, voltage source converter, Band pass filter.*

I. INTRODUCTION

The huge rise in demand for electrical power imposes the transmission lines to transmit bulk power. The series and shunt compensation using capacitors are the economic solutions to increase the transmission capability of long power lines, the stability of the system, as well as voltage regulation [1]–[3]. There occurs a potential SSR problem due to the series compensation of long line connected to turbine-generator [4], [5]. The previous research has proposed various SSDCs with FACTS devices, which are intended to boost the stability as well as voltage regulation and to mitigate the SSR.

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* Correspondence Author

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

M. Janaki*, School of Electrical Engineering, Associate Professor, Vellore Institute of Technology, Vellore, India. Email: mjanaki74@gmail.com

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In [6]–[8], SSSC using Low Pass Filter (LPF) is reported to mitigate SSR. The SSDC with SSSC based on Transfer Function (TF) is discussed in [9], which is used to mitigate SSR by decreasing the electrical resonant frequency. In [10], SSDC using gain/phase compensation is reported to damp the subsynchronous oscillations. The improved Blocking Filter (BF) is used to mitigate the various SSR problems in the Tuoketuo power system, and the family of Subsynchronous Dampers (SSDs) based SSDC is reported to damp the multi-modal SSR [11].

Our previous works report BPF and Kalman Filter (KF) based SSDC respectively, which significantly diminish the negative damping in the practical range of series compensation [12].

The aim of this paper is to enhance the damping of all critical torsional modes (TM) with minimum number of highly frequency selective BPFs. We present the analysis and simulation of SSR with passive series compensation and active compensation using SSSC. The SSR analysis is carried out on the modified IEEE First Benchmark Model (FBM) with SSSC and BPF based SSDC [12]. The damping torque, eigenvalue and transient simulation methods are performed with the linear model to analyze SSR. BPF based SSDC is designed on the basis of TM frequencies and damping torque. The number of BPFs is selected from the eigenvalue analysis. The estimated subsynchronous frequency components (output of BPF based SSDC) are used to modulate the reference value of SSSC injected voltage. Thereby, the SSSC can inject voltages in the transmission line to suppress the subsynchronous currents flowing to the generator. The performance of the BPF based SSDC with SSSC is validated through the damping torque, eigenvalue analysis and transient simulation under large disturbance. The results show that, in the entire range of TM frequencies the peak value of negative damping considerably decreases with proposed SSDC and mitigate the SSR.

The sections of this paper are organized as follows. The methods to analyze SSR is detailed in Section II. The system description and SSR analysis with SSSC are discussed in Section III. The design of BPF based SSDC is described in Section IV. The SSR with SSSC and BPF based SSDC is analyzed in Section V. The discussion on results and conclusions are presented in Section VI and Section VII, respectively.

II. METHODS TO ANALYZE SSR

The methods of SSR analysis are presented in the following subsections [3], [12].



A. Damping Torque Analysis

The dynamics of the mechanical system are neglected in the damping torque analysis.

From Fig.1, the damping torque is given as [3]

$$T_{de}(\omega) = \Re \left[\frac{\Delta T_e(j\omega)}{\Delta S_m(j\omega)} \right] = \Re [H(j\omega)]_{k=1} \quad (1)$$

The generator rotor speed is denoted by ΔS_m p.u and the electrical torque is denoted by ΔT_e p.u.

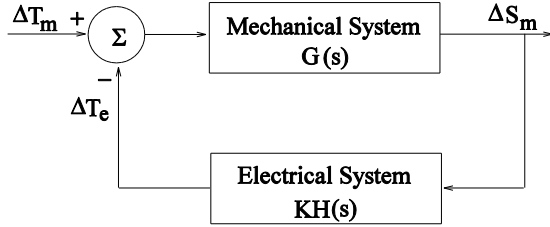


Fig. 1. Interaction between mechanical and electrical system [12].

The electrical damping torque (T_{de}) is calculated from the generator internal bus and it is given by [13]

$$T_{de}(\omega) = \Re \left[\frac{Y_{QD}\omega_0}{j\omega} + Y_{QD} \right] * E^2 \quad (2)$$

where T_{de} is the electrical damping torque

Y_{QD} and Y_{QD} are the admittance functions in DQ frame

ω_0 is the operating frequency and

E is the generator internal bus voltage.

At any frequency, if the damping torque is negative and if that particular frequency is matching with any of the TM frequency, then the corresponding TM may be unstable.

