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Design of Coordinated Control of PSS and TCSC using LQR Optimal Controller

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Abstract

An Optimal State Feedback Controller (OSFC) based on linear Quadratic Regulator (LQR) concept, is applied for simultaneous coordinated designing of the Power System Stabilizer (PSS) and Thyristor Controlled Series Capacitor (TCSC) as a damping controller in the Single Machine Infinite Bus (SMIB) power system. The performance of the proposed controllers is applied for nominal loading conditions. The eigen value analysis demonstrates the high performance of the proposed controllers and their ability to provide efficient damping of Low Frequency Oscillations (LFO's). The performance of the proposed controllers with LQR has an excellent capability in damping LFO's and enhance the dynamic stability of the system.

Keywords: Oscillation Damping, TCSC and PSS, Coordinated – Control, Optimal State Feedback Control

1. Introduction

The Electrical Power Systems (EPS) have become complex due to long transmission lines, placing of large synchronous machines, heavy loading and environment etc. For small disturbances there is effect on power flow during loading conditions. As a result, local mode oscillations shows the poor damping in the absence of stabilizer. In SMIB system only local oscillations are present. The stabilizer may provide sufficient damping to the critical modes and the oscillations are minimized.

Usually, PSS is placed to the exciter of synchronous machine to provide additional control action[1,2]. In some cases PSS not provide sufficient damping to the local oscillations in complex systems. Recent advances in power electronics introduce the use of Flexible Ac Transmission Systems (FACTS) controllers in power systems[3]. Flexible AC Transmission Systems (FACTS) damping stabilizers have to provide sufficient damping to the critical modes and the dynamic stability of the system is enhanced[4]. Because of fast control action of FACTS based stabilizer and PSS are capable to provide high stability to the EPS. Dynamic interactions are present for uncoordinated design of PSS and FACTS based damping stabilizer in complex systems. To prevent such possible interactions a coordinated control of PSS and FACTS may be needed. But, in EPS the coordinated combination also complex because of order of system matrix dimensions.

Various types of FACTS controllers have been applied to power systems like Static synchronous compensator (STATCOM), Series Static Synchronous Compensator (SSSC), and Unified power flow controller (UPFC), etc. These controllers are based on GTO-and IGBT-based voltage source converters[5–8]. TCSC is a series FACTS device is presented by vary the reactance of the line through the firing angle and to provide sufficient damping to the critical modes[9–11]. Subsequently, by using the series FACTS POD controllers with PSS has been demonstrated that variable series compensation is highly effective to

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control active power flow in the lines and in improving the damping of LFOs in a very fast manner[12,13].

In the design of conventional control techniques, PI controller is implemented to damp the LFOs in EPS. To reach steady state response more time needed with this conventional controller[14]. For sudden disturbances the design of adaptive controllers is less sensitive for parameter variations[15]. The mathematical model of intelligent controllers is not suited for parameter variations and sudden disturbances[15]. To overcome these limitations, alternate optimal state feedback controllers are needed. The design of state feedback controller based on LQR is more sensitive for parameter variations for sudden disturbances. The proposed LQR controller effectively damp the LFOs for sudden disturbances. The optimal gains of the LQR controller shift the critical modes to the left half of the s-plane results the settling time is reduced. The performance of the system is further improved by OSFC to the coordinated control of PSS and TCSC. The optimal control law based on the cost function. With the OSFC the eigenvalues are shifted to the left half of S-plane and improves the damping significantly.

The structure of the paper is as follows: Section II presents the power system model, Section III presents the general configuration models of the proposed PSS, TCSC and OSFC applied to the SMIB power system. Section IV presents the results and discussion analysis for proposed PSS, TCSC and OSFC joined with designed damping controller have been discussed. Finally, Specific important conclusions are summarized in Section V.

