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Application of Modern Optimal Control in Power System: Damping Detrimental Sub-Synchronous Oscillations

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1. Introduction

The occurrence of several incidents in different countries during the seventies and the eighties promoted investigations into the cause of turbine-generator torsional excitation and the effect of the stimulated oscillations on the machine shaft. The best known incidents are the two shaft failures that occurred in the Mohave station in Nevada in 1970 and 1971, which were caused by sub-synchronous resonance (SSR) (Walker et al., 1975; Hall et al., 1976). A major concern associated with fixed series capacitor is the SSR phenomenon which arises as a result of the interaction between the compensated transmission line and turbine-generator shaft. This results in excessively high oscillatory torque on machine shaft causing their fatigue and damage. These failures were caused by sub-synchronous oscillations due to the SSR between the turbine-generator (T-G) shaft system and the series compensated transmission network. These incidents and others captured the attention of the industry at large and stimulated greater interest in the interaction between power plants and electric systems (IEEE committee report, 1992; IEEE Torsional Issues Working Group, 1997; Anderson et al., 1990; Begamudre, 1997).

Torsional interaction involves energy interchange between the turbine-generator and the electric network. Therefore, the analysis of SSR requires the representation of both the electromechanical dynamics of the generating unit and the electromagnetic dynamics of the transmission network. As a result, the dynamic system model used for SSR studies is of a higher order and greater stiffness than the models used for stability studies. Eigenvalue analysis is used in this research. Eigenvalue analysis is performed with the network and the generator modelled by a system of linear simultaneous differential equations. The differential and algebraic equations which describe the dynamic performance of the synchronous machine and the transmission network are, in general, nonlinear. For the purpose of stability analysis, these equations may be linearized by assuming that a disturbance is considered to be small. Small-signal analysis using linear techniques provides valuable information about the inherent dynamic characteristics of the power system and assists in its design (Cross et al., 1982; Parniani & Iravani, 1995).

In this research, two innovative methods are proposed to improve the performance of linear optimal control for mitigation of sub-synchronous resonance in power systems. At first, a technique is introduced based on shifting eigenvalues of the state matrix of system to the left

hand-side of s plane. It is found that this proposed controller is an extended state of linear optimal controller with determined degree of stability. So this method is called extended optimal control. A proposed design, which is presented in this paper, has been developed in order to control of severe sub-synchronous oscillations in a nearby turbine-generator. The proposed strategy is tested on second benchmark model and compared with the optimal full-state feedback method by means of simulation. It is shown that this method creates more suitable damping for these oscillations.

In some of genuine applications, measurement of all state variables is impossible and uneconomic. Therefore in this chapter, another novel strategy is proposed by using optimal state feedback, based on the reduced - order observer structure. It was shown also that the Linear Observer Method can mitigate Sub-synchronous Oscillations (SSO) in power systems. The proposed methods are 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.

2. System model

The system under study is shown in Fig. 1. This is the IEEE Second benchmark model, with a fixed series capacitor 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 (Harb & Widyan, 2003).

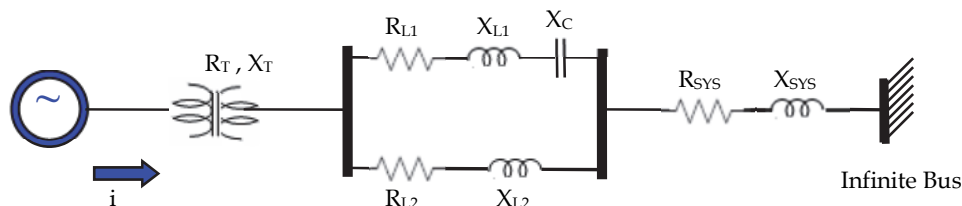


Fig. 1. Schematic diagram of the IEEE Second Benchmark System.

2.1 Electrical system

Using direct, quadrature (d-q axes) and Park's transformation, the complete mathematical model that describes the dynamics of the synchronous generator system:

$$\Delta \dot{X}_{Gen} = A_G \Delta X_{Gen} + B_{G1} \Delta U_1 + B_{G2} \Delta U_2 + B_{G3} \Delta U_3 + B_{G4} \Delta U_4 \quad (1)$$

$$\Delta y_{Gen} = C_G \Delta X_{Gen} \quad (2)$$

Where, C_G is an identity matrix. The following state variables and input parameters are used in (1):

$$\Delta X_{Gen}^T = [\Delta i_{fd} \quad \Delta i_d \quad \Delta i_{kd} \quad \Delta i_q \quad \Delta i_{kq}] \quad (3)$$

$$\Delta U_{Gen}^T = [\Delta V_O \quad \Delta \delta_g \quad \Delta \omega_g \quad \Delta E] \quad (4)$$

Where, ΔV_O is variation of infinitive bus voltage. In addition to the synchronous generator, the system also contains the compensated transmission line. The linearized model of transmission line is given by:

$$\Delta \dot{X}_{Line} = A_{Line} \Delta X_{Line} + B_{Line} \Delta U_{Line} \quad (5)$$

$$\Delta X_{Line}^T = [\Delta V_{Cd} \quad \Delta V_{Cq}] \quad (6)$$

$$\Delta U_{Line}^T = [\Delta i_d \quad \Delta i_q] \quad (7)$$

To obtain the electrical system, we can combine (1-7). Finally we can illustrate electrical system by below equations:

$$\Delta \dot{X}_{El} = A_{El} \Delta X_{El} + B_{El} \Delta U_{El} \quad (8)$$

$$\Delta X_{El}^T = [\Delta X_{Gen}^T \quad \Delta X_{Line}^T] \quad (9)$$

$$\Delta U_{El}^T = [\Delta U_{Gen}^T] \quad (10)$$

2.2 Mechanical system

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:

$$\Delta \dot{X}_{Mech} = A_M \Delta X_{Mech} + B_{M1} \Delta U_{M1} + B_{M2} \Delta U_{M2} \quad (11)$$

$$\Delta X_{Mech}^T = [\Delta \delta_1 \quad \Delta \omega_1 \quad \Delta \delta_g \quad \Delta \omega_g \quad \Delta \delta_2 \quad \Delta \omega_2 \quad \Delta \delta_3 \quad \Delta \omega_3] \quad (12)$$

$$\Delta U_{Mech}^T = [\Delta T_m \quad \Delta T_e] \quad (13)$$

The variation of electrical torque is denoted by ΔT_e and is given by:

$$\Delta T_e = P_1 \Delta i_{fd} + P_2 \Delta i_d + P_3 \Delta i_q + P_4 \Delta i_{kd} + P_5 \Delta i_{kq} \quad (14)$$

Parameters $P_1 - P_5$ can simplicity be founded by combination of electrical and mechanical system (Fig 2). Fig.3 illustrates the shaft system of the turbine-generator (T-G) in IEEE second benchmark model.

2.3 Combined power system model

The combined power system model is obtained by combining the linearized equations of the electrical system and mechanical system.