B. Eigenvalue Analysis

The eigenvalue analysis is carried out with a detailed model of both electrical and mechanical systems. The linear DQ model is developed in Matlab-Simulink using the system differential and algebraic equations. The state matrix is obtained to compute the eigenvalues. The sign of the real part of eigenvalues indicates either system is stable or unstable. The system is said to be unstable if any one of the eigenvalues has a negative real part [12].

C. Transient Simulation

The outcomes of damping torque and eigenvalue analysis are validated by time-domain simulation of the system with large disturbances. The linear DQ model is used to perform the analysis of transient SSR for the step disturbance at an operating point. The transient stability is assessed from the time response. In order to see the transient response, 10% fall in mechanical torque is initiated and removed at 0.5 sec and 1.0 sec respectively. The system is transiently stable if the oscillatory response decreases with time.

III. SYSTEM DESCRIPTION AND ANALYSIS OF SSR WITH SSSC

A. System Description

The study system is adapted from IEEE FBM with the

inclusion of SSSC [12]. The diagram of study system is shown in Fig. 2. The information of the electromechanical system are referred in [3], [14].

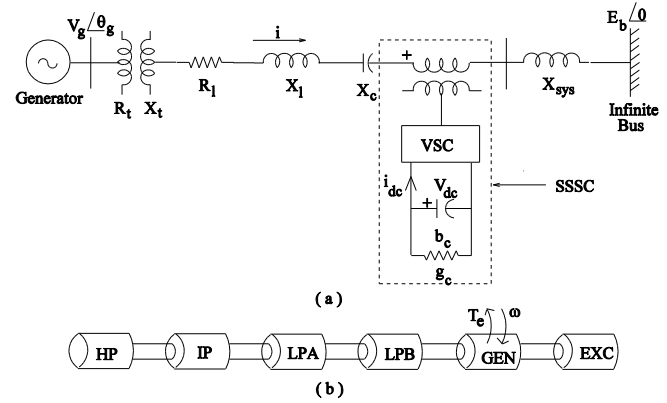


Fig. 2. Modified IEEE FBM with SSSC [12].

The damping torque analysis is executed with generator classical model. The state model of the network is derived from the generator terminal to infinite bus and it is given by [3]

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_e & \frac{\omega}{\omega_b} X_e \\ -\frac{\omega}{\omega_b} X_e & R_e \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{X_e}{\omega_b} \begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} + \quad (3)$$

$$\begin{bmatrix} \cos \delta & -\sin \delta \\ \sin \delta & \cos \delta \end{bmatrix} \left\{ \begin{bmatrix} V_{CD} \\ V_{CQ} \end{bmatrix} + \begin{bmatrix} E_D^i \\ E_Q^i \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} E_b \right\}$$

where i_d, i_q and V_d, V_q are the dq components of the line current and generator terminal voltage with respect to the machine reference frame.

X_e and R_e represent the equivalent reactance and equivalent resistance viewed from the generator terminal.

$\frac{\omega}{\omega_b}$ is the generator rotor speed in p.u.

δ is the generator rotor angle.

V_{CD} and V_{CQ} are the capacitor voltage DQ variables.

E_D^i and E_Q^i are the DQ components of the SSSC injected voltage.

E_b is the infinite bus voltage.

(1) Modeling of SSSC in D-Q reference frame

Fig. 3 and Fig. 4 show the schematic diagram and equivalent circuit of SSSC respectively [3], [12]. SSSC comprises a coupling transformer, Voltage Source Converter (VSC) and the DC link capacitor as shown in Fig. 3.

The DQ components of the injected voltage E^i are represented by E_D^i and E_Q^i respectively and are defined as follows:

$$E_D^i = M_k V_{dc} \sin(\phi + \gamma) \quad (4)$$

$$E_Q^i = M_k V_{dc} \cos(\phi + \gamma) \quad (5)$$

The magnitude of the output voltage at ac side of the converter in DQ reference frame is given by

$$E^i = \sqrt{E_D^2 + E_Q^2} = M_k V_{dc} \quad (6)$$

where M_k is the modulation index and is given as

$$M_k = p \rho \cos \beta_{se}$$

where $p = \frac{4\sqrt{6}}{\pi}$ for a 24-pulse converter.

ρ is the transformation ratio of SSSC interfacing transformer.

β_{se} is the dead angle.

V_{dc} is the dc capacitor voltage.

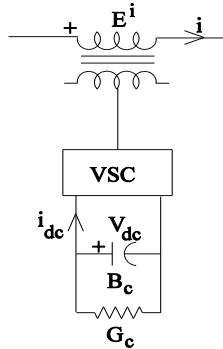


Fig. 3. Schematic diagram of SSSC [12], [15].

