Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Damping Subsynchronous Resonance in Power Systems Using Reduced Order Robust Control Approach

Basim T. Kadhem, Andrey N. Belyaev, and Serguei V. Smolovik

Abstract-- **This paper deals with application of LQG (Linear Quadratic Gaussian) technique to design of robust SVC (Static VAr Compensator), TCSC (Thyristor Controlled Series Compensator) and Excitation System controller for damping SSR (Subsynchronous Resonance) in power system. The controller uses only one measurable feedback signal (generator speed deviation). A reduced-order version of this controller is also obtained. The robust control results are compared to the "idealistic" full state optimal control. Loop transfer recovery (LTR) is then applied to reinforce regulator robustness of the LQG damping controller. The robustness of the designed controller is verified by nonlinear power system simulation, which shows that the regulator is effective for damping power system oscillations. Simulation results revealed that the technique damps all torsional oscillatory modes in a very short time, yet maintains reasonable control actions.**

***Index Terms*—FACTS (Flexible AC Transmission Systems), LQG (Linear Quadratic Gaussian) Control, LTR (Loop Transfer Recovery) method, power system oscillation damping.**

I. INTRODUCTION

Power transmitted through a power system network is influenced by three parameters namely voltage, impedance and phase difference. Development of high voltage and high current power semiconductor devices has led to flexible AC transmission systems (FACTS). Power electronics based systems and other static equipment which control one or more AC transmission system parameters are called FACTS devices in power systems to accommodate changes in operating conditions of an electric transmission system while maintaining sufficient steady-state and transient stability margins. Series compensation of a transmission line gives rise to the problem of subsynchronous resonance (SSR) in the system which has two distinctive effects, namely the induction generator effect and torsional interactions effect. Because of torsional oscillations the shaft of the Turbine –Generator (T-G) set may break with disastrous consequences [2]. A.H. Othman and A. Lennort. [3] developed an analytical model of thyristor controlled series compensation *(TCSC)* lo investigate subsynchronous torsional interaction between the TCSC and turbine generator shaft, and to evaluate control interactions between the TCSC and other devices in the power systems such as SVC (static VAr compensation) and excitation systems. J.V. Milanovic and I.A. Hiskcns [4] proposed the robust tuning of SVC, but results showed that die interarea mode is less damped when uncertain load parameters. From an exhaustive survey of the literature [1-9], it is observed that there are no controllers or schemes that can effectively damp all the SSR modes at different levels of series compensation, over a very light load to overload conditions for different types of severe fault (without considering the natural damping of the system).

This paper presents a robust control approach for damping inertial and torsional modes of T-G sets. The input to the controller is generator speed deviation and its outputs are three control signals. The controller is based on the Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR). The main advantage of this technique is its capability to offer good performance using only one output feedback. A reduction of the designed controller is also achieved. The performance of the LQG/LTR is compared to the full state feedback optimal control for evaluation purposes. The study is conducted on the system shown in Fig.1.

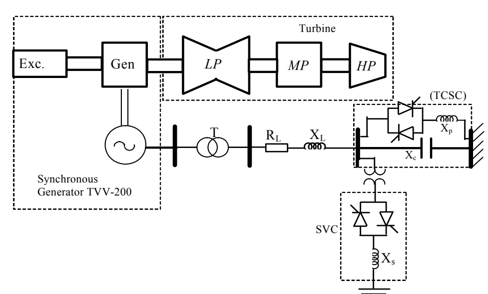

Fig.1. Schematic diagram of the system under study.

II. System Models.

A. Power System

The system under consideration consists of a steam turbine synchronous generator TVV-200MVA, connected to the infinite bus through a long transmission line with TCSC

B. T. Kadhem i is with the Department of Electrical Engineering, University of Basrah, Iraq (e-mail: basim72_sh@mail.ru).

A. N. Belyaev is with the Department of Electrical Power Systems and Networks, St-Petersbug State Technical University, Russia (e-mail: andreybelyaev@yandex.ru).

