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A New Method for Mitigation of Sub-synchronous Oscillations Using TCSC

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Abstract- The Linear Observer Method was adopted in this paper to study the SSR damping characteristics with TCSC. The study system was modified from the IEEE Second benchmark model by changing a part of the fixed series capacitor to TCSC. It is tried to stable torsional modes of turbine – generator units and improve their damping by using optimal linear control, with an practical viewpoint. In some of genuine applications, measurement of all state variables is impossible and uneconomic. Therefore in this paper, a novel approach is proposed by using optimal state feedback, based on the reduced order observer structure. It was shown also that the Linear Observer Method can mitigates Sub synchronous Oscillations (SSO) in power systems. The proposed method is applied to the IEEE Second Benchmark system for SSR studies and the results are verified based on comparison with those obtained from digital computer simulation by MATLAB.

Keywords: TCSC, Sub synchronous Oscillations, SSR, Linear Observer Method

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Nomenclature

L_{TCR}	**The Fixed Inductance of The TCR Branch**
L_{TCSC}	**Equivalent Variable Inductance of TCSC**
ΔX_{Gen}	**State Vector for Generator System Model**
A_G	**State Matrix for Generator System Model**
B_{Gi}	***i*th Input Matrix for Generator System Model**
Δy_{Gen}	**Output Vector for Generator System Model**
ΔU_{Gen}	**Input Vector for Generator System Model**
Δi_{fd}	**Variation of Field Winding Current**
$\Delta i_d, \Delta i_q$	**Variation of Stator Currents in the d-q Reference Frame**
$\Delta i_{kd}, \Delta i_{kq}$	**Variation of Damping Winding Current in the d-q RF**
$\Delta \delta_g$	**Variation of Generator Angle**
$\Delta \omega_g$	**Variation of Angular Velocity of Generator**
ΔV_O	**Variation of Infinitive Bus Voltage**
ΔE	**Variation of Field Voltage**
ΔX_{Mech}	**State Vector for Mechanical System Model**
A_M	**State Matrix for Mechanical System Model**
B_{Mi}	***i*th Input Matrix for Mechanical System Model**
Δy_{Mech}	**Output Vector for Mechanical System Model**
ΔU_{Mech}	**Input Vector for Mechanical System Model**
$\Delta \alpha$	**Variation of Firing Angle of The TCSC**
ΔV_{XC}	**Variation of Fixed Series Capacitor Voltage**
ΔX_{Line}	**State Vector for Transmission Line System**
A_{Line}	**State Matrix for Transmission Line System**
B_{Line}	**Input Matrix for Transmission Line System**
ΔU_{Line}	**Input Vector for Transmission Line System**
Δi_{TCR}	**Variation of The TCR Branch Current**
ΔV_{ref}	**Variation of Refrence Voltage**
ΔV_S	**Variation of Output PSS Signal**
ΔX_{EXC}	**State Vector for Excitation System Model**
A_{EXC}	**State Matrix for Excitation System Model**
B_{EXC}	**Input Matrix for Excitation System Model**
ΔU_{EXC}	**Input Vector for Transmission Line System**
ΔX_{Total}	**State Vector for Overall System Model**
A_{Total}	**State Matrix for Overall System Model**
B_{Total}	**Input Matrix for Overall System Model**
ΔU_{Total}	**Input Vector for Overall System Model**
C_{Total}	**Output Matrix for Overall System Model**
Δy_{Total}	**Output Vector for Overall System Model**
ΔX_{Obs}	**Unmeasurable State Variables**
ΔX_{Base}	**Measurable State Variables**
Δz	**State Vector of Reduced Order Observer**
$\Delta \hat{X}_{Total}$	**The Estimated State Vector**

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Introduction

Series compensation of power transmission lines is an important way to improve power transfer capability, especially where large amounts of power must be transmitted through long transmission lines. However, when these techniques applied together with a steam turbine-generator it may lead sub-synchronous resonance (SSR) phenomena. It means that, the interaction between the electrical oscillation modes of the series compensated network and the mechanical oscillation modes of the turbine-generator group may lead to oscillating torsional torques.

The advantages of the series compensation can be guaranteed without the danger of the SSR phenomena if series FACTS (Flexible AC Transmission System) devices is used. Some techniques to mitigate SSR with series FACTS devices can be found in the literature. This technique can provide controllable series compensation and reduce or eliminate the effects of the subsynchronous resonance [1].