2. Power System Model

The Differential Algebraic Equations of EPS as follows[16]

$$\dot{X} = Ax + Bu \tag{1}$$

$$0 = g(x, y) \tag{2}$$

where, "x" is a state vector of each machine, "y" is the set of algebric variables means voltage and current at all buses, "u" is a set of input vector for each machine, and "g" is the stator algebric and network equations. The dimensions of Eq. (1) is the 7m and Eq. (2) is 2(m+n). It can be expressed in state-space as [16].

$$\begin{bmatrix} \Delta\dot{X} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} A' & B_1' & B_2' \\ C_1' & D_{11}' & D_{12}' \\ C_2' & D_{21}' & D_{22}' \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Y_{?} \\ \Delta Y_B \end{bmatrix} + \begin{bmatrix} E_1 \\ 0 \\ 0 \end{bmatrix} \Delta u \tag{3}$$

In Eq. (3), D'_{22} is the load-flow Jacobian J'_{AE} is the network algebraic Jacobian. The system matrix A_{sys} from Eq. (3) is obtained as:

$$\Delta\dot{X} = A_{SYS}\Delta X + E\,\Delta U \tag{4}$$

where,

$$\int A_{sys} = [A'] - [B_1'.B_2']J'_{AE}\begin{bmatrix} C_1' \\ C_2' \end{bmatrix} \tag{5}$$

When a PSS and TCSC are placed to the system, the state variables belong to these controllers will be added to the system matrix.

SMIB System is a simplified classical model of the synchronous generator is shown in Figure 1 [17,18]. V_1 is the generator terminal voltage, V_2 is the infinite bus voltage and the reactance of the transmission is X_e, respectively. The generator and external data is given in Appendix[18].

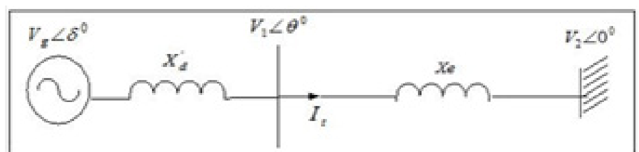

Fig.1. SMIB system configuration.

Figure 1. SMIB system configuration.

3. PSS and TCSC Damping Controller

3.1 PSS

The PSS accomplishment through the exciter to give a factor of added damping force combine with speed deviation. It contains a transfer function having a gain block; wash out block and lead-lag compensator[18]. Gain block serves the level of damping to the input. The wash-out block is omitted in this paper. Figure 2 shows the general block diagram of PSS damping controller. The transfer function of PSS structure is given by:

$$\frac{V_s}{\Delta\omega_m} = K_{pss}\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right) \tag{6}$$

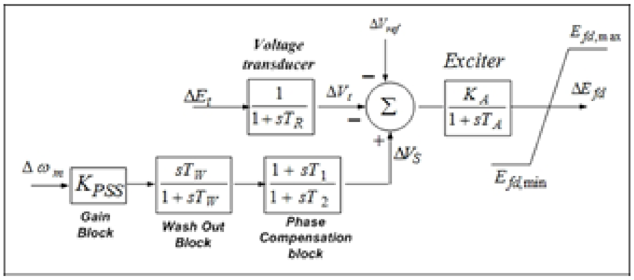

Figure 2. Simplified block diagram for proposed PSS

where, T_2 the lead is time constant and T_1 is the lag time constant. The input signal to the PSS is $\Delta\omega_m$ i.e. deviation in speed from synchronous speed and the output of PSS is the supplementary signal (V_S). V_S is added to $V_{S\,ref}$ and V_t to the exciter, so as to damp the LFO in a network. So, test system Eigen-values will be increased by one.[18]

3.2 TCSC Damping Controller

A speed input single-stage TCSC controller has been applied to the SMIB system as shown in Fig 3. TCSC configuration consists of a bidirectional thyristor T_1 and T_2, bypass inductor L and fixed series capacitor bank C. In stability studies the TCSC can be represented by an equivalent reactance X_{TCSC}. By proper variation of firing angle (α) of the thyristors, the value of X_{TCSC} is adjusted automatically to regulate the specific quantity of power flow through the transmission line[19].

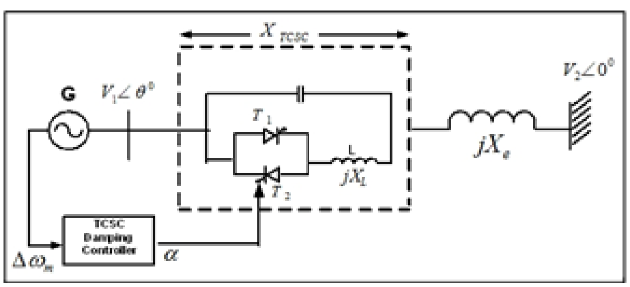

Figure 3. SMIB system with TCSC

$$\Delta \dot{X}_{TCSC} = -\frac{1}{T_{TCSC}}\Delta\alpha - \frac{1}{T_{TCSC}}\Delta X_{TCSC} \tag{7}$$

The transfer function model of TCSC controller is shown in Figure 4. It's composed of a gain block with gain K_T, a signal washout block, and a phase compensation block as shown in Figure 4. These blocks do for a similar function as in PSS.