S. V. Smolovik is with the Department of Electrical Power Systems and Networks, St-Petersbug State Technical University, Russia (e-mail: smol@robotek.ru).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

and SVC fixed capacitor and an inductor whose inductance is varied by adjusting the conduction angle of thyristor according to variation in terminal voltage as shown in Fig.1. The shaft system of the T-G set comprises five masses: one high-pressure turbine (HP), one mid-pressure turbine (MP), one low-pressure turbine (LP), generator rotor (G) and exciter (EXC). The shaft system has four torsional modes at frequencies 125 rad/sec, 174 rad/sec, 191 rad/sec and 407 rad/sec. At 60% level compensation the first torsional mode is unstable while the second mode and three mode is marginally stable for system without TCSC and SVC. A spring-mass model is used for the mathematical representation of the shaft system. The Park's two axes model is used to represent the generator electrical system. The rotor circuits are represented by one damper winding and one field winding on the *d-axis* and one damper windings on the *q-axis.* The step-up transformer and transmission lines are represented by their equivalent lumped parameters. The electro-mechanical data of the system is given in appendix I.

B. Excitation System

Fig. 2 shows the excitation system used for the studies. The main input to the excitation system is the terminal voltage error $\boldsymbol{V_e}$. The auxiliary stabilizing signal $\boldsymbol{U_{sf}}$ is added to $\boldsymbol{V_e}$ to damp the inertial and torsional oscillatory modes.

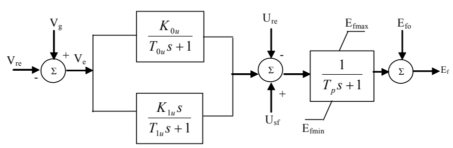

Fig. 2. Excitation system used in the study.

C. Static VAr Compensator (SVC)

A thyristor-controlled reactor (TCR) is used as the SVC in the studies. Fig. 3 shows the equivalent model of the SVC with its control system. The controlled reactor is represented as a controllable voltage source behind a fixed reactance [10]. The SVC unit is connected to the capacitor terminal as shown in Fig. 1. The primary function of the SVC is to control the reactive power and stabilize the system voltage. The auxiliary stabilizing signal $\boldsymbol{U_{sr}}$ is added to the main input of the SVC controller to damp the inertial and the torsional modes.

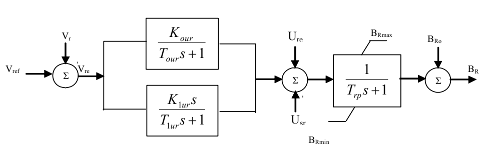

Fig.3. Modeling for Static VAr Compensator (SVC).

D. Thyristor controlled series compensation TCSC

One important FACTS component is the TCSC, which allows rapid and continuous change of the transmission line impedance. Active power flows along the compensated transmission line can be maintained at a specified value under range of operating conditions. Fig.4 is a schematic representation of a TCSC module, which consists of a series capacitor bank in parallel with a Thyristor controlled reactor (TCR). The equvilent model of TCSC can be represented in Fig.4, the main input to the TCSC is terminal voltage across fixed capacitor error $\boldsymbol{V_{ec}}$, the auxiliary stabilizing signal $\boldsymbol{U_{sc}}$ is added to $\boldsymbol{V_{ec}}$ to damp the inertial and torsional oscillatory modes.

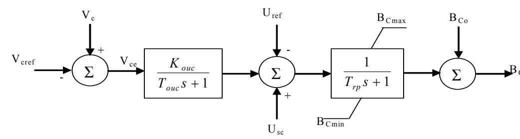

Fig.4 Modeling for thyristor controlled series compensation (TCSC).

III. The robust the LQG/LTR controls.

The design of a control system is usually based on a nominal model of the plant to be controlled. Oftentimes, the design procedure goes through the usual simplifications, such as linearization around an operating point or lumped parameter approximation and neglecting the effects of unmodeled dynamics, sensor/actuator noise, and undesired external disturbances on different parts of the system. The result is an approximate plant or, as often referred to, uncertain plant. The designer must, therefore, be concerned about how well the controller will work with the actual plant to achieve the desired objectives, and whether it is possible to design a controller that takes care not only of these given uncertainties but also of others. This leads to the emergence of what is, nowadays, referred to as *Robust Control.* The robust control problem is the problem of analyzing and designing an accurate control system given models with significant uncertainties.

Many approaches have been developed for the robust control problem and yet more are under investigation. However, *the Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR)* methodology is particularly attractive due to its effectiveness in accommodating plant uncertainties in a systematic and straightforward way [10-12].