The series FACTS devices most analyzed and applied to mitigate SSR is the Thyristor-Controlled Series Capacitor (TCSC). Pilotto et al.[2] have shown that TCSC operating with local current control can efficiently mitigate SSR problem. However, they have also shown that TCSC can not damp SSR when it is operating with large firing angle (between 170^o and 180^o). Kakimoto and Phongphanphanee [3] have also demonstrated that TCSC

$$L_{TCSC} = \frac{\pi . L_{TCR}}{2(\pi - \alpha) + \sin 2\alpha} \quad (1)$$

can damp SSR if its firing angle is modulated with the rotor angle variation. But in the practical environment (real world), access to all of the state variables of system is limited and measuring all of them is also impossible. So when we have fewer sensors available than the number of states or it may be undesirable, expensive, or impossible to observer is proposed. Therefore in this paper, a novel approach is introduced by using optimal state feedback, based on the reduced-order observer structure. Note that, in the simulation of this paper the IEEE Second benchmark model are used based on three cases, such as: a) fixed capacitor, b) With TCSC and c) With TCSC using reduced-order observer. Based on comparison of these cases, it has been observed that proposed method gives good results and the peak deviations of SSO is reduced by using this method with a practical viewpoint.

A. *System Model*

A. *Representation of a TCSC compensated Transmission Line*

A TCSC consists of a capacitor in parallel with an inductor that is connected to a pair of opposite-poled thyistors. By using the firing angle of the thyristors, the inductor reactance is varied, which in turn, changes the effective impedance of the TCSC. We can thus represent the TCSC as a variable impedance device. The TCSC is generally operated in the capacitive region, while inductive mode operation can be used during severe contingencies. The schematic of TCSC is shown in Fig. 1.

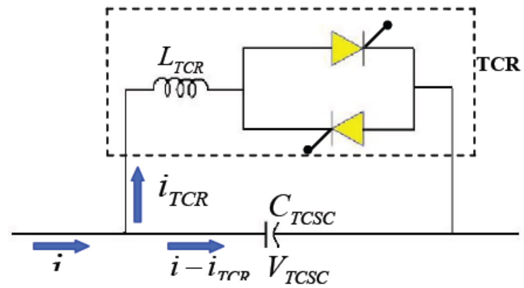


Fig. 1. Schematic representation of TCSC.

An approximate TCSC dynamic model is derived by representing the thyristor-controlled reactor (TCR) (See Fig. 1) of the TCSC as an equivalent variable inductance [4, 5].

B. *The Test System*

The system under study is shown in Fig. 2. This is the IEEE Second benchmark model, with a fixed series capacitor and a TCSC connected to it. This system is adopted to explain and demonstrate applications of the proposed method for investigation of the single-machine torsional oscillations. The system includes a T-G unit which is connected through a radial series compensated line to an infinite bus. The rotating mechanical system of the T-G set is composed of two turbine sections, the generator rotor and a rotating exciter. The system parameters are provided in [6].

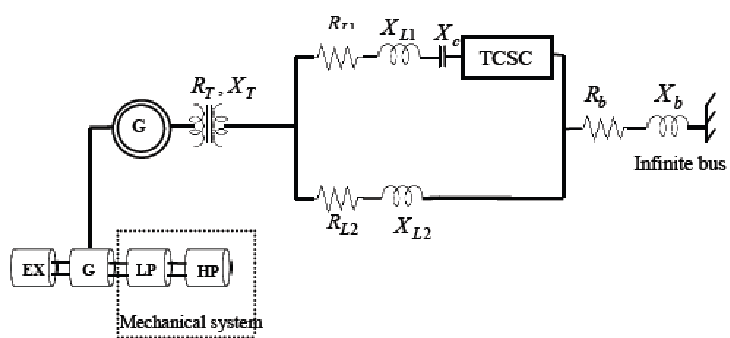


Fig. 2. Schematic diagram of the IEEE Second Benchmark System.