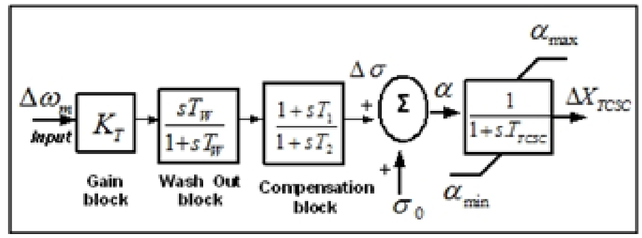

Figure 4. Simplified block diagram for proposed TCSC controller

In the damping controller the normalized speed deviation i.e. $\Delta\omega_m$ is the input signal and the deviation in thyristor conduction angle $\Delta\sigma$ is that the output of the proposed TCSC controller. The value of reactance included within the network is calculated by applying firing angle of thyristors respectively. $\Delta\sigma$ =0, under steady-state conditions and the $X_{EFF} = X_e - X_{TCSC}(\alpha_0)$, is the effective line reactance of the transmission line[2]. Where $X_{EFF} = X_e - X_{TCSC}(\alpha)$, in dynamic conditions. Where α is the firing angle of the thyristors respectively.[2]

3.3 Optimmal State Feedback Control

The optimal controller based on the state feedback control law[20]. This state feedback control law is developed based on the design of cost function. The OSFC has been broadly investigated from the precedent four decades[20]. The OSFC design problem is the formulation of the cost function and the elite of the state and control weighting matrices. The optimal gains of the system move the system states to left half of s-plane. The principal objective of OSFC is to accomplish the network highest damping efficiency and regulate the system stability. The proposed optimal controller algorithm for COC of SVeC and PSS solves a succession of constrained nonlinear optimization so that, critical Eigen-values of the unstable and lower damped modes are transferred to the conic region. The method is based on trial and error and does not offer a systematic way of choosing positive semi - definite matrix (Q) and positive definite matrix (R). The OSFC block diagram representation as given in Figure 5.

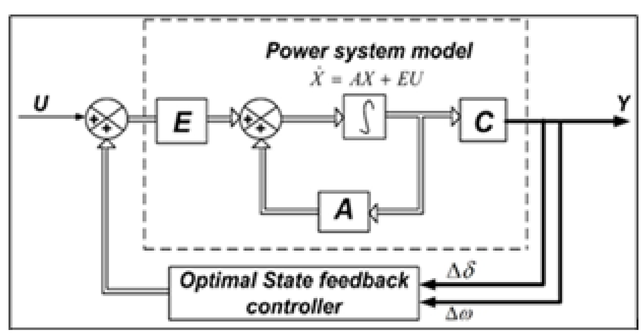

Figure 5. Block diagram representation of Optimal state feedback controller

Optimal control vector is represented in the form of K matrix (K is state feedback gain matrix)

$$u(t) = -K.x(t) \tag{8}$$

So minimize the performance index

$$J = \int_0^\infty (x^T Qx + u^T Ru)dt \tag{9}$$

where, Q is state weighting matrix and R is control weighting matrix. Optimal control matrix K is