Fig. 5 shows a block diagram of the system with the robust controller. The block named "system" embodies all the subsystems shown in Figs. 1, 2, 3 and 4. The goal is to construct a robust controller that compensates for variations in speed by generating three control signals *(*$\boldsymbol{U_{Sf}}$, $\boldsymbol{U_{Sr}}$ and $\boldsymbol{U_{SC}}$*)*. The signal $\boldsymbol{U_{sf}}$ - is to assist the PSS (power system stabilizer) by damping the electromechanical hunting modes [18], while the signal $\boldsymbol{U_{sr}}$ and $\boldsymbol{U_{sc}}$ are to assist the SVC and TCSC by damping torsional modes. This configuration is attractive because it not only uses minimum information (only the output), but also it is easy and inexpensive to implement with actual systems which should be the ultimate objective.

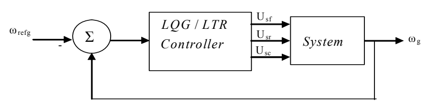

Fig. 5. System with robust controller.

The design procedure involves two steps. The first is a filter design and the second is a controller design. The underlying idea of the LQG/LTR is to treat the unstructured uncertainties on the plant as process and measurement noises. In such a case, a "fictitious" filter designed to reject these noises is in effect a filter rejecting the effects of uncertainties. In the first step of the design, a target feedback loop (TFL) with desired loop shape is constructed via Kalman filter; i.e., the Kalman filter is used to obtain a loop that serves as a target which the controlled system is to converge. The second step is mainly to recover the target loop shape using the Linear Quadratic Regulator (LQR)

A. Kalman Filter Design

The state space representation of a linear model is:

$$\frac{dx}{dt} = Ax + Bu + \Gamma\omega \tag{1}$$

$$y = Cx + Du + v \tag{2}$$

where w and v are zero-mean Gaussian white-noise processes with covariances Q_f and R_f, respectively. Here, Γ will serve as design parameters in the LQG/LTR procedure to synthesize a compensator that meets the desired specifications. The Kalman filter equations for the state estimate, the error, and the gain are

$$\frac{d\hat{x}}{dt} = A\hat{x} + K_f\left[y - C\hat{x}\right] + Bu \tag{3}$$

$$\frac{de}{dt} = \left[A - K_f C\right]e + \Gamma\omega + K_f v \tag{4}$$

$$K_f = P_f C^T R_f^{-1} \tag{5}$$

where e-is the error in state estimate, K_f – gain Kalman filter. P_i -is the positive-semidefinite solution to the Riccati equation

$$P_f A^T + AP_f - P_f C^T R_f^{-1} C P_f + \Gamma Q_f \Gamma^T = 0 \tag{6}$$

The goal, in this step of the design, is to construct a Target Feedback Loop (TFL), G_{KF}, by varying the filter gain, K_f. This method is often referred to as the Linear Quadratic Gaussian (LQG) method. It is worth mentioning here that this filter has the added benefit of avoiding torsional interference and, hence, negative damping of torsional oscillations is avoided [18].

B. Controller Design

This step is an optimal control problem. We need to solve for the full state feedback regulator gains K_c via the optimal control technique in order to recover the TFL. The performance measure is given by

$$J = \int_0^\infty \left[q y^T Q_C y + u^T R_c u\right] dt \tag{7}$$

where Q_c and R_c are positive definite matrices penalizing, respectively, the states and the controls and $q > 0$ is a scalar design parameter. In (7), y is the output of the system and u is the input vector $[U_{sf}, U_{sr}, U_{sc}]$. The optimal control law is given by:

$$u = -K_c x \tag{8}$$

$$K_c = R_c^{-1} B^T P_c \tag{9}$$

where P_c satisfies another algebraic Riccati equation,

$$A^T P_c + P_c A - P_c B R_c^{-1} B^T P_c + qC^T Q_c C = 0 \tag{10}$$

If one is able to: adjust K_f so that $G_{KF}(S)$ has the desired loop shape; and construct a K_c so that $G(s)K_c(s) \approx G_{KF}(S)$ over the band of frequencies relevant to our concerns of performance and robustness, then $K(s)$ is a robust compensator.

Such a compensator exists and the closed-loop system is internally stable, provided that the plant is stabilizable, detectable, has minimum phase, and fewer outputs than inputs [12]. The configuration of the dynamic robust controller $K(s)$ realized through the above steps is shown in Fig. 6.