Let us define a state vector as $\Delta X_{Sys}^T = [\Delta X_{El}^T \quad \Delta X_{Mech}^T]$. So we can write:

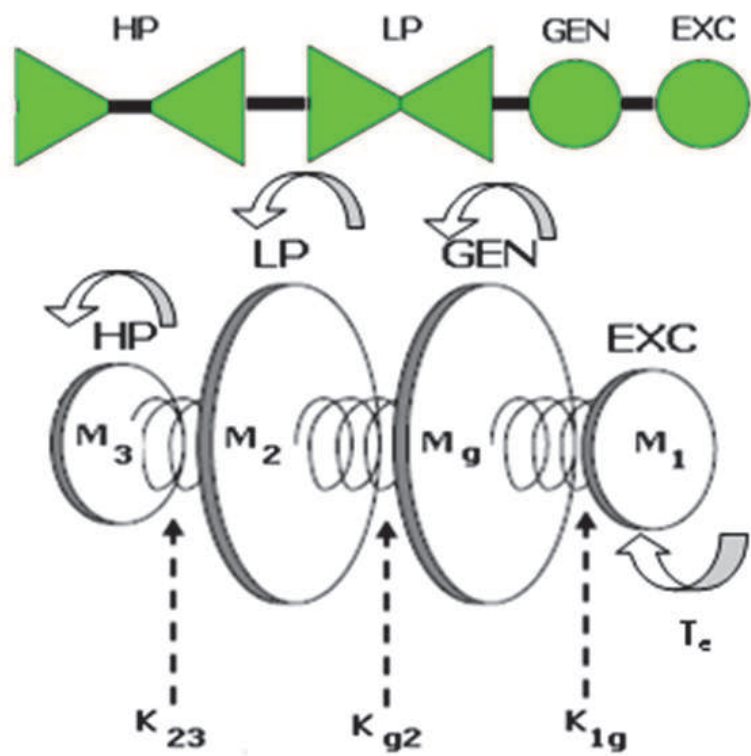


Fig. 3. Schematic diagram of the shaft system of the turbine-generator IEEE second benchmark model.

3. Modern optimal control

Optimal control must be employed in order to damp out the sub-synchronous oscillations resulting from the negatively damped mode. For the linear system, the control signal U which minimizes the performance index (Zhu et al., 1996; Patel & Munro, 1982; Khaki Sedigh, 2003; Ogata, 1990; Friedland, 1989; Kwakernaak, 1972):

$$J = \int [\Delta x_{sys}^T(t) Q \Delta x_{sys}(t) + \Delta u_{sys}^T R_{\mu} \Delta u_{sys}(t)] dt \tag{17}$$

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

$$U(t) = -K \cdot \Delta x_{sys}(t) \tag{18}$$

$$K = R_{\mu}^{-1} \cdot B_{sys}^T \cdot P \tag{19}$$

Where P is the solution of Riccati equation:

$$A_{sys}^T \cdot P + P \cdot A_{sys} - P \cdot B_{sys} R_{\mu}^{-1} B_{sys}^T \cdot P + Q = 0 \tag{20}$$

3.1 Extended optimal control

In this chapter, a strategy is proposed, based on shifting eigenvalues of the state matrix of system to the left hand-side of s plane, for damping all sub-synchronous torsional

oscillations. In order to have a complete research, optimal full state feedback control is designed and the results are compared with extended optimal control as proposed method. It is found that we can design linear optimal controller to obtain special degree of stability in optimal closed loop system by using this method. In the other hand, we can design a new controller that it transfers all of poles of optimal closed loop system to the left hand-side of $-\alpha$ (a real value) in S plane. For a linear system by (15), we can rewrite the performance index using proposed method:

$$J = \int e^{2\alpha t} [\Delta x_{sys}^T(t) Q \Delta x_{sys}(t) + \Delta u_{sys}^T R_{\mu} \Delta u_{sys}(t)] dt \quad (21)$$

For the linear system the control signal U which minimizes the performance index is given by the feedback control law in terms of system states:

$$U_{\alpha}(t) = -K_{\alpha} \cdot \Delta x_{sys}(t) \quad (22)$$

$$K_{\alpha} = R_{\mu}^{-1} \cdot B_{sys}^T \cdot P_{\alpha} \quad (23)$$

Where P_{α} is the solution of Riccati equation in this case:

$$(A_{sys} + \alpha I_n)^T \cdot P_{\alpha} + P_{\alpha} \cdot (A_{sys} + \alpha I_n) - P_{\alpha} \cdot B_{sys} R_{\mu}^{-1} B_{sys}^T \cdot P_{\alpha} + Q = 0 \quad (24)$$

Where I_n is an $n \times n$ identity matrix. So the state matrix of optimal closed loop system (A_{α}) is obtained by below:

$$(A_{sys} + \alpha I_n)^T \cdot P_{\alpha} + P_{\alpha} \cdot (A_{sys} + \alpha I_n) - P_{\alpha} \cdot B_{sys} R_{\mu}^{-1} B_{sys}^T \cdot P_{\alpha} + Q = 0 \quad (25)$$

In order to be asymptotically stable for A_{α} , we can write:

$$\lambda_i(A_{\alpha}) = \lambda_i(A_{sys} + \alpha I_n - B_{sys} \cdot K_{\alpha}) = \lambda_i(A_{sys} - B_{sys} \cdot K_{\alpha}) + \alpha \quad (26)$$

Where $\lambda_i(A_{\alpha})$ is eigenvalues of A_{α} for $i=1,2,\dots,n$. Because of $\text{Re}[\lambda_i(A_{\alpha})] < 0$, we can write :

$$\text{Re}[\lambda_i(A_{\alpha})] = \text{Re}[\lambda_i(A_{sys} - B_{sys} \cdot K_{\alpha}) + \alpha] = \text{Re}[\lambda_i(A_{sys} - B_{sys} \cdot K_{\alpha})] + \alpha < 0 \quad (27)$$

So we can write:

$$\text{Re}[\lambda_i(A_{sys} - B_{sys} \cdot K_{\alpha})] < -\alpha \quad (28)$$

In the other hand, all of eigenvalues of $(A_{sys} - B_{sys} \cdot K_{\alpha})$ are located on the left hand-side of $-\alpha$ in S plane. So the control signal U, which minimizes the performance index in (21), can create a closed loop system with determined degree of stability.

