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전력시스템 동요 억제를 위한 TCSC의 강인한 LQG/LTR 제어기 설계절차에 관한 연구

(Design Procedure of Robust LQG/LTR Controller of TCSC for Damping Power System Oscillations)

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요 약

본 논문에서는 전력동요 억제를 위한 TCSC의 강인한 LQG/LTR (Linear Quadratic Gaussian with Loop Transfer Recovery) 제어기 설계에 관한 연구를 하였다. LQG/LTR 제어기를 설계할 때 성능을 극대화하기 위해서는 여러 단계의 파라미터 조정을 하여야 한다. 이에 본 논문에서는 다 변수 LQG/LTR 안정화 제어기 설계를 체계적으로 할 수 있는 방법을 제안하였다. 설계된 제어기를 실제의 비선형 전력시스템에 적용함으로써 전력동요억제 효과를 검증하였다.

Abstract

This paper deals with the design of a robust LQG/LTR (Linear Quadratic Gaussian with Loop Transfer Recovery) controller of the TCSC for the power system oscillation damping enhancement. Designing LQG/LTR controller involves several design parameter adjustment processes for performance improvement. This paper proposes a systematic design parameter adjustment procedure which is suitable for robust multi-mode stabilization. The designed controller is verified by nonlinear power system simulation, which shows that the controller is effective for damping power system oscillations.

Key Words : FACTS, TCSC, LQG/LTR controller

1. Introduction

It is well known that power oscillation damping can be improved by appropriate switching of series capacitor after a disturbance [1]. The history of the work in this area is well documented in [2]. Recently, TCSC(Thyristor Controlled Series Compensator) are highlighted because it can rapidly control the amount of compensation level over a continuous range from inductive to capacitive range. Its characteristics gives much flexibility for control of power system dynamics.

It was shown in [3] that damping effect of series

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compensation increases as the transmission line loading increases. Design of the LQG damping controller via time-scale separation of the power system has been proposed [4].

Historically, LQG/LTR approach is based on the LQR(linear quadratic regulator) method. The LQR regulator has excellent robustness properties. However, LQG regulator which take advantage of LQR and Kalman filter results loses these properties. LQG/LTR approach is an attempt to recover the robustness of the LQG regulator to that of the LQR regulator by LTR technique.

In this paper, we discuss the adaptation of LQG/LTR (Linear Quadratic Gaussian with Loop Transfer Recovery) controller design procedure to the TCSC for improving multi-machine power system oscillation damping.

In the control literature, LQG/LTR procedure is devised to consider a tracking problem. However, power system oscillation damping problem is inherently a regulator problem. So not only the performance such as command following ,but also a robust stabilization of the dominant oscillation mode is an important issue.

Conventional LQG/LTR technique proposes systematic enhancement of the frequency domain performance by shaping the singular values of the loop transfer function and sensitivity transfer function. For example, it is generally accepted that for good command following and disturbance rejection, the singular values of the loop transfer function at low frequencies should be large enough.

In a power system oscillation damping problem, however, the main concern is how to improve the damping of the dominant oscillation modes. Improvement of the freqency domain performance does not necessarily means that damping of the dominant mode is improved.

From this point of view, this paper proposes a way to consider damping improvement of the oscillation mode in LQG/LTR procedure. This method selects appropriate Kalman filter parameters which locate the zeros of the target feedback loop, so that the dominant oscillation modes shift toward the zeros as the gain of the controller is increased. Robustness is also considered in the design stage.

LQG/LTR approach has the weak point that it requires design plant model be minimum phase plant in order to guarantee the LTR procedure work well. However, recent approach of LQG/LTR to SVC[5] resolves this problem successfully using the method described in [6]. This paper assumes that the plant is minimum phase, but if not, the results of this paper can be readily extended to nonminimum phase case.

2. Design Procedure

2.1. The LQG/LTR Approach

Let the plant to be controlled be as follows.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bx(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

where x and y are vectors with dimension n,m respectively.