$$K = R^{-1}.E^T.P \tag{10}$$

Solve the Riccati equation for matrix P

$$P\,A^T P + PA - PE.R^{-1}.E^T.P + Q = 0; \tag{11}$$

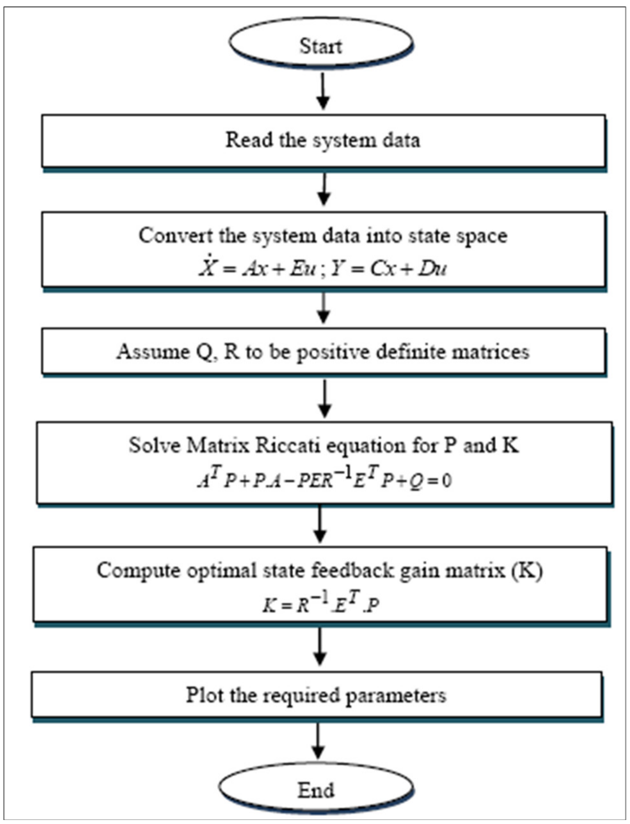

Figure 6. Flow Chart for the design of OSFC

4. Results and Discussions

A MATLAB/ Simulink program for the test system without control, with TCSC and OSFC control for COC of TCSC and PSS at nominal load condition has been carried out.

Table 1 lists the Eigen-values of test system without control, total 4 Eigen-values are present at nominal operating condition. In the total 4 Eigen-values, 4 are complex conjugate. In Table-1, without damping controller, the important dominant mode is (-0.0300±j7.7617) and has the DR of 0.0039 and therefore this mode has been referred to as critical swing mode. This DR can be improved by adding PSS to the network. So, the critical swing mode shifted to a most desirable position in the s plane.

Table 1. Eigen-values of test system without control

Mode	Without Control	Damping Ratio (ζ)	Frequency (rad/sec)
$\Lambda_{1,2}$	-2.6852±j15.3260	0.1733	15.600
$\Lambda_{3,4}$	-0.0300±j7.7617	0.0039	7.76

The second column of Table 2 lists the Eigen-values of test system with PSS. Total 5 eigenvalues are present. Four are complex conjugate and one is real value. The critical mode moves to (-0.3792 ± j7.55571) and has the DR of 0.0501, respectively. Now the DR is improved to 0.0426. The DR further improved by placing the TCSC in the system.

Table 2. Eigen-values of test system with PSS

Mode	Without Control	Damping Ratio (ζ)	Frequency (rad/sec)
$\Lambda_{1,2}$	-2.1215± j15.4873	0.1360	15.6
$\Lambda_{3,4}$	-0.3792±j7.55571	0.0501	7.57
Λ_{5}	-10.4290	1.0	10.42

Table 3 presents the eigenvalues of the test system with TCSC. Total 6 eigenvalues are present with TCSC. In 6 Eigen values, 4 are complex conjugate and remain are real values. With TCSC, the critical mode shifted to (-0.9712±j4.6285) and has the DR of 0.205, respectively at 50% compensation. The DR with TCSC is improved to 0.1549. The DR has been further improved by LQR optimal controller.

Table 3. Eigen-values of test system with TCSC

Mode	Without Control	Damping Ratio (ζ)	Frequency (rad/sec)
$\Lambda_{1,2}$	-3.2065± j16.077	0.196	16.4
$\Lambda_{3,4}$	-0.9712±j4.6285	0.205	4.73
Λ_{5}	-17.7874	1.0	17.7874
Λ_{6}	-0.0400	1.0	0.0400

Table 4 lists the Eigen-values of test system LQR optimal controller. Total 6 Eigen-values are present in the total 6 Eigen-values, 4 are complex conjugate and 2 are real values. The critical mode shifted to (-0.9738 ± j 3.6278) and has the DR of 0.2590 . The DR has been improved by 0.054 with LQR optimal control.

$$K = \begin{bmatrix} -0.0000 & -0.0000 & 0.0385 & -0.0000 & 0.0007 & 0; \\ 0.0000 & 0.0000 & -0.0168 & 0.0000 & -0.0004 & 0 \end{bmatrix}$$

$$P = \begin{bmatrix} 1.45E\text{-}06 & -2.82E\text{-}06 & -0.00032 & 9.66E\text{-}09 & -4.89E\text{-}06 & 0 \\ -2.82E\text{-}06 & 6.56E\text{-}05 & -0.00077 & 1.75E\text{-}08 & -3.83E\text{-}05 & 0 \\ -0.00032 & -0.00077 & 0.310608 & -8.40E\text{-}06 & 0.006401 & 0 \\ 9.66E\text{-}09 & 1.75E\text{-}08 & -8.40E\text{-}06 & 3.27E\text{-}10 & -1.83E\text{-}07 & 0 \\ -4.89E\text{-}06 & -3.83E\text{-}05 & 0.006401 & -1.83E\text{-}07 & 0.000149 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Table 4. Eigen-values of test system for COC of TCSC and PSS with OSFC