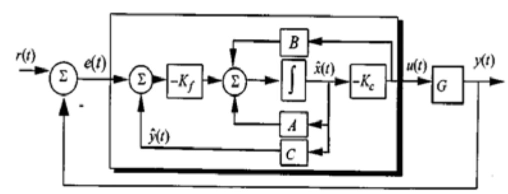

Fig. 6. Dynamics of the LQG/LTR controller.

IV. Model Order Reduction

Modern control design methods such as LQG or H_∞, produce controllers of order at least equal to the order of the plant, and usually higher with the incorporation of the required extra weights. Model order reduction is required to simplify the design procedure and, thus, the complexity of the final controller. The reduced plant used in the design must be a good approximation of the full order equivalent, for appropriate control design. Hence, the central problem addressed is as follows.

Given a high-order linear model $G(s)$, derive a low-order approximation $G_r(s)$ such that the infinity norm of their difference $||G - G_r||_\infty$ is sufficiently small.

The same applies in the controller reduction approach. Our design involve model and controller reduction based upon the Schur balanced model reduction procedure [16]. The reduction objective in this case is defined as follows.

Compute the k^{th}-order reduced model $G_r(s) = C_r(sI - A_r)^{-1}B_r + D_r$ from an n^{th}-order full model $G(s) = C(sI - A)^{-1}B + D$ such that

$$\left\|G - G_r\right\|_\infty \le 2\sum_{i=k+1}^{n} \sigma_i \tag{11}$$

where σ_i denotes the Hankel singular values of $G(j\omega)$, i.e., the square roots of the eigenvalues of their controllability and observability grammians

$$\sigma_i := \sqrt{\lambda_i(PQ)} \quad (12)$$

where $\lambda_i(PQ)$ is the ith largest eigenvalue of PQ and P, Q are the solutions of the following Lyapunov equalities:

$$PA^T + AP + BB^T = 0 \text{ (controllability grammian)} \quad (13)$$

$$QA + A^TQ + C^TC = 0 \text{ (absorbability grammian).} \quad (14)$$

Note that A, B, C, and D are the state space matrices of the full order model $G(s)$, while A_r, B_r, C_r, and D_r are the state space matrices of the reduced-order model $G_r(s)$. In cases involving large number of state variables (i.e., > 1000), one might have to employ numerical techniques, e.g., Krylov subspace-based technique, as the analytical techniques alone will not work [17].

The optimal Hankel norm approximation technique is used in getting a reduced order model for controller design. It gives the optimal reduced order model that minimize the error bound of the frequency response between the nominal and the reduced order model for the specified order [16-18]. It blends well with the LQG design in that it is numerically efficient and the given error bound can be used as a criterion to decide the order of the reduction.

V. Centralized control method

A. Application of LTR

Fig. 7 shows the LTR procedure for q = 1, 5, 10, 100, 1000 is given in (7) and (10). The measurement noise covariance, is chosen quite low in order to depict the characteristics of high quality sensor equipment [17]. The controller used to produce the results in Fig. 7 is the full 29th order for purposes of appropriate comparison. For the rest of the design q was set to a fixed value of 10, which involves sufficient recovery within the frequency range of interest and a faster roll-off at high frequencies compared to q= 1000.

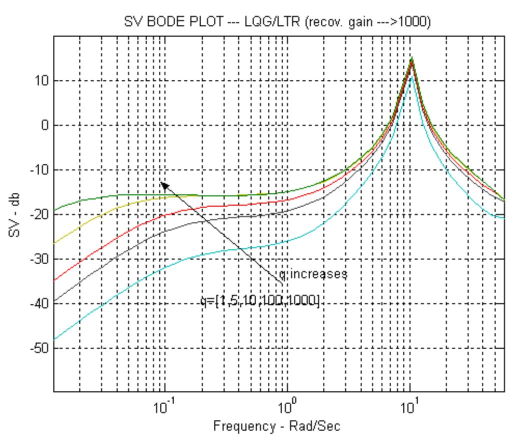

Fig.7. LTR method at plant input for various q parameter values.

B. LQG Controller Reduction

In this system, the full order controller is of 29th order. The designed LQG controller, with its transfer function given in (15), is of 14th order equal to the order of the design (reduced) plant. It is desired to reduce the controller size further, while satisfying the required damping ratios for the torsional modes for the full power network model. The reduction process uses the Schur balanced reduction method as discussed in Section IV [14-15].

$$K_{lqg} = \begin{bmatrix} A_r - B_rK_c - K_fC_r & K_f \\ -K_c & 0 \end{bmatrix} \quad (15)$$

where A_r, B_r, and C_r are the state space matrices of the reduced-order plant for the design (D_r = 0). Fig. 8 presents the singular value plot for a number of reduced size controller choices compared to the initial 29th-order designed controller. In addition, Fig.9 presents the error bound (the infinity norm of the difference between full and reduced controller) for a number of reduced size controller choices.