If the system [A,B] is stabilizable, the standard LQ regulator cost functional can be defined as

$$J = \int [x^T(t)Qx(t) + u(t)^T Ru(t)]dt \tag{2}$$

Here, Q is positive semi-definite state weighting matrix and R is positive definite control weighting matrix. The optimal control problem is to find the control law minimizing the cost functional (2) under the constraint (1). The optimal control not only exits uniquely but also can be realized as a feedback form of (3) if all state variables can be measured.

$$u(t) = -Gx(t),\ G = R^{-1}B^TK \qquad (3)$$

Here, K is the unique positive definite solution of the following control algebraic Riccati equation

$$KA + A^TK + Q - KBR^{-1}B^TK = 0. \qquad (4)$$

Measuring all state variables is difficult to implement. By output feedback this shortcoming can be overcome. One way to do so is to design by LQG method.

When only output can be measured, with the above design plant model (1), we construct model based compensator which has the dynamics as follows.

$$\begin{aligned} \dot{z}(t) &= Az(t) + Bu(t) + H[y - Cz(t)] \\ u(t) &= -Gz(t) \end{aligned} \qquad (5)$$

In LQG method the plant is assumed to have the following form:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + L\xi(t) \\ y(t) &= Cx(t) + \phi(t) \end{aligned} \qquad (6)$$

Here, $\xi(t)$ is white gaussian process noise with the intensity matrix Ξ, and $\phi(t)$ is white gaussian measurement noise with the covariance Θ. Let the covariance of the state estimation error to be Σ, then the optimal estimation problem is to find optimal gain matrix H of (5) which minimizes trace of Σ subject to algebraic constraints.

If [A,C] is detectable, Σ is the unique, symmetric, and positive semi-definite solution of the following filter algebraic Riccati equation.

$$A\Sigma + \Sigma A^T + L\Xi L^T - \Sigma C^T\Theta^{-1}C\Sigma = 0 \qquad (7)$$

H can be computed from the equation

$$H = \Sigma C^T\Theta^{-1}. \qquad (8)$$

Fig. 1 shows the structure of the LQG controller, which is the same as that of the LQG/LTR controller.

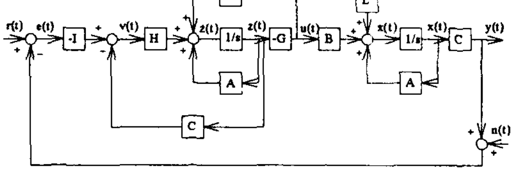

Fig. 1. Structure of the LQG/LTR controller

The separation property gives the separation of the closed loop poles into two distinct groups. One is called 'the LQR loop', and the other is called 'Kalman filter loop'. The loop transfer function of the Kalman filter loop $G_{KF}(s)$ has the following form.

$$G_{KF}(s) = C(sI - A)^{-1}H \qquad (9)$$

The LQG controller has the weakness that it loses the robustness which the LQR regulator has. The LQG/LTR method recovers the robustness of LQG regulator to that of LQR regulator. LQG/LTR controller has the same structure as LQG regulator, but has a special design procedure which is called a Loop Transfer Recovery (LTR) [7].

In using the LQG theory as a method for synthesizing controllers, the parameters which appear in the problem formulation of Kalman filter as a estimator is considered as 'tuning parameters' rather than as representation of aspects of the real world. By fixing some of the LQG design parameters and changing others in a very special way, robustness of the LQG regulator is recovered to that of the LQR regulator. LQG/LTR design procedure is as follows.

The first stage finds filter gain matrix H of the

Kalman filter loop by putting $\Xi = I$ and $\Theta = \mu I$, where design parameters are L and μ. These design parameters are adjusted for satisfying the given performance specifications such as command following, disturbance rejection and noise suppression by shaping the transfer functions of the loop transfer function and the sensitivity transfer function appropriately.

The second stage, which is called LTR stage, solves the cheap control LQR problem with putting $Q = C^T C$, $R = \rho I$. LTR is achieved as ρ approaches zero. As LTR is achieved, the closed loop transfer function converges to the Kalman filter loop. So, the design emphasis shifts into the Kalman filter loop (9) which is called the Target Feedback Loop (TFL).