3.1.1 Numeral sample

This subsection gives a dimensional example in which the controllable system is to be designed in according to the proposed method. Suppose the nominal plant used for design of the controller is:

$$\frac{d}{dt} X = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} X + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} U \quad (29)$$

Where $X=[x_1(t) \ x_2(t)]^T$ and $U=[\mu_1(t) \ \mu_2(t)]^T$. We want to design an optimal controller in which the closed-loop system achieves to a favourite prescribed degree of stability. In this case, we chose $\alpha=2$. Suppose that

$$Q = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (30)$$

The solution of Riccati equation in this case is equal to:

$$P_\alpha = \begin{bmatrix} 3.9316 & 1.1265 \\ 1.1265 & 4.4462 \end{bmatrix} \quad (31)$$

To obtain the feedback control law in terms of system states, we can combine (23) with (29 – 31). Finally the optimal controller is given by:

$$U_\alpha(t) = -R^{-1}.B^T.P_\alpha.x(t) = \begin{bmatrix} -3.9316 & -1.1265 \\ -1.1265 & -4.4462 \end{bmatrix}.x(t) \quad (32)$$

And then the state matrix of optimal closed loop system (A_α) is obtained by:

$$A_\alpha = A + 2I_n - B.K_\alpha = \begin{bmatrix} -3.9316 & -0.1265 \\ -1.1265 & -4.4462 \end{bmatrix} \quad (33)$$

So the poles of optimal closed loop system are located in -3.7321 and -4.6458. It can be seen that both of them shift to the left hand-side of $-\alpha$ ($\alpha=2$) in S plane.

3.2 Reduced order 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. 3. For the controllable and observable system that is defined by (15), there is an observer structure with size of (n-1). 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:

$$\Delta z(t) = L.\Delta x_{Total}(t) \quad (34)$$

$$\dot{z}(t) = D.z(t) + T.y_{Total}(t) + R.u_{Total}(t) \quad (35)$$

To determine L, T and R is basic goal in reduced-order observer. In this method, the estimated state vector $\Delta \hat{X}_{Total}(t)$ includes two parts. First one will obtain by measuring $\Delta y_{Total}(t)$ and the other one will obtain by estimating $\Delta z(t)$ from (34). We can take:

$$\begin{bmatrix} \Delta y_{Total}(t) \\ \Delta z(t) \end{bmatrix} = \begin{bmatrix} C_{Total} \\ L \end{bmatrix}.\Delta \hat{X}_{Total}(t) \quad (36)$$

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

$$\Delta \hat{X}_{Total}(t) = \begin{bmatrix} C_{Total} \\ L \end{bmatrix}^{-1} \cdot \begin{bmatrix} \Delta y_{Total}(t) \\ \Delta z(t) \end{bmatrix} \quad (37)$$

By definition:

$$\begin{bmatrix} C_{Total} \\ L \end{bmatrix}^{-1} = [F_1 \ F_2] \quad (38)$$

We get:

$$\Delta \hat{X}_{Total}(t) = F_1 \cdot \Delta y_{Total}(t) + F_2 \cdot \Delta z(t) \quad (39)$$

Where:

$$F_1 \cdot C_{Total} + F_2 \cdot L = I_n \quad (40)$$

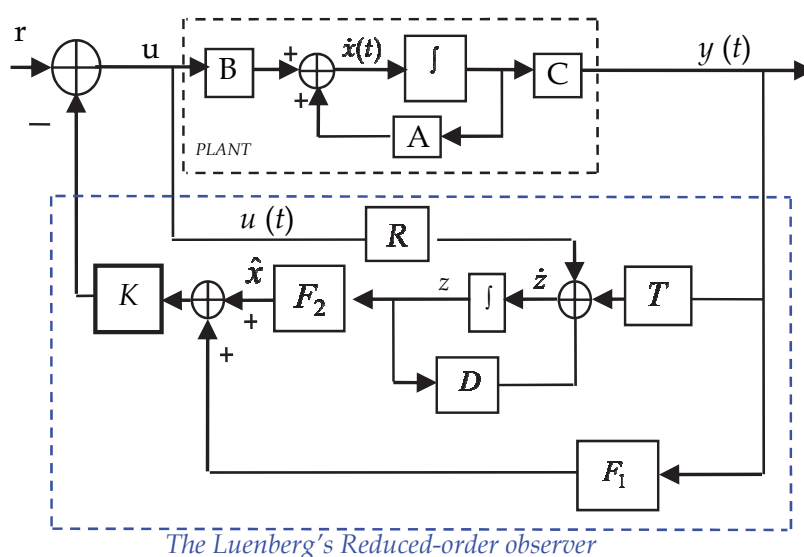


Fig. 4. Schematic Diagram of State Feedback Using Luenberger Reduced Order Observer

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

$$\Delta U_{Total}(t) = -K \cdot \Delta \hat{X}_{Total}(t) = K \cdot F_1 \cdot C_{Total} \cdot \Delta X_{Total}(t) - K \cdot F_2 \cdot \Delta z(t) \quad (41)$$

By assumption $R=L \cdot B_{Total}$ in (35), descriptive equations of closed loop control system with reduced-order observer are:

$$\begin{bmatrix} \Delta \dot{X}_{Total}(t) \\ \Delta \dot{z}(t) \end{bmatrix} = \begin{bmatrix} A_{Total} - B_{Total} \cdot F_1 \cdot C_{Total} & -B_{Total} \cdot K \cdot F_2 \\ T \cdot C_{Total} - L \cdot B_{Total} \cdot K \cdot F_1 \cdot C_{Total} & D - L \cdot B_{Total} \cdot K \cdot F_2 \end{bmatrix} \cdot \begin{bmatrix} \Delta X_{Total}(t) \\ \Delta z(t) \end{bmatrix} \quad (42)$$

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

$$\dot{e}(t) = \Delta \dot{z}(t) - L.\Delta \dot{X}_{Total}(t) \quad (43)$$

Combine (35) and (36), we get:

$$\begin{bmatrix} \Delta \dot{X}_{Total}(t) \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A_{Total} - B_{Total}.K & -B_{Total}.K.F_2 \\ 0 & D \end{bmatrix} \begin{bmatrix} \Delta X_{Total}(t) \\ e \end{bmatrix} \quad (44)$$

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 (Luenberger, 1971).

3.2.1 Numeral sample

The longitudinal equations of an aircraft are presented in steady state format (Rynaski, 1982):

$$\frac{d}{dt} \begin{bmatrix} \Delta v(t) \\ \alpha(t) \\ \theta(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} \alpha_{11} & a_{12} & 0 & -g \\ a_{21} & a_{22} & 1 & 0 \\ a_{31} & a_{32} & a_{33} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x(t) - \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ 0 \end{bmatrix} \delta_e(t) \quad (45)$$

Where Δv is variation of velocity, α is angle of attack, θ is pitch angle, δ_e is elevator angle and q is pitch rate. This equation in special state is presented by:

$$\frac{d}{dt} X(t) = \begin{bmatrix} -0.0507 & -3.861 & 0 & -9.8 \\ -0.00117 & -0.5164 & 1 & 0 \\ -0.000129 & 1.4168 & -0.4932 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} X(t) - \begin{bmatrix} 0 \\ -0.0717 \\ -1.645 \\ 0 \end{bmatrix} \delta_e(t) \quad (46)$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} X(t) \quad (47)$$

So Δv and α are measurable state variables. Therefor we can get final result by MATLAB simulations.

4. 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. It is assumed that the fixed capacitive reactance (X_C) is 81.62% of the reactance of the transmission line ($X_{L1}=0.48$ P.u).

The simulation studies of IEEE-SBM carried out on MATLAB platform is discussed here. The following cases are considered for the analysis.