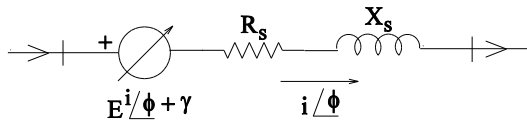


Fig. 4. SSSC equivalent circuit [12].

In the control perspective, it is convenient to represent the real voltage (E_p) and reactive voltage (E_R) as components of converter voltage (E^i). The real voltage (E_p) being in phase and the reactive voltage (E_R) is in quadrature with the line current (i).

$$E_R = E_D^i \cos \phi - E_Q^i \sin \phi \quad (7)$$

$$E_p = E_D^i \sin \phi + E_Q^i \cos \phi \quad (8)$$

The reactive voltage E_R injected by SSSC is related to the magnitude of line current i as

$$E_R = \sqrt{i_D^2 + i_Q^2} * X_{SSSC} \quad (9)$$

where X_{SSSC} represents the compensation provided by SSSC.

Here, E_R with positive sign represents the inductive operation of SSSC.

The dc side capacitor voltage is calculated by the dynamic equation as

$$\frac{dV_{dc}}{dt} = -\frac{\omega_b}{B_c} i_{dc} - \frac{\omega_b G_c}{B_c} V_{dc} \quad (10)$$

where $\omega_b = 2\pi f_b$, (f_b - base frequency)

B_c = Capacitive susceptance of dc side capacitor.

G_c = Conductance of dc side capacitor.

$$i_{dc} = -[M_k \sin(\phi + \gamma) i_D + M_k \cos(\phi + \gamma) i_Q]$$

The schematic representation of the type-1 controller for SSSC is shown in Fig. 5 [12].

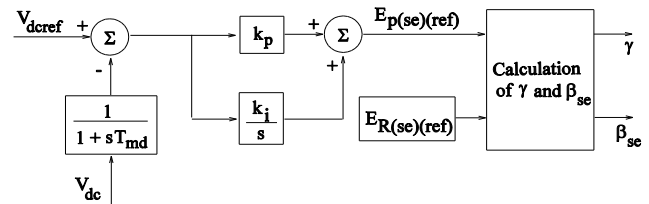


Fig. 5. Type-1 controller of SSSC [12].

The magnitude of output voltage at ac side of the converter (E^i) and its phase angle (γ) are controlled with type-1 controller. The V_{dc} is maintained by varying γ . By varying dead angle (β_{se}), the modulation index can be varied and hence the magnitude of the converter output voltage is controlled. From the dc voltage controller, $E_{p(se)(ref)}$ is calculated, whereas the $E_{R(se)(ref)}$ is kept constant.

In Fig. 5, the phase angle γ and dead angle β_{se} are calculated from the reference values of $E_{p(se)(ref)}$ and $E_{R(se)(ref)}$ as

$$\gamma = \tan^{-1} \left[\frac{E_{R(se)(ref)}}{E_{P(se)(ref)}} \right] \quad (11)$$

$$\beta_{se} = \cos^{-1} \left[\frac{\sqrt{E_{P(se)(ref)}^2 + E_{R(se)(ref)}^2}}{p \rho V_{dc}} \right] \quad (12)$$

(2) Operating Points and Assumptions

The operating points and assumptions made in the analysis are given by

- (1) The power output of the generator is set to 0.9 p.u.
- (2) Power input of mechanical system is assumed to be constant.
- (3) Hybrid series compensation is provided with $X_c = 0.51$ p.u and $X_{SSSC} = -0.25$ p.u.
- (4) The case study-1 is without BPF based SSDC
- (5) The case study-2 is with BPF based SSDC.

B. Analysis of SSR with SSSC (Case study-1)

The variation in electrical damping torque with SSSC for case study-1 is observed in Fig. 6. In the case study-1, the damping torque having a large negative peak is near the frequency of TM-2 (127 rad/sec). Hence, at this compensation, severe torsional interactions may occur.

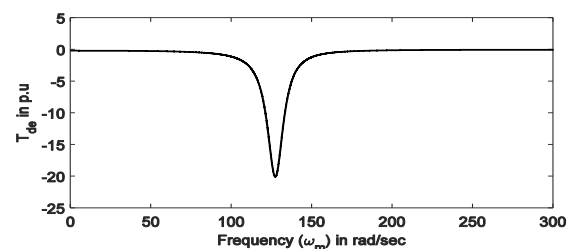


Fig. 6. Damping torque in case study-1.