2.2. Design of the Target Feedback Loop

2.2.1. SISO Optimal Root Locus Property :

The Kalman Frequency Domain Equality (KFDE) [8] provides the frequency domain properties of the TFL. The SISO version of the KFDE is given as (10).

$$\begin{aligned}[1+G_{KF}(s)][1+G_{KF}(-s)] = \\ 1+\frac{1}{\mu}[C\Phi(s)L][C\Phi(-s)L]\end{aligned} \qquad (10)$$

In SISO case the root loci of the TFL obeys the rule which is similar to the conventional root locus method. If s is a closed loop pole then $1+G_{KF}(S)$ is 0. Hence, the closed loop poles of the TFL must satisfy the following equation (11).

$$\begin{aligned}1+\frac{1}{\mu}[C\Phi(s)L][C\Phi(-s)L] = \\ 1+\frac{1}{\mu}G_{FOL}(s)G_{FOL}(-s) = 0\end{aligned} \qquad (11)$$

where $C(sI-A)^{-1}L$ is defined as $G_{FOL}(s)$ which is called the Filter Open Loop Transfer Function,

$$G_{FOL}(s) = C(sI-A)^{-1}L \qquad (12)$$

This is exactly the same as the standard root locus method if we set the controller gain to be $1/\mu$ and the loop transfer function to be $G_{FOL}(s)G_{FOL}(-s)$. As μ decreases from infinity to 0, the closed loop poles depart from the open loop poles and arrive at the open loop zeros or go to infinity. From the above equation, however, there are 2n poles in the s-plane with complete symmetry about the $j\omega$ axis. Here, the n poles in the left half plane are the only valid closed loop poles since the Target feedback loop is always stable from the LQG theory.

2.2.2. Select Design Parameter L That Gives Desired Location of Zeros of TFL Transfer Function

From the observation of (11) and (12), the zeros of the loop transfer function of the TFL are determined by the design parameter L.

Now the relationship between the L and the location of the zero of the TFL is investigated. $L = [l_1\ l_2\ \cdots\ l_n]^T$ is a column vector with dimension n, each of which is an independent design parameter. The following gives a method to select each design parameter of L. Let $u_i = [0 \cdots 0\ 1\ 0 \cdots 0]^T$ be a column basis vector which has 1 as an i-th entry and others 0, then L can be expressed as a linear combination of u_i s.

$$L = l_1 u_1 + l_2 u_2 + \cdots + l_n u_n \qquad (13)$$

Substitution of each u_i to equation (12) gives a transfer function vector $g_i(s)$.

$$g_i(s) = C(sI-A)^{-1} u_i \quad i=1,2,\cdots,n \quad (14)$$

Linear combination of numerator zero polynomial of each $g_i(s)$ gives the zero polynomial of the original filter open loop transfer function.

$$G_{FOL}(S) = \sum_{i=1}^{n} l_i g_i(s) \quad (15)$$

We get the coefficients of each zero polynomial of $g_i(s)$ to form the column vector z_i, and collect each z_i to form a coefficient matrix Z_C.

$$Z_C = [z_1 \ z_2 \ \cdots \ z_n] \quad (16)$$

And if we set the coefficient of the desired zero polynomial of the TFL to be z_d, which is a column vector, then (17) holds.

$$Z_C L = z_d \quad (17)$$

Uniqueness of the solution L is guaranteed if the rank of Z_C is n. This condition is satisfied if the plant does not have a repeated eigenvalue. Power system can be assumed to satisfy this condition without loss of generality.

From (17) we can obtain the parameter value L to give the desired zero location.

$$L = Z_C^{-1} z_d \quad (18)$$

2.2.3. Robustness Against Modeling Errors due to Parameter Change

Damping controller is designed based on the nominal operating condition, but power system oscillation is generated mainly by the faults, which requires the disconnection of the faulted device from the power system. So the controller should operate under changed environment which is represented as a parameter change of the design plant model. This discrepancy between nominal model and actual model can be defined by (19).

$$G_A(s) = [1 + E(s)]\, G(s) \quad (19)$$

where G(s) is nominal model, $G_A(s)$ is the actual model, and E(s) is the multiplicative modeling error.

Under the modeling error (19) the following 'stability-robustness test' can be derived from the SISO nyquist stability criterion. If the closed loop transfer function C(s) satisfy (20), then the closed loop system is stable in spite of the modeling error defined in (19).[7]

$$|C(j\omega)| < \frac{1}{|E(j\omega)|} \quad \text{for all } \omega \quad (20)$$

This criterion is applicable to any control system , but is only a necessary condition. That is, a closed loop system that does not satisfy (20) is not necessarily unstable. So care should be taken in applying the criterion to designing controller.