C. *Mathematical Model*

Using direct, quadrature (d-q axes) and Park's transformation, the complete mathematical model that describes the dynamics of the system can be found in [7]:

$$\Delta\dot{X}_{Gen} = A_G \Delta X_{Gen} + B_{G1}\Delta U_1 + B_{G2}\Delta U_2 + B_{G3}\Delta U_3 + B_{G4}\Delta U_4 \quad (2)$$

$$\Delta y_{Gen} = C_G \Delta X_{Gen} \tag{3}$$

It is noted that C_G is an identity matrix. The following state variables and input parameters are used in (2):

$$\Delta X_{Gen}{}^T = \begin{bmatrix}\Delta i_{fd} & \Delta i_d & \Delta i_{kd} & \Delta i_q & \Delta i_{kq}\end{bmatrix} \tag{4}$$

$$\Delta U_{Gen}{}^T = \begin{bmatrix}\Delta V_O & \Delta\delta_g & \Delta\omega_g & \Delta E\end{bmatrix} \tag{5}$$

The shaft system of the T-G set is represented by four rigid masses. The linearized model of the shaft system, based on a mass-spring-damping model is:

$$\Delta \dot{X}_{Mech} = A_M \Delta X_{Mech} + B_{M1}\Delta U_{M1} + B_{M2}\Delta U_{M2} \tag{6}$$

$$\Delta y_{Mech} = C_M \Delta X_{Mech} \tag{7}$$

Where, C_M is an identity matrix. The following state variables and input parameters are used in (6):

$$\Delta X_{Mech}{}^T = \begin{bmatrix}\Delta\delta_1 & \Delta\omega_1 & \Delta\delta_g & \Delta\omega_g & \Delta\delta_2 & \Delta\omega_2 & \Delta\delta_3 & \Delta\omega_3\end{bmatrix} \tag{8}$$

$$\Delta U_{Mech}{}^T = \begin{bmatrix}\Delta T_m & \Delta T_e\end{bmatrix} \tag{9}$$

It is available All parameters which in use (2) - (9) at [6]. For finding mathematical model of Transmission Line, we can assume:

$$\Delta V_C = \Delta V_{XC} + \Delta V_{TCSC} \tag{10}$$

Where, ΔV_{XC} is variation of fixed series capacitor voltage. Linearized model of a TCSC compensated transmission line is:

$$\Delta \dot{X}_{TCSC} = A_{TCSC}\Delta X_{TCSC} + B_{TCSC}\Delta U_{TCSC} \tag{11}$$

The following state variables and input parameters are used in (11):

$$\Delta X_{TCSC}{}^T = \begin{bmatrix}\Delta V_{TCSC(d)} & \Delta V_{TCSC(q)} & \Delta i_{TCR(d)} & \Delta i_{TCR(q)}\end{bmatrix} \tag{12}$$

$$\Delta U_{TCSC}{}^T = \begin{bmatrix}\Delta i_d & \Delta i_q & \Delta\omega_g & \Delta\alpha\end{bmatrix} \tag{13}$$

The expressions of matrices A_{TCSC} and B_{TCSC} can be found in Appendix A. Mathematical model of Transmission Line without TCSC can be written:

$$\frac{d}{dt}\Delta V_{XC(d)} = \omega_0 k_{SBM} X_C \Delta i_d + \omega_0 \Delta V_{XC(q)} \tag{14}$$

$$\frac{d}{dt}\Delta V_{XC(q)} = \omega_0 k_{SBM} X_C \Delta i_q - \omega_0 \Delta V_{XC(d)} \tag{15}$$

Where K_{SBM} is represented by:

$$K_{SBM} = \sqrt{\frac{R_{L2}{}^2 + X_{L2}{}^2}{(R_{L1}+R_{L2})^2 + (X_{L1}+X_{L2}-X_C)^2}} \tag{16}$$

By combining (10)-(15), Linearized model of transmission line is given by:

$$\Delta \dot{X}_{Line} = A_{Line}\Delta X_{Line} + B_{Line}\Delta U_{Line} \tag{17}$$

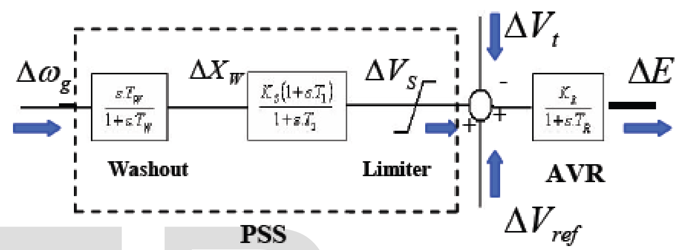
$$\Delta X_{Line}{}^T = \begin{bmatrix}\Delta V_{C(d)} & \Delta V_{C(q)} & \Delta i_{TCR(d)} & \Delta i_{TCR(q)}\end{bmatrix} \tag{18}$$