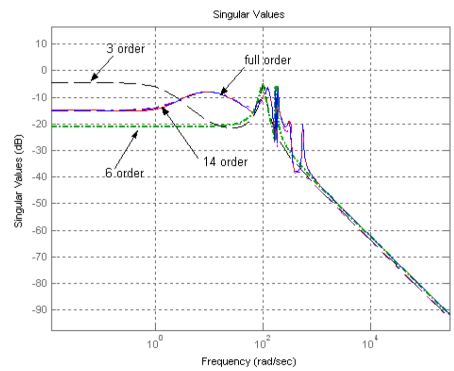

Fig.8. Singular value plot of controller approximation.

It can be shown from Fig.8 that the 14thorder controller is nearly indistinguishable compared to the original 29thorder (full order), while deterioration starts occurring as the order is further reduced. This is further justified in Fig.9, where it can be clearly shown that after the choice of the 14th order controller, the error bound is substantially increasing. It can be concluded from Fig. 9 that 14th order reduced order model is a good choice without causing much error. The error bound at reduced order to 14th is equal $\|G(j\omega) - G_r(j\omega)\| = 0.026964$

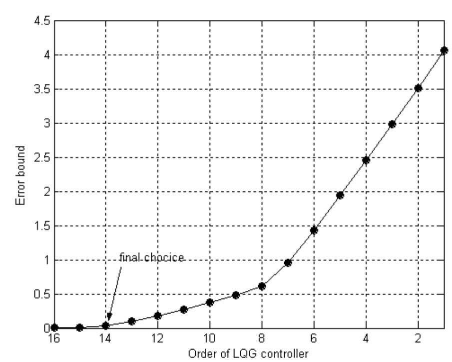

Fig.9. Controller reduction error bound.

Table I presents the "ideal" eigenvalues for the closed-loop based upon the reduced-order system using LQR state feedback, eigenvalue for open loop shown the all mode is marginally stable because the system open loop without only additional signal to excitation system, TCSC and SVC.

Table I
Eigenvalue of open loop and closed loop for reduced order regulator

	Mode 1 @125 rad/sec	Mode 2 @174 rad/sec	Mode 3 @191 rad/sec
Open loop	**-0.06733**	**-0.02514**	-0.020288
Closed loop with Full order 29 th	**-7.2484**	**-0.6856**	-1.4146
Closed loop with Order 14 th	**-6.9585**	**-0.66597**	-1.3661
Closed loop with Order 12 th	**-5.3898**	**-0.5286**	-1.1234
Closed loop with Order 9 th	**-4.2458**	**-0.40775**	-0.81285
Closed loop with Order 6 th	**-1.3449**	**-0.12783**	-0.33268
Closed loop with Order 3 rd	-1. 2074	-0.058126	-0.073612

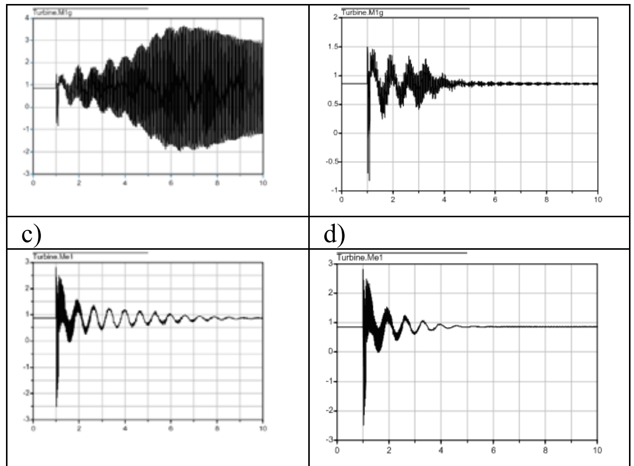

Fig.10 System response for three phase short circuit 0.1sec at time t=1sec.

a) Torque between the low-pressure turbine and the generator (ΔT_{ig}) without controller
b) Torque between the low-pressure turbine and the generator (ΔT_{ig}) with full order controller for 29th.
c) Electromechanical torque (ΔT_e) without controller.
d) Electromechanical torque (ΔT_e) with full order controller.