2.2.4. Design procedure

Conventional LQG/LTR design procedure checks the shape of the 'sensitivity or loop transfer function' for good command following and noise rejection the magnitude of the sensitivity transfer function should satisfy some performance condition. But in the oscillation damping problem this is not an important issue. Instead of the above mentioned performance, the damping of the poles that have significant impact on the oscillation - dominant oscillation modes - should be improved. So the behavior of the dominant oscillation modes under the LQG/LTR control should be carefully designed. Design procedure proposed is as follows.

Step 1 : Select design parameter L by locating zeros for damping improvement of dominant oscillation mode

Set initially L=C in (12). This means the loop transfer function of the TFL is set to be equal to the plant loop transfer function. Judging from the pole-zero pattern of the TFL, identify the zeros that have an significant effect on the shifting of the dominant oscillation mode. Among them , the zeros that hinders the shifting of the dominant poles are shifted to the left or rotated in the direction to gives better damping in order to attract the closed loop poles.

After selection of the desired zero locations, corresponding L is found from the relation (18). This ensures that the TFL has the zeros of the loop transfer function that can shift the dominant oscillation mode effectively.

Step 2 : Examine root loci for dominant oscillation modes

With L found in step 1 , applying the conventional root locus method to the TFL shows the behavior of the dominant poles. If the improvement of damping of the dominant mode is satisfactory go to the next step, or go to step 1.

Step 3 : Adjust the design parameter for increased damping.

After selecting the design parameter L by locating the zeros of the TFL. The closed loop poles of the TFL changes as the design parameter μ changes. If L is selected appropriately, decreasing μ continuously improves the damping of the dominant oscillation modes. But robustness requirement (20) imposes a limitation on decreasing μ.

Step 4 : Perform Loop Transfer Recovery.

After successful design of the TFL, the LTR procedure is performed in a straightforward manner. Set the design parameter $Q=C^TC$, and then decrease the design parameter ρ from some value until the closed loop transfer function converges to the transfer function of the designed TFL.

Step 5 : Verify by the time domain nonlinear simulation. If not satifactory go to Step 1

Although the controller is designed based on the linearized version of the power system model, the controller should be installed on the nonlinear power system. So the controller should be verified by the time domain nonlinear simulation.

3. Power System Model

3.1. Power System Dynamic Models Including TCSC for Controller Design

In order to consider the effects of the flux decay dynamics and the damper winding , 2 axis generator model is used, and IEEE type 1 exciter is adopted. The notation is standard as in [9]. The mechanical input torque is assumed to be constant. Here, time is in second, rotor angle δ is in radian and the other variables are per unit values.

$$\dot{E}_q' = \frac{1}{T_{do}'}\{-E_q' - (x_d - x_d')i_d + E_{FD}\} \quad (21)$$

$$\dot{E}_d' = \frac{1}{T_{qo}'}\{-E_d' + (x_q - x_q')i_q\} \quad (22)$$

$$\dot{\delta} = \omega_0(\omega - 1) \quad (23)$$

$$\dot{\omega} = \frac{1}{2H}\{-(E_d'i_d + E_q'i_q) - D(\omega-1) + T_m\} \quad (24)$$

$$\dot{V}_R = \frac{1}{T_a}\left\{K_aR_f - \frac{K_aK_f}{T_f}E_{FD} - V_R - K_a(V_t - V_{ref})\right\} \quad (25)$$

$$\dot{E}_{FD} = \frac{1}{T_e}\{-(K_e + S_e)E_{FD} + V_R\} \qquad (26)$$

$$\dot{R}_f = \frac{1}{T_f}\left\{-R_f + \frac{K_f}{T_f}E_{FD}\right\} \qquad (27)$$

In this paper, the dynamics of TCSC is represented as a first order dynamic model as in [10]. Reference input being set to a point controlling steady state power flow, the supplementary input is controlled to stabilize the disturbed power system. Hence, the model considered can be written as follows.

$$\dot{X}_c = \frac{1}{T_c}(X_{ref} + X_{sup} - X_c),\ X_{cmin} \le X_c \le X_{cmax} \qquad (28)$$

where X_C is the impedance of TCSC, Xref is a reference input, and Xsup is a supplementary input respectively.