Note that, in (17), Matrix ΔU_{Line} is similar to ΔU_{TCSC}. The excitation system model is given in Fig. 3. This includes a static exciter containing an automatic voltage regulator (AVR) and a PSS. The PSS contains a washout circuit and a lead-lag block in addition to a limiter. The input to the PSS is angular velocity of generator ($\Delta\omega_g$). From Fig. 3, the exciter state space Linearized equation can be written as:

$$T_W \frac{d}{dt}\Delta X_W + \Delta X_W = T_W \frac{d}{dt}\Delta\omega_g \tag{19}$$

$$T_2 \frac{d}{dt}\Delta V_S + \Delta V_S = T_1 K_S \frac{d}{dt}\Delta X_W + K_S \Delta X_W \tag{20}$$

$$T_R \frac{d}{dt}\Delta E + \Delta E = K_R\left(\Delta V_{ref} + \Delta V_S - \Delta V_t\right) \tag{21}$$



After more computational efforts, the state space description of the excitation system model is given by:

$$\Delta \dot{X}_{EXC} = A_{EXC}\Delta X_{EXC} + B_{EXC}\Delta U_{EXC} \tag{22}$$

$$\Delta X_{EXC}{}^T = \begin{bmatrix}\Delta X_W & \Delta V_S & \Delta E\end{bmatrix} \tag{23}$$

$$\Delta U_{EXC}{}^T = \begin{bmatrix}\Delta U_{Mech} & \Delta X_{Mech} & \Delta V_{ref}\end{bmatrix} \tag{24}$$

All parameters of the excitation system model are given by [6]. With considering to (2)-(22), overall system model is obtained:

$$\Delta \dot{X}_{Total} = A_{Total}\Delta X_{Total} + B_{Total}\Delta U_{Total} \tag{25}$$

$$\Delta y_{Total} = C_{Total}.\Delta X_{Total} \tag{26}$$

$$\Delta X_{Total}{}^T = \begin{bmatrix}\Delta X_{Gen} & \Delta X_{Mech} & \Delta X_{Line} & \Delta X_{EXC}\end{bmatrix} \tag{27}$$

$$\Delta U_{Total}{}^T = \begin{bmatrix}\Delta T_m & \Delta V_O & \Delta V_{ref} & \Delta\alpha\end{bmatrix} \tag{28}$$

Where, ΔV_O is variation of infinitive bus voltage.

Controller Design

A. Linear Optimal Controller

Optimal control must be employed in order to damp out the subsynchronous oscillations resulting from the negatively damped mode. For the linear system the control signal U which minimizes the performance index:

$$J = \int [\Delta x_{Total}{}^T(t) Q \Delta x_{Totalt}(t) + \Delta u_{Total}{}^T R_\mu \Delta u_{Total}(t)]dt \tag{29}$$

is given by the feedback control law in terms of system states:

$$U(t) = -K \cdot \Delta x_{Total}(t) \tag{30}$$

$$K = R_{\mu}^{-1}.B_{Total}^{T}.P \tag{31}$$

Where P is the solution of Riccati equation:

$$A_{Total}^{T}.P + P.A_{Total} - P.B_{Total}R_{\mu}^{-1}B_{Total}^{T}.P + Q = 0 \tag{32}$$

In this paper to improve damping of subsynchronous oscillation (SSO) pragmatically, reduced order observer method is proposed, but to have a complete research, optimal full state feedback control is designed and the results are compared. When feedback control law is $U(t) = -K.\Delta X_{Total}$, if some of the state variables in vector Δx_{Total} is not measurable, observers may be used. A full order observer estimates all the states in a system, regardless whether they are measurable or not but when some of the state variables are measurable using a reduced-order observer is so better. By assumption $\Delta X_{Gen1}=\Delta X_{Gen}^{T}.\eta_{Gen1}$ and $\Delta X_{Mech1}=\Delta X_{Mech}^{T}.\eta_{Mech1}$ the state variables are unmeasurable, are given by:

$$\Delta X_{Obs}^{T} = [\Delta X_{Gen1} \quad \Delta X_{Mech1} \quad \Delta X_{Line} \quad \Delta X_{EXC}] = \Delta\hat{X}^{T} \tag{33}$$