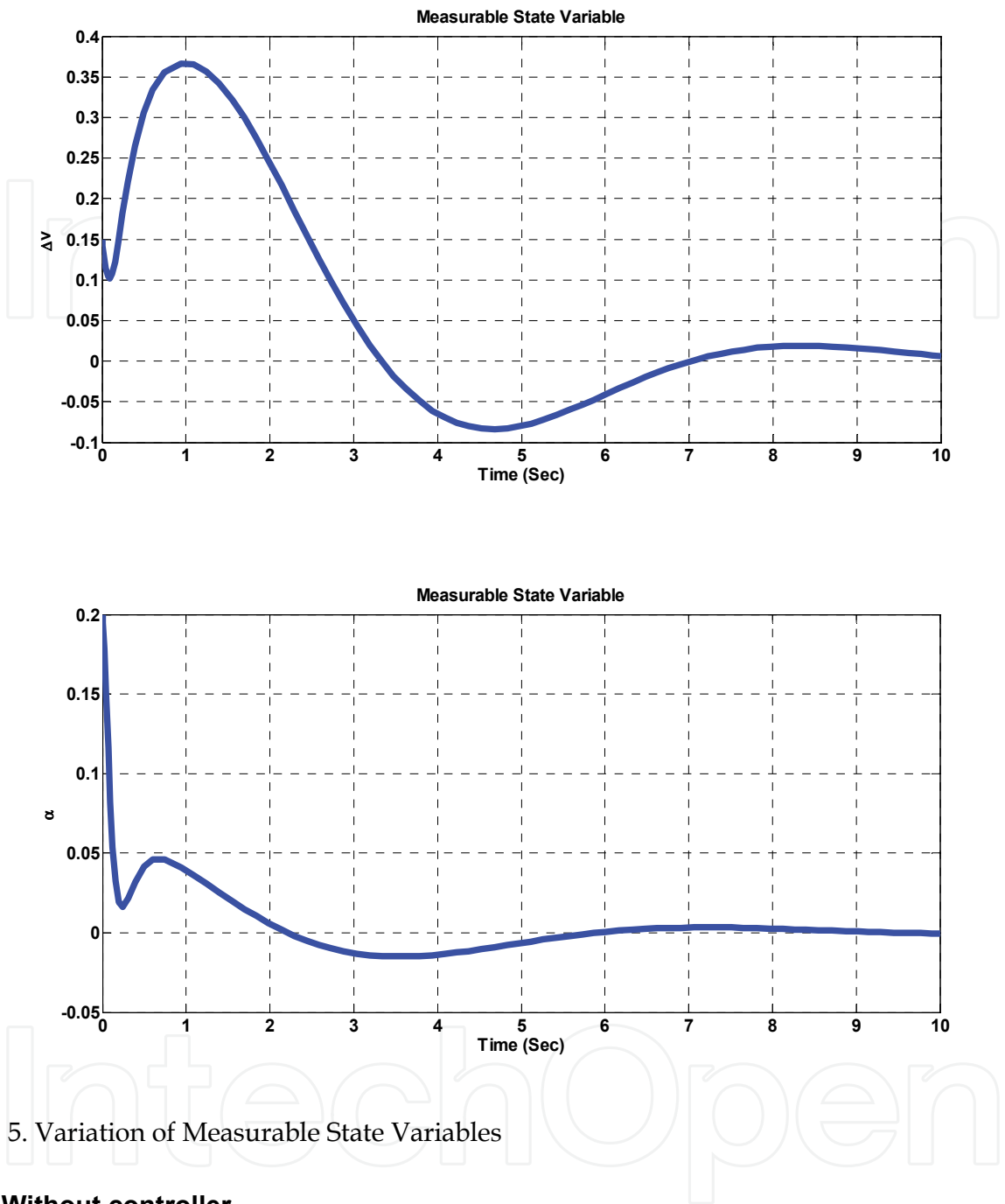


Fig. 5. Variation of Measurable State Variables

4.1 Without controller

In the first Case, second benchmark model is simulated without any controller in initial conditions. Fig. 7 shows the variation of torque of the rotating mechanical system of the T-G set. It can be seen that variations of torque of the mechanical system are severe unstable and then power system tends to approach to the SSR conditions.

The study is carried out with heavily loaded synchronous generator of $P_G=0.9$ p.u, $Q_G=0.43$ p.u and $V_t=1.138$ p.u. Figure. 8 shows the variation of real and imaginary parts of the eigenvalues of A_{sys} with the compensation factor $\mu_C=X_C/X_{L1}$. It can be observed that the first torsional mode is the most unstable modes at $\mu_C=81.62\%$. The unstable range of variation of torsional modes has been illustrated in Fig. 8.