Mode	OSFC control	Damping Ratio (ζ)	Frequency (rad/sec)
$\Lambda_{1,2}$	-3.4066 ± j 16.077	0.207	16.5000
$\Lambda_{3,4}$	-0.9738 ± j 3.6278	0.2590	3.76
Λ_5	-0.0450	1	0.0450
Λ_6	-17.7882	1	17.788

It is observed that the TCSC and PSS with OSFC can simultaneously improving the damping of the test system compared to the no control, PSS and TCSC.

The eigenvalues of the SMIB bus at nominal load with different controllers are presented in Figure 7. The Eigen values are more shifted to left of the S-plane with LQR control compared to other and without controllers. The settling is reduced with LQR controller.

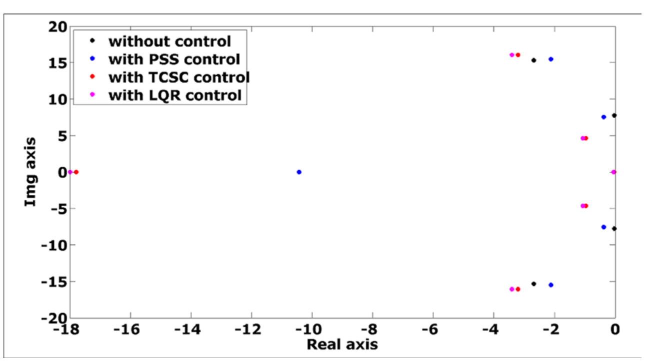

Figure 7. Eigenvalues for the SMIB bus at nominal load

The rotor angle deviations for without and with different controllers are plotted in Figure 8. It has been found that the oscillations damp faster with the application of LQR controller compared to that of other controllers. In view of these results, it may be concluded that LQR controller has lesser settling time and peak overshoot compared to TCSC, PSS and without control in damping the oscillations.

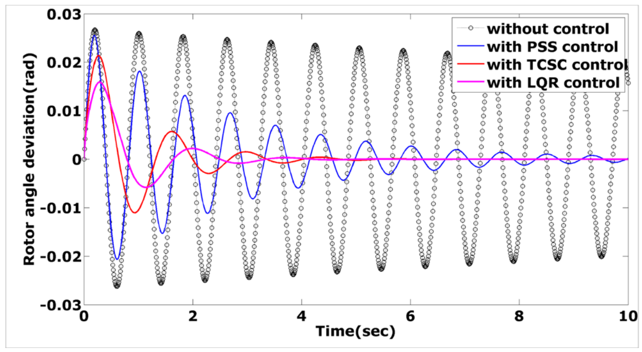

Figure 8. Rotor angle response of SMIB system

5. Conclusion

In this paper an approach for COC of TCSC and PSS with OSFC for power oscillation damping has been proposed. The approach is verified by means of Eigen-value analysis at nominal load. The Eigen-value analysis results at without control, with PSS, with TCSC and COC of SVeC and PSS with OSFC are compared. The results obtained for a SMIB test system demonstrate the applicability of the controller and its ability to damp LFO at nominal loading condition. It can be concluded that the proposed COC of SVeC and PSS with OSFC has better in damping LFO in keeping dynamic stability. Our future research would be developing COC of TCSC and PSS with OSFC to damp the LFO at different loading conditions.

$$X_{SVeC} = -k^2(1 - D_s)^2 X_C$$

6. References

1. Kundur P, Klein M, Rogers GJ, Zywno MS, Application of power system stabilizers for enhancement of overall system stability. IEEE Transactions on Power Systems. 1989; 4(2):614–26. https://doi.org/10.1109/59.193836
2. Ahmed A, Muqabel BA, Mohammad A. Abido, Review of conventional power system stabilizer design methods. Proceedings of IEEE Conference; 2006. p. 1–7. https://doi.org/10.1109/IEEEGCC.2006.5686203