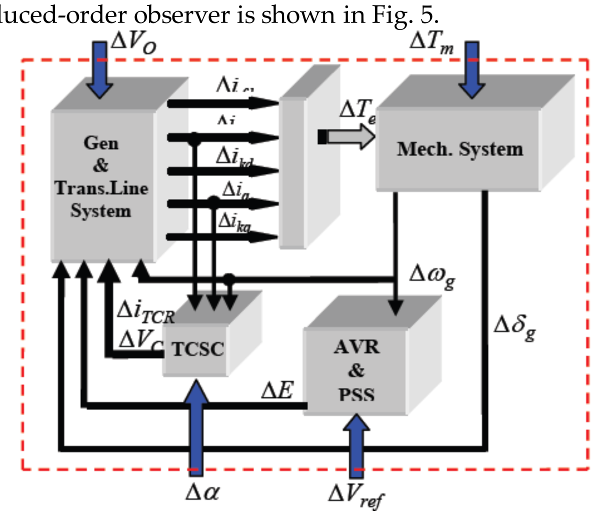
It is noted that η_{Gen1} and η_{Mech1} are matrix square with size five and eight orderly. The basic diagonal elements of η_{Gen1} are 0,0,1,0 and 1 respectively .This elements for η_{Mech1} are 0,1,0,1,0,1,0 and 1. The other elements are zero. If we get $\Delta X_{Gen2}=\Delta X_{Gen}^{T}.\eta_{Gen2}$ and $\Delta X_{Mech2}=\Delta X_{Mech}^{T}.\eta_{Mech2}$, the state variables are measurable, are obtained by (34).

$$\Delta X_{Base}^{T} = [\Delta X_{Gen2} \quad \Delta X_{Mech2}] \tag{34}$$

η_{Gen2} and η_{Mech2} are matrix square with size five and eight orderly. The basic diagonal elements of η_{Gen2} are 1,1,0,1 and 0 respectively. This elements for η_{Mech2} are 1,0,1,0,1,0,1 and 0.The other elements are zero.

B. *Linear Observer*

The Luenberger reduced-order observer is used as a linear observer in this paper. The block diagram of this reduced-order observer is shown in Fig. 5.



For the controllable and observable system that is defined by (25), there is an observer structure with size of $(n-l)$. The size of state vector is n and output vector is l. The dynamic system of Luenberger reduced-order observer with state vector of $z(t)$, is given by:

$$\Delta z(t) = L.\Delta x_{Total}(t) \tag{35}$$

$$\dot{z}(t) = D.z(t) + T.y_{Total}(t) + R.u_{Total}(t) \tag{36}$$

To determine L, T and R is basic goal in reduced-order observer. In this method, the estimated state vector $\Delta\hat{X}_{Total}(t)$ include two parts. First one will obtain by measuring $\Delta y_{Total}(t)$ and the other one will obtain by estimating $\Delta z(t)$ from (35).

We can take:

$$\begin{bmatrix} \Delta y_{Total}(t) \\ \Delta z(t) \end{bmatrix} = \begin{bmatrix} C_{Total} \\ L \end{bmatrix} . \Delta\hat{X}_{Total}(t) \tag{37}$$

By assumption full rank $[C_{Total}^{T} \quad L^{T}]^{T}$, we can get:

$$\Delta\hat{X}_{Total}(t) = \begin{bmatrix} C_{Total} \\ L \end{bmatrix}^{-1} . \begin{bmatrix} \Delta y_{Total}(t) \\ \Delta z(t) \end{bmatrix} \tag{38}$$

By definition:

$$\begin{bmatrix} C_{Total} \\ L \end{bmatrix}^{-1} = [F_1 \quad F_2] \tag{39}$$

We get:

$$\Delta\hat{X}_{Total}(t) = F_1.\Delta y_{Total}(t) + F_2.\Delta z(t) \tag{40}$$

Where:

$$F_1.C_{Total} + F_2.L = I_n \tag{41}$$

Using estimated state variables, the state feedback control law is given by:

$$\begin{aligned} \Delta U_{Total}(t) &= -K.\Delta\hat{X}_{Total}(t) \\ &= K.F_1.C_{Total}.\Delta X_{Total}(t) - K.F_2.\Delta z(t) \end{aligned} \tag{42}$$