VI. Study results.

The two control schemes investigated are full-order robust control, and reduced order robust control. The simulation scenario is as follows. The system is in steady state up to the time t = 1 seconds. At time t = 1 seconds, a three phase short circuit at generator terminal for duration 0.1 seconds is injected at three input channels and the controller is not active. At t = 3 seconds, the controller is activated.

Fig.10 shows that system response for three phase short circuit 0.1sec at time = 1sec. Fig.10,a,b show the torque between the low-pressure turbine and the generator (ΔT_{ig}) without and with full order LQG controller for 29th respectively and Fig.10.c,d show the electromechanical torque (ΔT_e) without and with full order LQG controller for 29th respectively.

Fig.11,a show the torque between the low-pressure turbine and the generator (ΔT_{ig}) with reduce order LQG controller to 3rd and Fig.11,b with reduce order LQG controller to 14th.

Since the controller is based on full state feedback (during the design and not the implementation) it ends up of the same order of the open-loop system. The LQG is of 29th order. In many cases, a controller reduction is possible. The controller state-space model can be normalized, using a similarity transformation, to obtain a balanced state-space realization [13-15].

The balanced realization indicates states that can be removed to reduce the model to lower order. In this system, the full order controller is of 29th order. Therefore, the controller can be reduced from 29th order to only 14th with little loss in performance. The performance of the reduced-order robust controller is shown in Fig. 11 and Fig. 12.

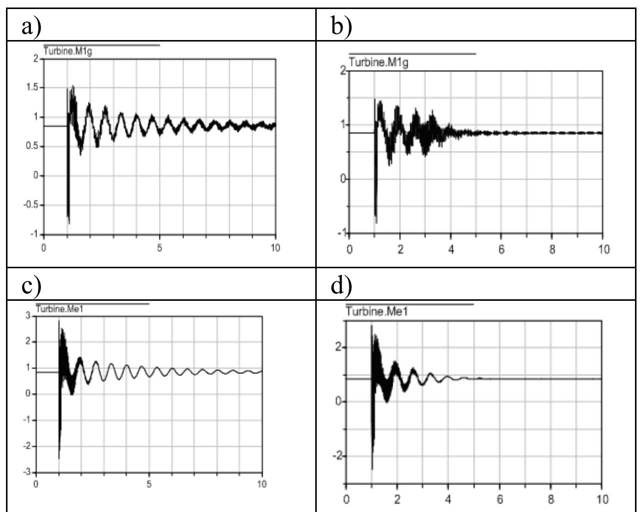

Fig.11: System response for three phase short circuit 0.1sec at time t=1sec.

a) Torque between the low-pressure turbine and the generator (ΔT_{ig}) with reduce order controller to 3rd.
b) Torque between the low-pressure turbine and the generator (ΔT_{ig}) with reduce order controller to 14th.
c) Electromechanical torque (ΔT_e)) with reduce order controller to 3rd.
d) Electromechanical torque (ΔT_e) with reduce order controller to 14th .

.

This reduced order LQG/LTR controller to 14th can effectively damp all the SSR modes at different levels from 30% to 90% of series compensation Fig 13 shown that rotor angle oscillations, level compensation, and SVC susceptance for three different level compensation

a)	b)

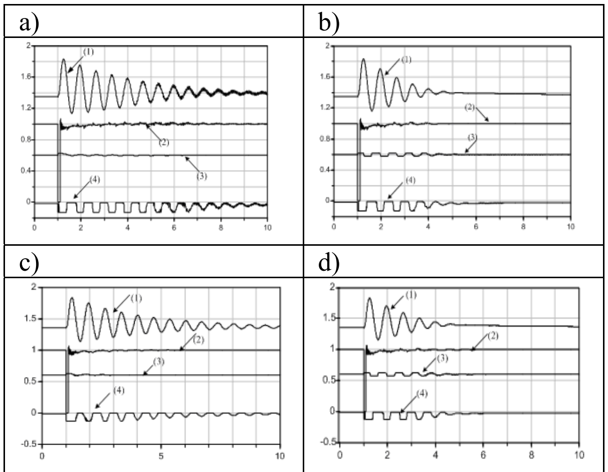

Fig. 12: System response for three phase short circuit 0.1sec at time t=1sec. (1). Rotor angle oscillations, (2).terminal voltage generator, (3). level compensation, (4). SVC susceptance.

a) Without controller.
b) With full order controller for 29th.
c) With reduce order controller to 3rd.
d) With reduce order controller to 14th.