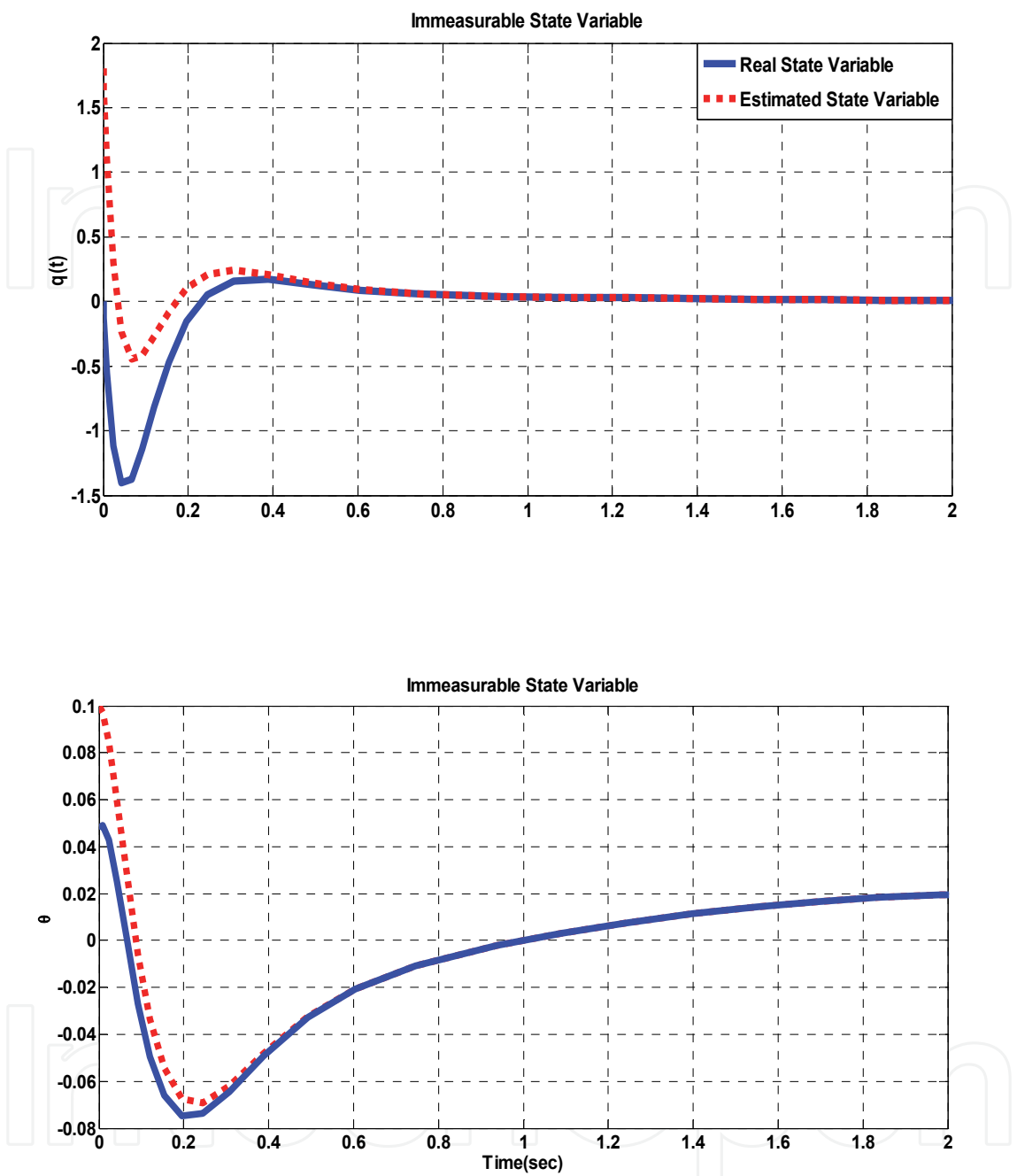


Fig. 6. Variation of Immeasurable State Variables

4.2 With proposed controller: Extended optimal control

For presentation of the first proposed controller, power system is simulated by extended optimal control with using (20-24). Proposed method is carried out on second benchmark simultaneously. The obtained results have been compared with prevalent optimal control in (17-20) by Fig. 9-(a). It is observed that the proposed method has created more suitable damping for first torsional mode of second benchmark model than prevalent method. As

similar way, this proposed method has suitable results on second torsional mode. Fig. 9-(b) clearly illustrates this point.

Fig. 10 illustrates variation of torque of the mechanical system in T-G set. It can be observed that the proposed method has more effect on the output of power system than prevalent method.

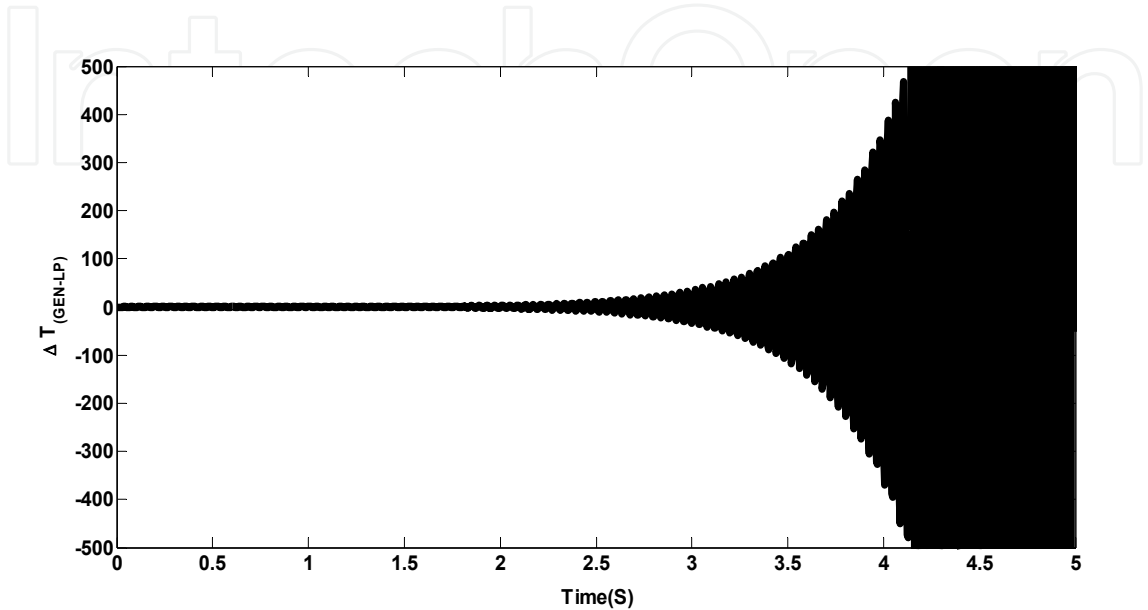


Fig. 7. Variation of torque of generator – low pressure turbine in the T-G set for $\mu_C=81.62\%$ without any controller.

4.3 With proposed controller: Reduced order observer

In order to have a complete research, optimal full state feedback control is designed and the results are compared with reduced-order method. Some parameters, such as Δi_{kd} and Δi_{kq} , are not physical variables. ΔV_{Cd} and ΔV_{Cq} are transmission line parameters that they are not accessible. So let us define:

$$\Delta \hat{X}_{Sys}^T = [\Delta i_{kd} \quad \Delta i_{kq} \quad \Delta V_{Cd} \quad \Delta V_{Cq}] \tag{48}$$

$$\Delta y_{Sys}^T = [\Delta T_{EXC-GEN} \quad \Delta T_{GEN-LP} \quad \Delta T_{LP-HP}] \tag{49}$$

Where Δy_{Sys}^T is used to obtain variation of torque of the rotating mechanical system of the T-G set . Full order observer estimates all the states in a system, regardless whether they are measurable or immeasurable. When some of the state variables are measurable using a reduced-order observer is so better.

In this scenario, proposed method is carried out on second benchmark model simultaneously. The obtained results have been illustrates in Fig. 11. It is observed that the reduced-order method has created a suitable estimation from immeasurable variables that are introduced in (48).

Fig. 12 shows variation of torque of the mechanical system in T-G set. It can be observed that the proposed method has small effect on the output of power system