3. Hingorani NH, Gyugyi L. Understanding FACTS: Concepts and technology of flexible AC transmission system. Wiley-IEEE press; 2000. https://doi.org/10.1109/9780470546802
4. Lei X, Lerch EN, Povh D. Optimization and coordination of damping controls for improving system dynamic performance. IEEE Transactions Power Systems. 2001; 16(3):473–80. https://doi.org/10.1109/59.932284
5. Pourbeik P, Gibbard MJ. Simultaneous coordination of power-system stabilizers and FACTS device stabilizers in a multimachine power system for enhancing dynamic performance. IEEE Transactions Power Systems. 1998; 13(2):473–9. https://doi.org/10.1109/59.667371
6. Ramirez JM, Castillo I. I, PSS and FDS simultaneous tuning. Electric Power Systems Research. 2004; 68(1):33–40. https://doi.org/10.1016/S0378-7796(03)00148-2
7. Lopes LAC, Joos G. Pulse width modulated capacitor for series compensation. IEEE Transactions Power Electronics. 2001; 16(2):167–74. https://doi.org/10.1109/63.911140
8. Venkataramanan G, Johnson BK. Pulse width modulated series compensator. IEEE Proceedings of Generation, Transmission and Distribution. 2002; 149(1):71–5. https://doi.org/10.1049/ip-gtd:20020004
9. Gonzalez JM, Canizares CA, Ramirez JM. Stability modeling and comparative study of series vectorial compensators. IEEE Transactions Power Delivery. 2010; 25(2):1093–103. https://doi.org/10.1109/TPWRD.2009.2034905
10. Wang L, Truong D-N. Dynamic stability enhancement of a single-machine infinite bus system using a series vectorial compensator. Proceedings of IEEE Conference; 2013. p. 1–6.
11. Wang L, Truong D-N. Application of a SVeC and a SSSC on damping improvement of a SG-based power system with a PMSG-based offshore wind farm. Proceedings of IEEE Conference; 2012. p. 1–7. https://doi.org/10.1109/PESGM.2012.6344732
12. Safari A, Shayeghi H, Shayanfar HA. Coordinated control of pulse width modulation based AC link series compensator and power system stabilizers. Electrical Power and Energy Systems. 2016; 83:117–23. https://doi.org/10.1016/j.ijepes.2016.03.042
13. Kothari DP, Nagrath IJ. Modern power system analysis, Tata McGraw-Hill Publishing Company Ltd; 2009.
14. Ibraheem, Kumar P, Kothari P. Recent philosophies of automatic generation control strategies in power systems. IEEE Transactions Power Systems. 2005; 20(1):346–57. https://doi.org/10.1109/TPWRS.2004.840438
15. Sauer PW, Pai MA. Power system dynamics and stability, New Jersey, 1st ed, Prentice-Hall publisher; 1998.
16. Himaja K, Surendra TS, Kalyani ST. Coordinated design of PSS and Series vectorial compensator controllers for damping power system oscillations. Journal of Electrical Engineering. 2016; 16(4):507–12.
17. Kundur P, Balu NJ, Lauby MG. Power system stability and control. Vol 7, McGraw-Hill, New York; 1994.
18. Mondal D, Chakrabarti A, Sengupta A. Power system small signal stability and control: Academic Press, Elsevier; 2014. https://doi.org/10.1016/B978-0-12-800572-9.00001-9
19. Zak SH. Systems and Control, Oxford University Press, 2003.

Appendix

TCSC:

Conduction angle= 0.8727; X_{TCSC}= 0.7044;

dX_{TCSC}= 10.4013; X_T= 1.6494; K_{TCSC}=10.0;

K_P=4.0;T_1=0.5;T_2=0.1;T_{TCSC}=25; X_L=0.0049pu;

X_C=0.0284 pu ;T_{TCSC}=17ms

SMIB SYSTEM:

H=2.37s; D=0.0; K_A=400; Rs=0.0pu; Re=0.02pu;

Td=5.90s; T_A=0.2s; Ws=314 rad/sec; Xd=1.70pu;

Xd'=0.245pu; Xe=0.7pu; Xq=1.64pu; Vinf=1.00<$0^{0;}$

Vt=1.72<19.31^0

PSS:

K_{PSS}=10; T_{1PSS}=0.4; T_{2PSS}=0.15