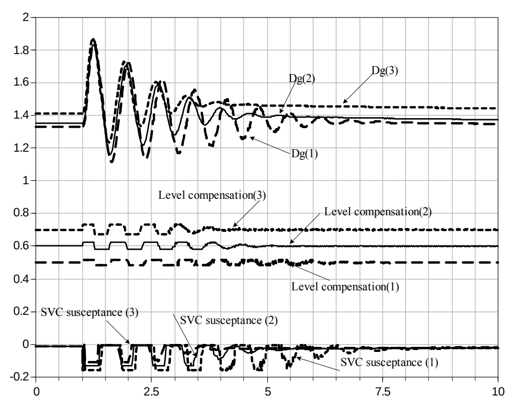

Fig.13: System response for three phase short circuit 0.1sec at time t=1sec, with reduce order controller to 14th. Rotor angle oscillations, level compensation, and SVC susceptance for three cases according the following

1-for level compensation = 50%
2- for level compensation = 60%
3- for level compensation = 70%

VII. Conclusion

This paper presents a procedure to design LQG control of VSC, TCSC and excitation system for damping subsynchronous resonance oscillations. A robust control using LQG was designed to use one feedback signal (angular speed deviation) and generate three control signals capable of damping all unwanted oscillations. This configuration is both simple and practical since it uses a measurable quantity. The full-order robust controller was reduced to a 14th order one and maintained the same good performance.

VIII. Appendix I.

Generator data

$X_d=1.869$, $X_q=1.869$, $X_s=0.194$, $X'_d=0.3016$, $X''_d=0.2337$, $X'_q=0.2337$, $R_a=0.0022$, $Rr=904e\text{-}6$, $R_{1d}=3.688e\text{-}3$, $R_{1q}=0.00108$,

Transformer data

$Rt=0.005$, $Xt=0.12$.

Excitation system data

$K_{ou}=-15$, $K_{1u}=-7.2$, $T_{ou}=0.09$, $T_{1u}=0.039$, $T_p=0.07$,

Transmission line data

$R_L=0.025$, $X_L=0.5$

SVC data

$K_{our}=-15$, $K_{1ur}=-10$, $T_{our}=0.09$, $T_{1ur}=0.39$, $T_{pr}=0.001$, $BLo=-0.01$, $BLmax=-0.0001$, $BLmin=-0.25$;

TCSC data

$K_{ouc}=-0.5$, $T_{ouc}=0.039$, $T_{pc}=0.001$, $Bco=3.333$; $Bcmax=1000$, $Bcmin=2$.

Generator as five-mass units

Mass	*Shaft*	*Inertia (H) s*	*K(p.u.torque/rad)*
HP		*0.079*	
	HP-IP		*64.478*
IP		*0.336*	
	IP-LP		*67.52*
LP		*1.4425*	
	LP-GEN		*85.8*
GEN		*1.15*	
	GEN-EXC		*11.44*
EXC		*0.063*	

IX. References

[1]. SONG, Y.H., and JOHNS, A.T. Flexible AC transmission systems (FACTS)', (IEEE, London, UK, 1999)

[2] IEEE Subsynchronous Working Group, "Second Benchmark Model for Computer Simulationof Subsynchronous Resonance," *IEEE Trans.*, vol. PAS-104, pp. 1057–1066, 1985.

[3]. OTHMAN, A.H., and LENNORT, A. "Analytical modelling of TCSC for SSR studies, " *IEEE Tram. Power Svxt.,* 1996, 11, (1), pp. 119-127

[4]. M1LANOVIC, J.V., and HISKENS, 1.A. "Damping enhancement by robust tuning of SVC controllers in the presence of load parameters uncertainty," *IEEE Tram. Power Syst.,* 1998, 13, (4), pp. 1298-1303

[5]. GIBBARD, M.J. "Interactions between and effectiveness of power system stabilizers and FACTS devices stabilizers in multimachine systems," *IEEE Tram. Power Syst.,* 2000, 15, (2), pp. 748-755

[6]. YANG, Z. *el at.* "Integration of StatCom and battery energy storage," *IEEE Trans. Power Syst.,* 2001, 16, (2), pp. 254-260

[7].DAS, P.K. "Damping multimodal power system oscillation using a hybrid fuzzy controller for series connected FACTS devices," *IEEE Trans. Power Syst.,* 2000, 15, (4), pp. 1360-1366

[8]. PADIYAR, K.R., and VERMA, R.K. "Damping torque analysis of static VAR system controllers," *IEEE Trans. Power Syst.,* 1991, 6, (2), pp. 458-465.