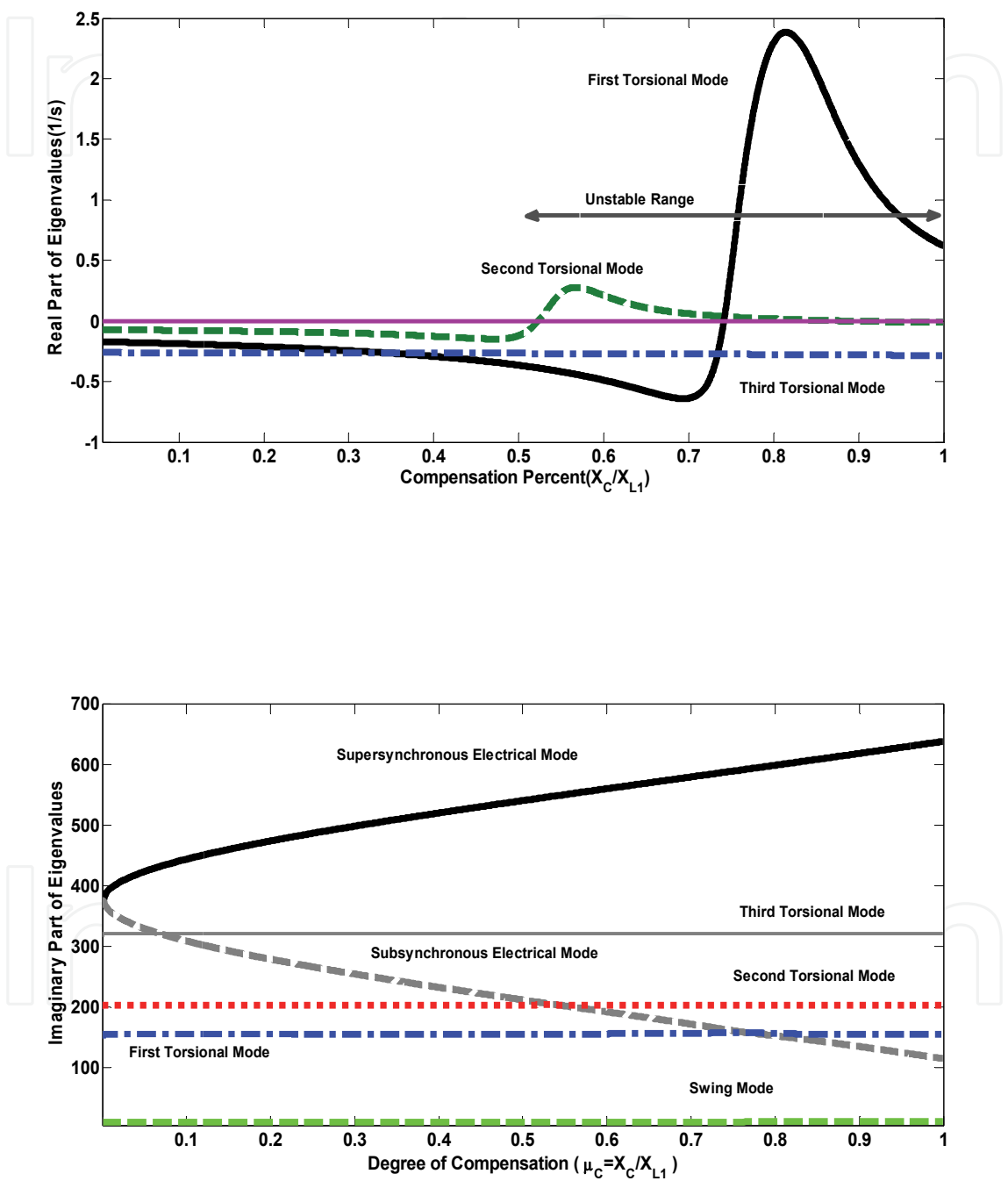


Fig. 8. Variation of real and imaginary parts of eigenvalues as a function of μ_C

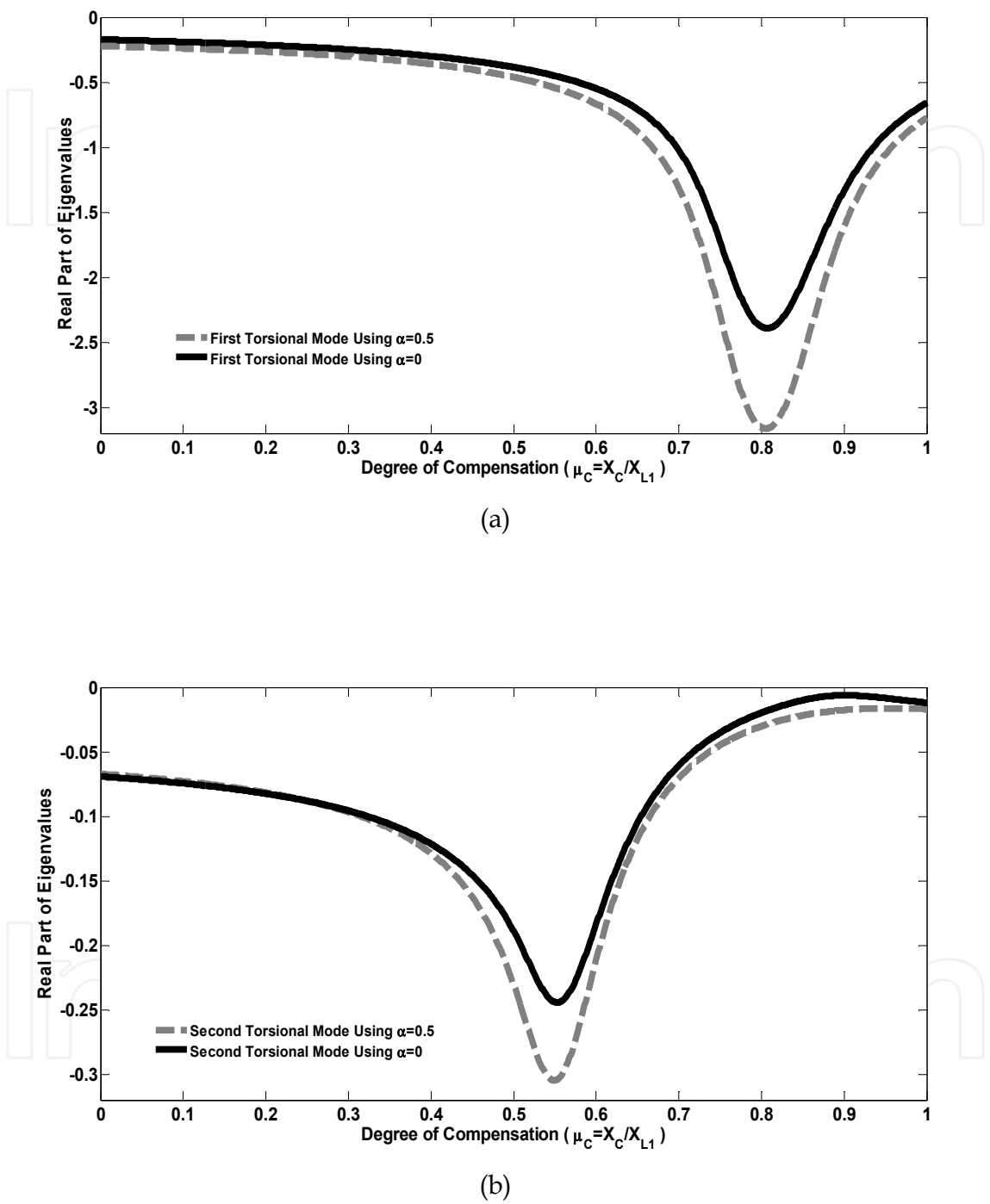


Fig. 9. Variation of first torsional mode (a) and second mode (b) in IEEE second benchmark to degree of compensation: Dotted (proposed controller), Solid (prevalent controller).