3.2. Sample Power System

Model power system for TCSC controller design is WSCC 9 bus system as shown in Fig. 2. The machine parameters are listed on the table 2,3 in the Appendix. This system has 2 modes that have poor damping this is clear from the mode analysis. These modes are numbered as 1 and 2 as in the Fig.3. These modes have high participation to the oscillation of the rotor angle of the generators, which means that these modes are closely related to the oscillation phenomena and controlling them improves that phenomena.

As is stated in [11], residue analysis shows that the line between bus 6 and bus 9 is a good candidate of TCSC installation for damping. This paper also assume that TCSC is installed in the middle of the line 6-9, and the TCSC has the capability of ±0.05 PU. Prior to fault, the TCSC is set to be 0 PU. The candidate of the input to the controller is the quantity measurable at the TCSC bus. In this case, real power through the TCSC is selected as an input to the controller.

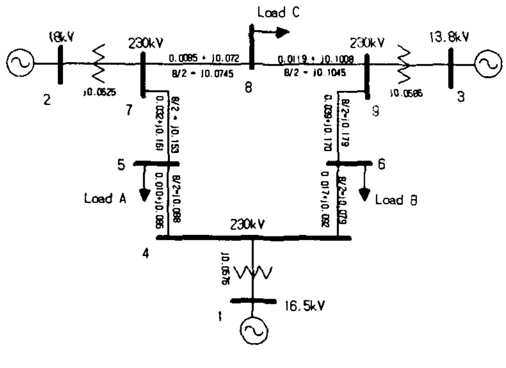

Fig. 2. A Sample Power System

4. Controller Design

4.1. Design Target Feedback Loop

Fig. 3 shows the pole-zero pattern of the open loop plant when the real power is taken to be an output to be fed back to the controller. Two zeros-z1 and z2 in the Fig.3-are located near the dominant oscillation mode p1 and p2 . So the classical control method has a difficulty in controlling the 2 modes simultaneously.

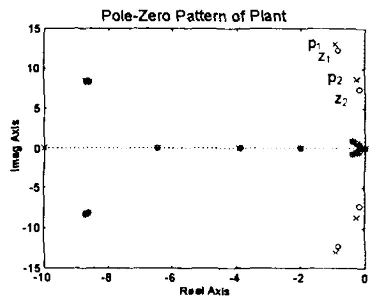

Fig. 3. Pole-zero pattern of the plant

plant loop tAs a first step of the controller design, zeros of ransfer function is taken to be that of the target feedback loop by letting L=C. The zeros with poor damping is rotated first 30 ° and then shifted slightly to the left to effectively attract the poles with poor damping. The relocated zeros z1 and z2 of the loop transfer function of the TFL is shown in Fig. 4.

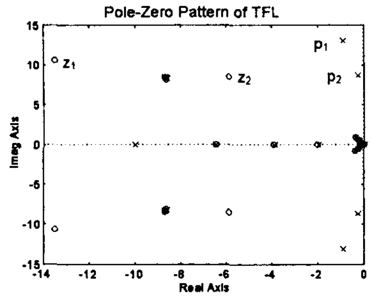

Fig. 4. Pole-zero pattern of the TFL

Fig. 5 represents the loot loci of the TFL by decreasing μ. Damping of the dominant oscillation mode p1 and p2 are continuously improved with as μ decreases, which shows that design parameter L is appropriately selected. If the root loci are not satisfactory, go to the previous step and retry the location of the zeros to give good root loci.

In (20), modeling error should be set according to the worst contingency case, but in this case modeling error is taken to be the assumed fault in the case study for simplicity. The magnitude of the closed loop transfer function should be below the reciprocal of the magnitude of the error transfer function for all frequencies.