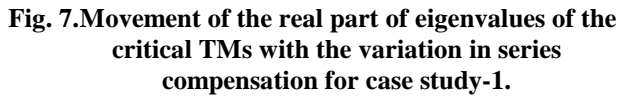


Figure 10 consists of two vertically stacked plots sharing a common x-axis representing 'Time in sec' from 0 to 15.

The top plot shows 'LPA - LPB section torque in p.u.' on the y-axis, ranging from 0.5 to 0.9. The torque starts at approximately 0.7 p.u., drops sharply to a minimum of about 0.55 p.u. at 1 second, and then settles into a high-frequency oscillation between approximately 0.6 and 0.8 p.u. for the remainder of the 15-second period.

The bottom plot shows 'Rotor angle in deg' on the y-axis, ranging from 65 to 80. The rotor angle starts at 76 degrees, drops to a minimum of about 69 degrees at 1 second, and then settles into a damped oscillation, eventually stabilizing at approximately 75.5 degrees after 10 seconds.

IV. DESIGN OF BPF BASED SSDC

In Fig. 7, we observe that in a particular range of series compensation both TM-1 and TM-2 are unstable due to the interaction of subsynchronous network mode. Hence, we design single BPF to extract both TM-1 and TM-2 is used. At the same time, BPFs with narrow bandwidth are preferred as to high frequency selectivity.

upon the range of subsynchronous network mode frequency for which critical TMs are unstable. The pictorial representation of SSDC using BPFs and gains is shown in Fig. 9.

[illegible]

The output of BPF based SSDC (DQ components) is transformed into in-phase and quadrature components namely real and reactive voltages (V_{Psub} and V_{Rsub}) respectively.



V. ANALYSIS OF SSR WITH SSSC AND BPF BASED SSDC

In this section, the results of two case studies are compared to evaluate effectiveness of BPF based SSDC.

A. Damping Torque Analysis

The electrical damping torque (T_{de}) is computed in the range of frequency from 0 to 300 rad/sec. Variation in the electrical damping is observed in Fig. 11. In case study-1, the damping torque having a large negative peak is seen near the frequency of TM-2 (127 rad/sec). In case study-2, the negative damping torque is considerably diminished with BPF based SSDC. Also, the negative value of damping torque is negligible in the full range of TM frequencies.

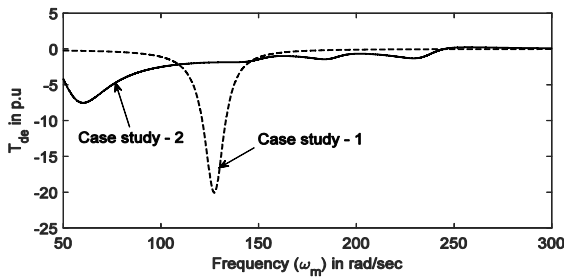


Fig. 11. Damping torque without and with BPF based SSDC on SSSC.

Further, the admittances Y_{QD} and Y_{QO} are computed in the range of frequency from 0 to 300 rad/sec. The variations in admittances Y_{QD} and Y_{QO} for case study-1 and case study-2 are shown in Fig. 12 and Fig. 13 respectively.

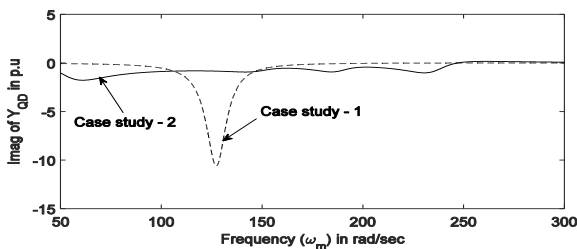


Fig. 12. Admittance Y_{QD} without and with BPF based SSDC on SSSC.

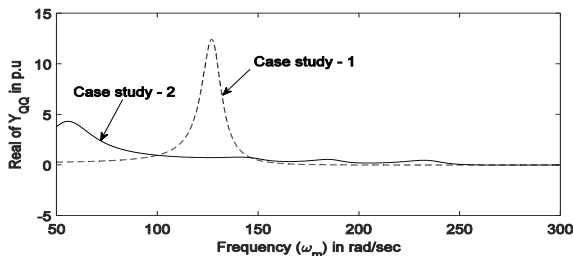


Fig. 13. Admittance Y_{QO} without and with BPF based SSDC on SSSC.