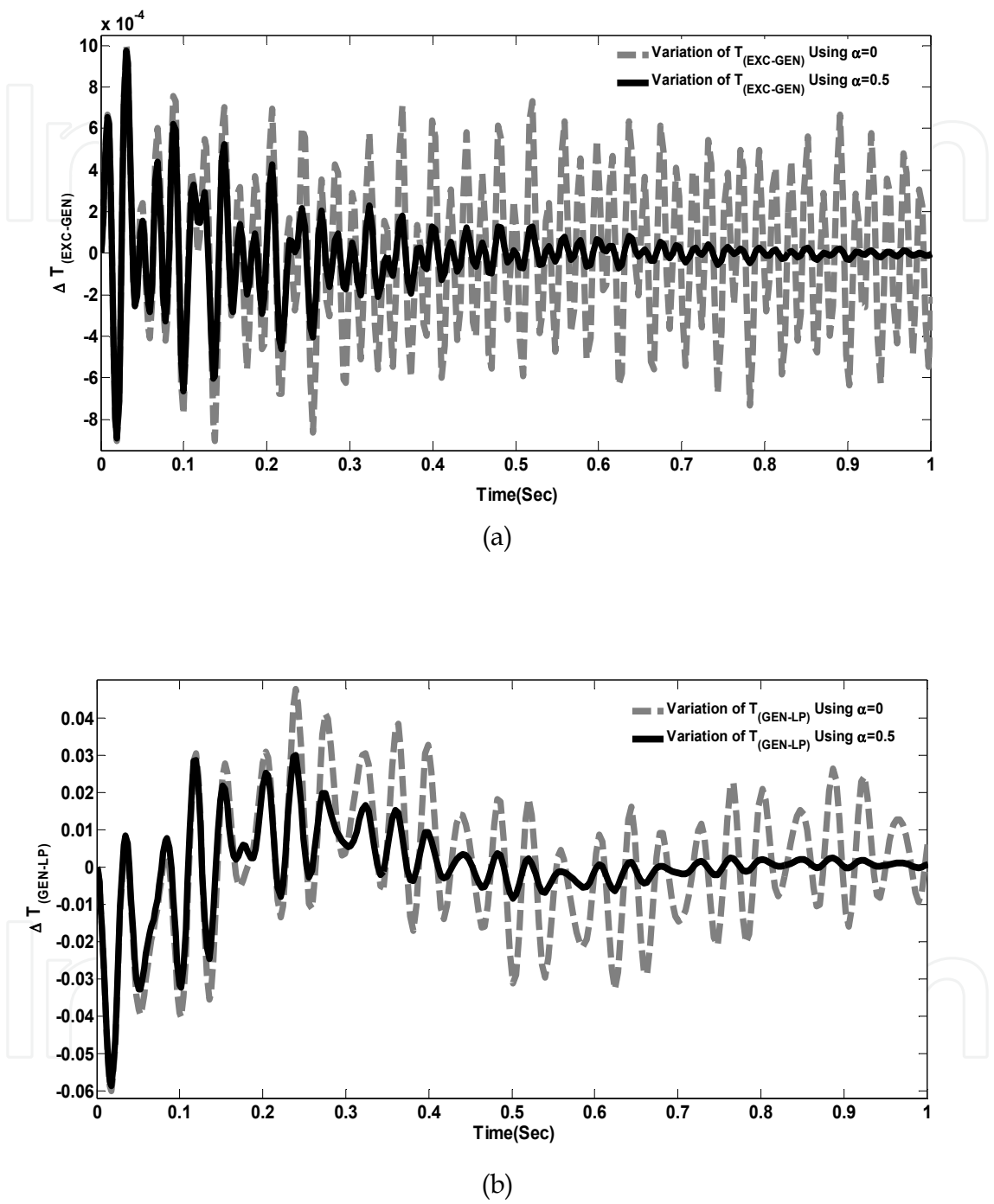
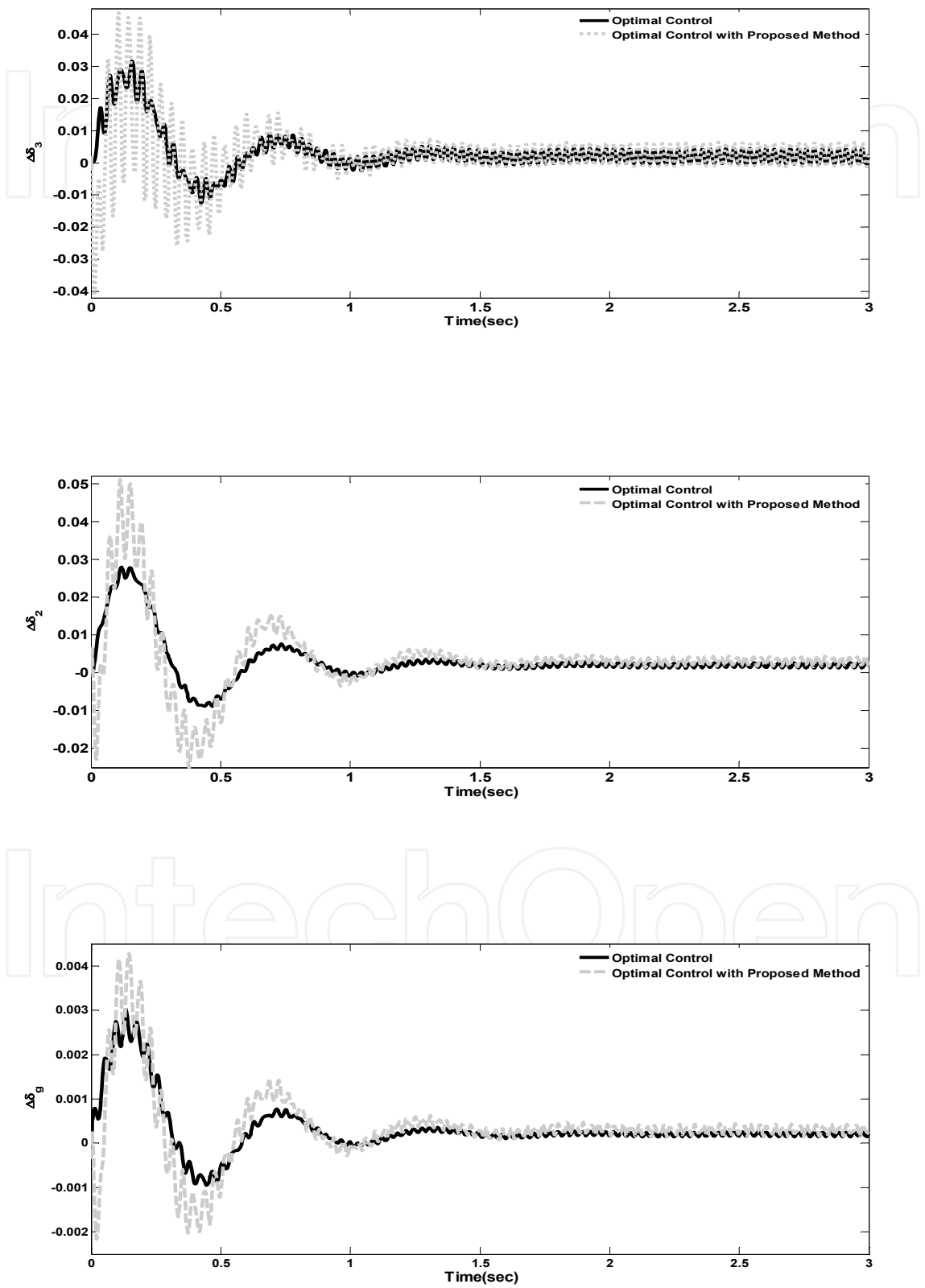


Fig. 10. Variation of torque of exciter-generator (a) and generator-low pressure (b): (proposed controller), Dotted (prevalent controller).