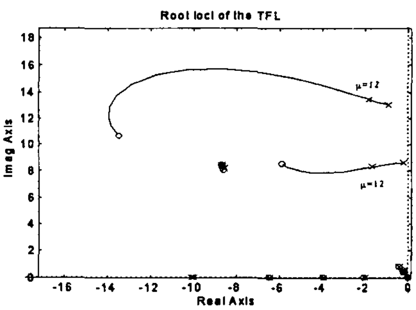

Fig 5. Root loci of the TFL decreasing

From Fig. 6, we can see that as we decrease μ the closed loop system get closer to the stability boundary. When μ becomes 12, the closed loop transfer function almost touches the stability robustness bound. In this design μ is set to be 12.

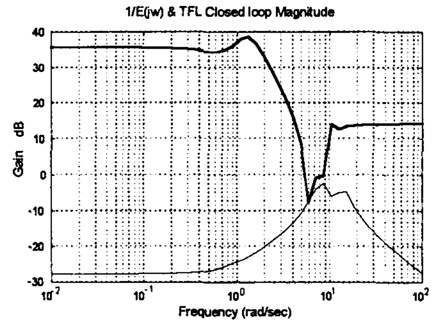

Fig. 6. Magnitude of the closed loop TFL (thin line) and the reciprocal of the error transfer function (thick line)

Table 1 shows the dominant open loop and closed loop eigenvalues of the target feedback loop with the parameters selected from the previous process. The results show that damping is improved significantly with control.

Table 1. Oscillation modes of the targetfeedback loop (inf:without control)

	mode 1		mode 2	
μ	Eigenvalue	Damping	Eigenvalue	Damping
Inf	-0.9198±i13.0473	0.0703	-0.2568±i8.6248	0.0298
12	-1.8321±i13.4510	0.1350	-1.6911±i8.3097	0.1994

Finally, the frequency domain performance is checked by examining loop shape of the TFL loop transfer function and the sensitivity transfer function. Fig. 7 shows that performance around the 1~2 Hz is good for oscillation damping.

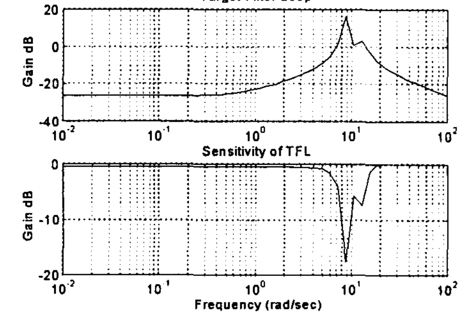

Fig. 7. Loop transfer function and the sensitivity function of the TFL

4.2. Loop Transfer Recovery

It can be thought that decreasing ρ smaller and smaller can give good recovery. But too low ρ means very high controller gain and this can excite the modeling error and the nonlinear effect, which can cause the real system unstable. So the designer should find the tradeoff point. Fig.8 shows the loop transfer function of the TFL and the closed loop transfer function. When ρ becomes 0.01, the figure tells that the recovery is satisfactory, so stop to decrease the ρ value at 0.01.

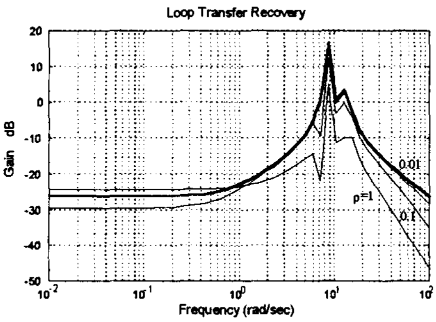

Fig. 8. Loop transfer recovery

4.3. Time Domain Verification

It is assumed that line 5-7 consists of 2 circuit, and a 3 phase 6 cycle fault occurs on one circuit near bus 7, followed by the disconnection of that circuit. Fig. 9 and 10 shows that the oscillation is effectively damped out by introducing the control of TCSC.

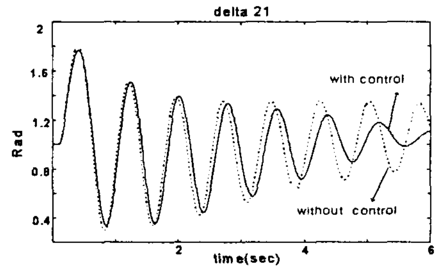

Fig. 9. Torque angle difference between generator #2 and #1

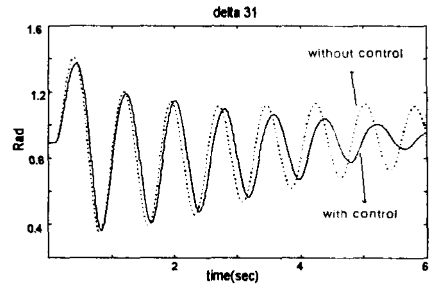

Fig. 10. Torque angle difference between generator #3 and #1

5. Conclusions

This paper presents a procedure to design LQG/LTR controller for damping multi-machine power system oscillations. LQG/LTR approach is suited to controlling TCSC to damp out multi-mode oscillations. A locally measurable quantity estimates the whole states of the multi-machine power system of high order.