By assumption $R=L.B_{Total}$ in (36), descriptive equations of closed loop control system with reduced-order observer are:

$$\begin{bmatrix} \Delta\dot{X}_{Total}(t) \\ \Delta\dot{z}(t) \end{bmatrix} = \begin{bmatrix} A_{Total} - B_{Total}.F_1.C_{Total} & -B_{Total}.K.F_2 \\ T.C_{Total} - L.B_{Total}.K.F_1.C_{Total} & D - L.B_{Total}.K.F_2 \end{bmatrix} . \begin{bmatrix} \Delta X_{Total}(t) \\ \Delta z(t) \end{bmatrix} \tag{43}$$

Dynamic error between linear combination of states of $L.\Delta X_{Total}(t)$ system and observer $\Delta z(t)$ is defined as:

$$\dot{e}(t) = \Delta\dot{z}(t) - L.\Delta\dot{X}_{Total}(t) \tag{44}$$

Combine (36) and (37), we get:

$$\begin{bmatrix} \Delta\dot{X}_{Total}(t) \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A_{Total} - B_{Total}.K & -B_{Total}.K.F_2 \\ 0 & D \end{bmatrix} . \begin{bmatrix} \Delta X_{Total}(t) \\ e \end{bmatrix} \tag{45}$$

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For stability of the observer dynamic system, the eigenvalues of D must lie in the left hand-side of s plane. By choosing D, we can calculate L, T and R [8].

Simulation Results

Eigenvalue analysis is a fast and well-suited technique for defining behavioral trends in a system that can provide an immediate stability test. The real parts of the eigenvalue represent the damping mode of vibration, a positive value indicating instability, while the imaginary parts denote the damped natural frequency of oscillation.

As mentioned earlier, the system considered here is the IEEE Second benchmark model (IEEE-SBM). It is assumed that the fixed capacitive reactance (X_C) is 77% of the reactance of the transmission line (X_{L1}=0.48 $P.u$). For the nominal operating point, the TCSC firing angle is chosen such that the total series capacitive compensation is 60% of trans- mission line reactance. The simulation studies of IEEE-SBM carried out on MATLAB platform is discussed here. The following cases are considered for the analysis.

Case-1: Without TCSC (compensation only by fixed capacitor, X_C = 0.3696 using linear optimal controller).

Case-2: With TCSC (X_C=0.0816, X_{TCSC}=0.288 without linear observer).

Case-3: With TCSC (X_C=0.0816, X_{TCSC}=0.288 using reduced-order observer).

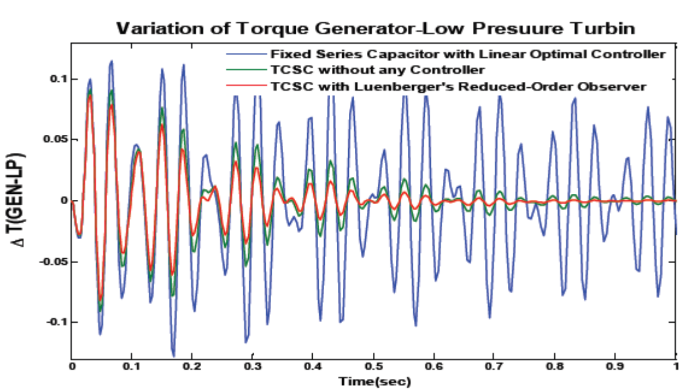
For obtaining variation of torque of the rotating mechanical system of the T-G set, we have [4]:

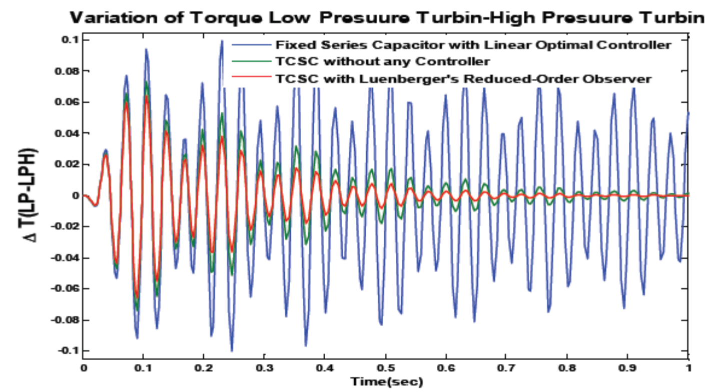
$$\Delta T_{EXC-GEN}(t) = k_{1g}[\Delta\delta_g(t) - \Delta\delta_1(t)] \quad (46)$$