From the Fig. 12 and Fig. 13, we observe that the negative value of Y_{QD} and Y_{QO} is significantly reduced with BPF based SSDC. From the results of damping torque and impedance analysis, all the TMs are expected to be stable.

B. Eigenvalue Analysis

The eigenvalues for case study-1 and case study-2 are tabulated in Table-1. From the Table-1 we observe that in case study-1 the frequency of subsynchronous network mode is close to TM-2, and hence the TM-2 is unstable. In case study-2 (SSSC with BPF based SSDC), it is interesting that, all the eigenvalues have negative real parts, which indicating that the system is stable. Comparing with case study-1, the damping of all TMs is considerably improved in case study-2.

Table- I: Eigenvalues for case study-1 and case study-2

TM	Case study-1: With SSSC	Case study-2: With SSSC and BPF based SSDC
0	$-1.7102 \pm j 8.2105$	$-1.3516 \pm j 8.2735$
1	$0.0977 \pm j 99.080$	$-0.4484 \pm j 98.477$
2	$0.1578 \pm j 127.00$	$-0.0850 \pm j 126.99$
3	$-0.6670 \pm j 160.46$	$-0.6838 \pm j 160.53$
4	$-0.3790 \pm j 202.85$	$-0.3986 \pm j 202.89$
5	$-1.8504 \pm j 298.17$	$-1.8504 \pm j 298.17$
NMsub	$-3.7702 \pm j 128.42$	$-12.247 \pm j 235.37$
NMsup	$-4.8842 \pm j 590.20$	$-5.7889 \pm j 613.54$

C. Transient Simulation

The transient simulation is a time-domain analysis, which is used to validate the outcomes of electrical damping torque and eigenvalue method. In Fig. 14, the time responses for case study-2 are plotted. In Fig. 14, it is interesting to observe that oscillations in time response decrease with time when BPF based SSDC initiated at 5 sec. The results of transient simulation of case study-2 show that the system is stable with BPF based SSDC.

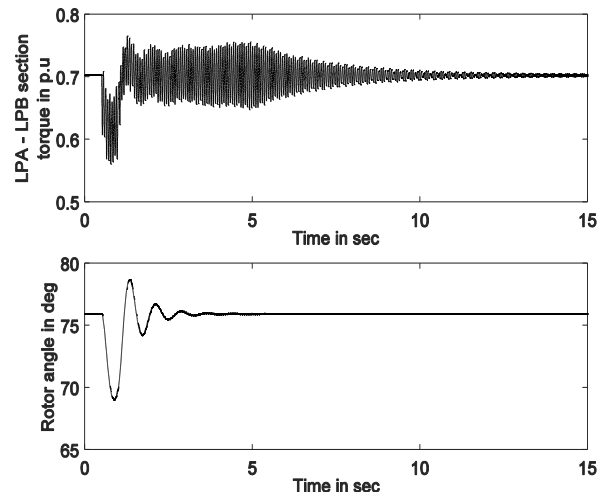


Fig. 14. Step response in case study-2: sectional torque (LPA-LPB) and rotor angle with BPF based SSDC initiated at $t = 5$ sec.

VI. RESULT AND DISCUSSION

The investigations and simulation of SSR with hybrid series compensation using fixed capacitor and SSSC for active compensation is presented.

- 1) We propose a BPF based SSDC to estimate the subsynchronous frequency current components from the transmission line current.

- 2) The BPF based SSDC is designed to boost the damping of all critical torsional modes with the minimum number of BPFs having good frequency selectivity.
- 3) The performance of the proposed BPF based SSDC in damping torque and eigenvalue analysis is validated through the transient simulation under large disturbance.
- 4) The results show that the negative damping is considerably reduced with the proposed SSDC in the entire range of torsional mode frequencies.
- 5) From the results, it is clear that the outcomes of the three methods are consistent. The outcomes of three methods show the effectiveness of the proposed BPF based SSDC in improving the damping of all torsional modes.

VII. CONCLUSION

In this paper, SSR is analyzed on the modified IEEE FBM model with hybrid compensation using a fixed series capacitor and SSSC. The BPF based SSDC is designed on the basis of TM frequencies and damping torque. The BPF based SSDC is intended to enhance the damping of all torsional modes with minimum number of highly frequency selective BPFs. The IEEE FBM has five torsional modes. We propose BPF based SSDC using three BPFs to extract the components of four torsional modes. The results show that the negative damping is considerably reduced with the proposed SSDC in the entire range of torsional mode frequencies. It is evident that, the proposed SSDC effectively mitigates SSR at practical compensation levels.