[9] A. E. Hammad and M. El-Sadek, "Application of a Thyristor Controlled Var Compensator for Damping

Subsynchronous Oscillations in Power Systems," *IEEE Trans.*, vol. PAS-103, pp. 198–212, 1984.
[10] Q. H. Wu and B. W. Hogg, "Robust Self Tuning Regulator for a Synchronous Generator," *IEE Proc.*, pt. D, vol. 135, no. 6, pp. 463–473, November 1988.
[11] A. Ben-Abdennour, K. Y. Lee, and R. M. Edwards, "Multivariable robust control of a power plant deaerator," *IEEE Transactions on Energy Conversion*, vol. 8, no. 1, pp. 123–129, 1993.
[12] J. C. Doyle and G. Stein, "Multivariable feedback design: concepts for a classical/modern synthesis," *IEEE Transactions on Automatic Control*, vol. AC-26, pp. 4–16, February 1981.
[13] B. Moore, "Principle component analysis in linear systems: controllability, observability, and model reduction," *IEEE Transactions on Automatic Control*, vol. 26, no. 1, February 1990.
[14] M. G. Safonov and R. Y. Chiang, "A Schur Method for Balanced Model Reduction," *IEEE Trans. on Automat. Contr.*, vol. AC-2, no. 7, July 1989, pp. 729-733.
[15] M. G. Safonov, R. Y. Chiang and D. J. N. Limebeer, "Optimal Hankel Model Reduction for Nonminimal Systems," *IEEE Trans. on Automat. Contr.*, vol. 35, No. 4, April, 1990, pp. 496-502.
[16] Kwang M. Son*,* and Jong K. Park. "On the Robust LQG Control of TCSC for Damping Power System Oscillations, " *IEEE Trans. On Power Syst,* Vol. 15, no. 4, November 2000.
[17] Argyrios C. Zolotas*,* , Balarko Chaudhuri*,* , Imad M. Jaimoukha, and Petr Korba "A Study on LQG/LTR Control for Damping Inter-Area Oscillations in Power Systems ," *IEEE Trans. On control systems technology*, vol. 15, no. 1, January 2007.
[18] Adel Ben Abdennour, Rizk M. Hamouda, and A. A. Al-Ohaly "Countermeasures for Self-Excited Torsional Oscillations Using Reduced Order Robust Control Approach," *IEEE Trans. On Power Syst,* Vol. 15, no. 2, May 2000.

X. Biographies

Basim T. Kadhem Iraqi. Citizen was born in Basrah (Iraq) July 9, 1972.He received the B.Sc. and M.Sc. degree in Electrical Engineering from university of Basrah, in 1998 and 2001 respectively. Presently, he is the Ph.D study at the Department of Electrical Power Systems and Networks, St-Petersbug State Polytechnical University, Russia. His primary areas of research interests include: softswitching converters., FACTS and applications of high-power inverters, power circuit modeling, and study, torsional dynamics of powerful steam turbo generators, power system control.

Andrey N. Belyaev was born in Leningrad, USSR, on February 6,1974. He received the M.Sc. and Ph.D. degrees from the Department of Electrical Power Systems and Networks, St-Petersbug State Technical University, Russia in 1997 and 2000, respectively. Dr. Belyaev is currently an Associate Professor in the Department of Electrical Power Systems and Networks, St-Petersburg State Polytechnical University. His research interests include power system stability and control technologies.

Serguei V. Smolovik was born in Leningrad, USSR, on September 16, 1940.He received the M.Sc. degrees from the Department of High-Voltage Technology Leningrad Polytechnic Institute, USSR in 1963 and Ph.D. degree in 1971 from the Department of Electrical Power Systems and Networks. In 1989 he defended his Doctor of Science dissertation. He is currently Professor and the Head of Department of Electrical Power Systems and Networks, St-Petersburg State Polytechnical University. His research interests include power system stability problems as well as the issues of large energy pools operation, analysis and planning.