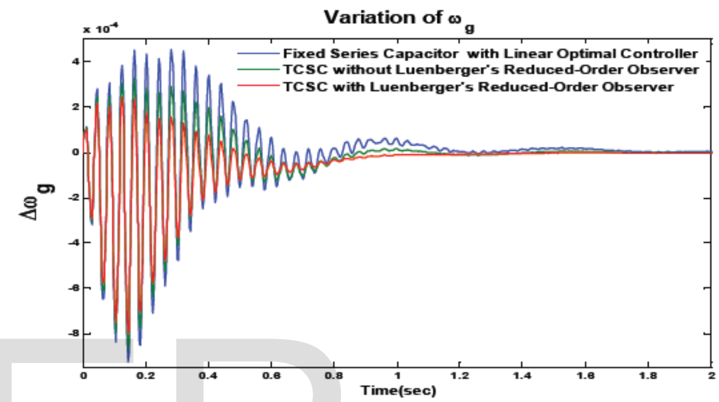
$$\Delta T_{GEN-LP}(t) = k_{g2}[\Delta\delta_2(t) - \Delta\delta_g(t)] \quad (47)$$

$$\Delta T_{LP-HP}(t) = k_{23}[\Delta\delta_g(t) - \Delta\delta_3(t)] \quad (48)$$

Where, k_{1g}, k_{g2} and k_{23} are given by [7]. Fig. 6 observes the variations of torque of the rotating mechanical system of the T-G set for cases-1, 2 and 3. It is noted that, with case-1, amplitude of oscillations is maximum. Its SSO is damped in a longer time. Also it illustrates that, with case-3, amplitude of oscillations is minimum. Its SSO is damped in an earlier time. It is observed that, Using the proposed method the torque deviation of case-3 have a better dynamic response in comparing with the other cases.







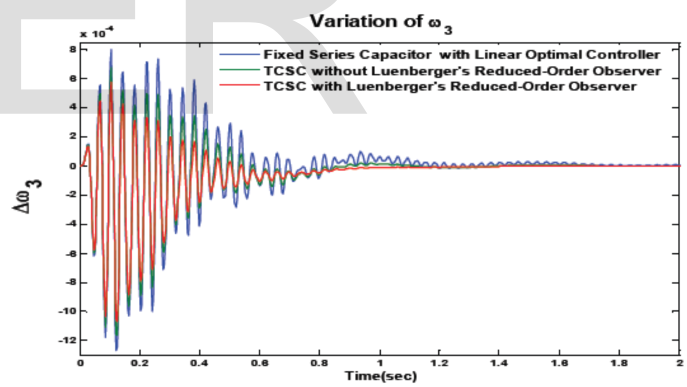


Fig. 6 observes the variations of torque of the rotating mechanical system of the T-G set for cases-1, 2 and 3.

Conclusion

In this paper, Linear Observer Method for studing the SSR damping characteristics with TCSC is investigated. It is tried to stable torsional modes of turbine – generator (T-G) units and improve their damping by using optimal linear control, with an operative overview. The proposed method is applied to the IEEE Second Benchmark system for SSR studies and the results are verified based on comparison with those obtained from eigenvalue studies and digital computer simulation by MATLAB.

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In the practical environment (real world), access to all of the state variables of system is limited and measuring all of them is also impossible. So when we have fewer sensors available than the number of states or it may be undesirable, expensive, or impossible to directly measure all of the states, using a reduced-order observer is proposed. Therefore in this paper, a novel approach is introduced by using optimal state feedback, based on the Reduced – Order Observer structure.

The simulation results of IEEE-SBM carried out on 3 cases. Variation of angular velocity and torque of the rotating mechanical system of the T-G set for all cases was studied.

Analysis reveals that the proposed technique gives good results and the peak deviations of SSO and inadvertent interchange is reduced by using this method with a practical viewpoint. It can be concluded that using TCSC with reduced order observer controller will mitigate SSO suitably. Also this method can keep accuracy in the results obtained from simulations in an appropriate level. In the other hand, by presented estimation method, it is obtained better damping and satisfactory accuracy for SSO.

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