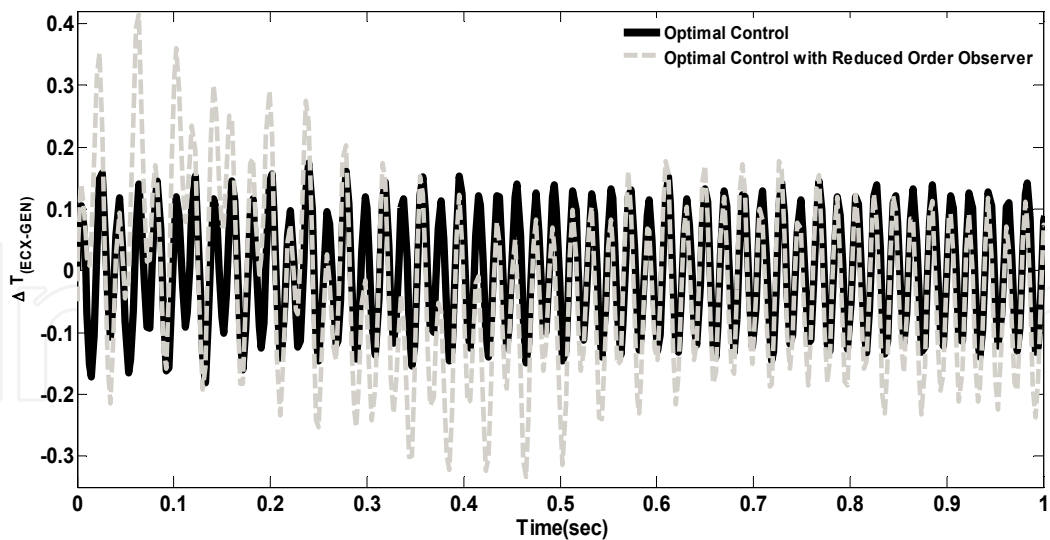


Fig. 11. Variation of δ_g , δ_2 and δ_3 : Solid (optimal full state feedback), Dotted (reduced-order observer control).

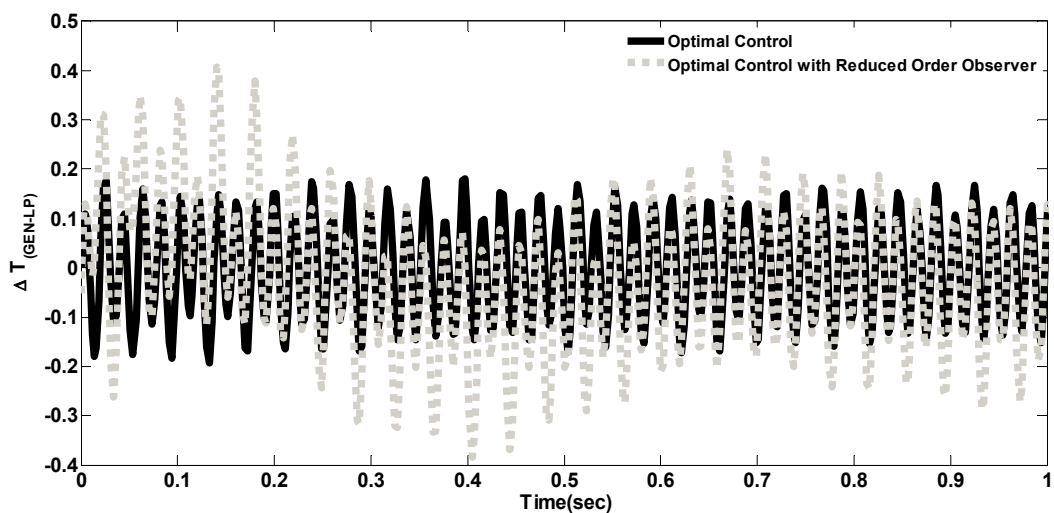


Fig. 12. Variation of torque of exciter – generator and generator – low pressure turbine in the T-G set: (reduced-order observer control), Solid (optimal full state feedback).

5. Conclusion

Fixed capacitors have long been used to increase the steady state power transfer capabilities of transmission lines. A major concern associated with fixed series capacitor is the sub-synchronous resonance (SSR) phenomenon which arises as a result of the interaction between the compensated transmission line and turbine-generator shaft. This results in excessively high oscillatory torque on machine shaft causing their fatigue and damage.

This chapter presents two analytical methods useful in the study of small-signal analysis of SSR, establishes a linearized model for the power system, and performs the analysis of the SSR using the eigenvalue technique. It is believed that by studying the small-signal stability of the power system, the engineer will be able to find countermeasures to damp all sub-synchronous torsional oscillations.

The first strategy is proposed, based on shifting eigenvalues of the state matrix of system to the left hand-side of s plane, for damping all sub-synchronous torsional oscillations. 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. Analysis reveals that the proposed technique gives more appropriate results than prevalent optimal controller. 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 chapter, another novel approach is introduced by using optimal state feedback, based on the Reduced – order observer structure. Analysis reveals that the proposed technique gives good results. It can be concluded that the application of reduced-order observer controller to mitigate SSR in power system will be provided a practical viewpoint. Also this method can be used in a large power system as a local estimator.

6. Acknowledgement

The authors would like to express their sincere gratitude and appreciations to the Islamic Azad University, Gonabad Branch, as collegiate assistances in all stages of this research.

7. Appendix (Nomenclature)

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 Reference Frame
$\Delta \delta_g$	Variation of Generator Angle
$\Delta \omega_g$	Variation of Angular Velocity of Generator
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
ΔT_m	Variation of Mechanical Torque
ΔT_e	Variation of Electrical Torque
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
ΔX_{Sys}	State Vector for Combined Power System Model

A_{Sys}	State Matrix for Combined Power System Model
B_{Sys}	Input Matrix for Combined Power System Model
ΔU_{Sys}	Input Vector for Combined Power System Model
ΔE	Variation of Field Voltage
J	Performance Index
K	Gain Feedback Vector in Linear Optimal Control
K_{α}	Gain Feedback Vector in Linear Optimal Control with Determined Degree of Stability
P	Solution of Riccati Equation in Linear Optimal Control
P_{α}	Solution of Riccati Equation in Linear Optimal Control with Determined Degree of Stability

8. References

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