Future research is directed to the optimal model order reduction of the power system which blends well with LQG/LTR controller design technique for extremely high order complex power system application.

6. APPENDIX

Machine and exciter parrameters ate listed in table 2 and 3.

Table 2. Machine parameters

generator	1	2	3
H	23.64	6.4	3.01
D	0	0	0
Tdo'	8.96	6.0	5.89
Tqo'	0.5	0.535	0.6
xd	0.1460	0.8958	1.3125
xd'	0.0608	0.1198	0.1813
xq	0.0969	0.8645	1.2578
xq'	0.0608	0.1198	0.1813

Table 3. Exciter parameters

Ta	0.06	Te	0.5
Tf	1.0	Ka	25.0
Ke	0.0445	Kf	0.26
Asat	0.001123	Bsat	0.3043

State variables of the sample power system are

$$x = [E_{q1}'\ E_{q2}'\ E_{q3}'\ R_{f1}\ R_{f2}\ R_{f3}\ E_{d1}'\ E_{d2}'\ E_{d3}'\ \delta_{21}\ \delta_{31}\ \omega_1\ \omega_2\ \omega_3\ V_{R1}\ V_{R2}\ V_{R3}\ E_{FD1}\ E_{FD2}\ E_{FD3}\ X_C]^{'}$$

References

[1] R.H. Webster, A.P. Mane, O.J.M. Smith, "Series Capacitor Switching to Quench Electromechanical Transients in Power Systems", IEEE Transactions on Power Apparatus and Systems, Vol.PAS-90, No.2, March/April, 1971. pp.427-433.

[2] L.Angquist, B.Lundin and J.Samuelsson, "Power Oscillation Damping Using Controlled Reactive Power Compensation - A Comparison Between Series and Shunt Approaches", IEEE Transactions on Power Systems, Vol.8, No.2, May 1993, pp.687-700.

[3] M. Noroozian and G. Andersson, Damping of Power System Oscillations By Use of Controllable Components, IEEE Transactions on Power Delivery, Vol.9, No.4, October 1994, pp.2046-2054.

[4] Kwang M. Son, Jong-Keun Park, "Design of an LQG controller of TCSC via time scale separation of the power system", The Transactions of the Korean Institute of Electrical Engineers, Vol.47, No.7, July 1998, pp.880-885.(in Korean)

[5] F. Fatehi, J.R. Smith and D.A. Pierre, "Robust Power System Controller Design Based On Measured Models", IEEE Transactions on Power Systems, Vol.11, No.2, May 1996, pp.774-780.

[6] B.D.O. Anderson, J.B. Moore, Optimal Control - Linear Quadratic Methods, Prentice-Hall, 1989, pp.241-246.

[7] M. Athans, Lecture Notes on Multivariable Control System, Vol I and II, MIT, 1986.

[8] H. Kwakernaak and R. Sivan, Linear Optimal Control Systems, John Wiley & Sons, 1972.

[9] P.M. Anderson, A.A. Foud, Power System Control and Stability, IEEE Press, 1994.

[10] J.J. Paserba, N.W. Miller, E.V. Larsen and R.J. Piwko, "A Thyristor Controlled Series Compensation Model for Power System Stability Analysis", IEEE Transactions on Power Delivery, Vol. 10, No.3, July, 1995, pp.1471-1478.

[11] X.R. Chen, N.C. Pahalawaththa, U.D. Annakkage and C.S. Kumble, "Controlled Series Compensation for Improving the Stability of Multi-machine Power Systems", IEE Proceedings - Gener. Transm. Distrib., Vol. 142, No.4, July 1995, pp. 361-366.

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