REFERENCES

1. M. C. Hall and D. A. Hodges, "Experience with 500 kV subsynchronous resonance and resulting turbine generator shaft damage at Mohave generating station," in *Analysis and Control of Subsynchronous Resonance*, IEEE Publ. 76 CH 1066-0-PWR, 1976, pp. 22–25.
2. S. Venkateswarlu, M. Janaki, R. Thirumalaivasan and Nagesh Prabhu, "A review on damping torsional interactions using VSC based FACTS and subsynchronous damping controller," *Annual Reviews in Control*, vol. 46, Aug. 2018, pp. 251–264.
3. K. R. Padiyar, *Analysis of Subsynchronous Resonance in Power Systems*. Boston: Kluwer Academic Publishers, 1999.
4. IEEE Subsynchronous resonance working group, "Proposed terms and definitions for subsynchronous oscillations," *IEEE Trans. on Power App. Syst.*, vol. PAS-99, no. 2, Mar/Apr. 1980, pp. 506–511.
5. IEEE Subsynchronous resonance working group of the system dynamic performance subcommittee, "Reader's guide to subsynchronous resonance," *IEEE Trans. on Power Syst.*, vol. 7, no. 1, Feb. 1992, pp. 150–157.
6. M. Bongiorno, J. Svensson and L. Angquist, "On control of static synchronous series compensator for SSR mitigation," *IEEE Trans. on Power Electronics*, vol. 23, no. 2, Mar. 2008, pp. 735–743.
7. M. Bongiorno, L. Angquist and J. Svensson, "A novel control strategy for subsynchronous resonance mitigation using SSSC," *IEEE Trans. on Power Delivery*, vol. 23, no. 2, Apr. 2008, pp. 1033–1041.
8. M. Bongiorno, J. Svensson and L. Angquist, "Online estimation of subsynchronous voltage components in power systems," *IEEE Trans. on Power Delivery*, vol. 23, no. 1, Jan. 2008, pp. 410–418.
9. K. R. Padiyar and Nagesh Prabhu, "A comparative study of SSR characteristics of TCSC and SSSC," in *Proc. PSCC conf.*, Aug. 2005.
10. D. Rai, S. O. Faried, G. Ramakrishna and Abdel Aty (Aty) Edris, "An SSSC-based hybrid series compensation scheme capable of damping subsynchronous resonance," *IEEE Trans. on Power Delivery*, vol. 27, no. 2, Apr. 2011, pp. 531–540.
11. Liang Wang, Xiaorong Xie, Qirong Jiang and Hemanshu R. Pota, "Mitigation of multimodal subsynchronous resonance via controlled injection of supersynchronous and subsynchronous currents," *IEEE Trans. on Power Syst.*, vol. 29, no. 3, May. 2014, pp. 1335–1344.

12. R. Thirumalaivasan, M. Janaki and Nagesh Prabhu, "Investigation of SSR characteristics of hybrid series compensated power system with SSSC," *Advances in Power Electronics*, May. 2011, pp. 1–8.
13. K. R. Padiyar and Nagesh Prabhu, "Investigation of SSR characteristics of unified power flow controller," *Electrical Power Systems Research*, vol. 74, no. 2, May. 2005, pp. 211–221.
14. K. R. Padiyar, *Power System Dynamics – Stability and Control-Second edition*. Hyderabad: B. S. Publications, 2002.
15. N. G. Hingorani and L. Gyugyi, *Understanding FACTS*. New York: IEEE Press, 2000.

AUTHORS PROFILE



S. Venkateswarlu has student IEEE membership from the year of 2018. He received B. Tech degree in electrical and electronics engineering from Jawaharlal Nehru Technological University, Anantapur, India, in 2011 and M. Tech degree in electrical power engineering from Jawaharlal Nehru Technological University, Hyderabad, India, in 2014. He is currently pursuing Ph. D degree with the Vellore Institute of Technology, Vellore, India. His research interests including FACTS and power system stability and control.



M. Janaki has senior IEEE membership from the year of 2018. She received B.E. degree in electrical and electronics engineering from Madras University, Chennai, India, in 1996, M.E. degree in control and instrumentation from Anna University, Guindy, Chennai, India, in 2002 and Ph. D degree from the Department of Electrical Engineering, Jawaharlal Nehru Technological University, Hyderabad, India, in 2015. She is an Associate Professor in the School of Electrical Engineering, Vellore Institute of Technology, Vellore, India. Her research interests including FACTS, HVDC and power system stability and control.