DAMPING POWER SYSTEM ELECTROMECHANICAL OSCILLATIONS USING A ROBUST ADAPTIVE TCSC CONTROLLER

André M. D. Ferreira*, José A. L. Barreiros, Walter Barra Jr.**, Jorge Roberto Brito-de-Souza**, Carlos Tavares-da-Costa Jr.****

** Federal Center for Education in Technology of Pará (CEFET-PA)*
Av. Almirante Barroso, 1155 (Marco), CEP: 66093-020, Belém - PA, Brazil
*** Electrical and Computer Engineering Department, Federal University of Pará (UFPA)*
Campus Universitário do Guamá, CEP: 66075-900, Belém - PA, Brazil
Phone Number: +55 91 3183 1680 Fax: +55 91 3183 1634
E-mails: andre@amazon.com.br, barreiro@ufpa.br, walbarra@ufpa.br, jrgbrito@ufpa.br

Abstract: This paper is concerned with the evaluation of a robust adaptive control technique applied to damp power systems oscillations. This robust technique is based on the LQG/LTR control method, used in a self-tuning way. The stabilizer synthesized with this method is used in a TCSC device to increase the damping of low frequency electromechanical oscillations modes. The method is evaluated in a 4-machine benchmark system and simulation results show that the proposed controller presents a good performance, improving power system stability margins.

Keywords: Power System Stabilizers, Power System Control, Dynamic Stability, Adaptive Control, LQG Control, Robust Control.

1. INTRODUCTION

The use of damping controllers is a necessity for safe and reliable operation in modern power systems. With the interconnection of large generation centers, small magnitude and low frequency oscillations arise intrinsically in the system controlled variables (voltage, frequency, electric power, etc.). If these kind of electromechanical oscillations are not damped properly, they can affect the system normal operation and in some cases take the system to an unstable condition (Rogers, 2000). This problem was solved initially with the called Power System Stabilizers (PSS), that provide an auxiliary stabilizing signal to the excitation system generators in order to improve power system dynamic performance. These conventional PSS have fixed structure and parameters, being designed from a linear model of the electric power system using classical linear control techniques. Even though these stabilizers are tuned for a specific system operation point, they must present a satisfactory performance in a wide range of electric power system conditions (Larsen and Swann, 1981).

The use of conventional PSS still is the most used solution in real systems to damp power system electromechanical oscillations. However, with the need of better quality energy supply, many researches have been accomplished in the last decades, with several methods being proposed to design a PSS that could get better performance than a conventional one (Gu and Bollinger, 1989; Hsu and Chen, 1991; Hiyama *et al.*, 1996). Besides, since the later nineties a great interest in the use of FACTS (Flexible AC Transmission Systems) devices to damp power systems electromechanical oscillations has been observed, specially with the SVC (Static VAr Compensator) and the TCSC (Thyristor Controlled Series Compensation) (Larsen *et al.*, 1995). Since then, many works using series and shunt FACTS devices have been proposed to improve power system dynamic stability with promising results (Noroozian, 1998; Fan and Feliachi, 2001). However, in the same way as the conventional PSS, the Power System Damping Controllers (PSDC) used with these FACTS devices are also designed using linear control techniques for a particular power system operating condition.

The main objective of this paper is to investigate the use of a robust adaptive control technique to design a damping controller for a TCSC in a multi-machine power system. The proposed controller uses the Self-tuning LQG/LTR (Linear Quadratic Gaussian / Loop Transfer Recovery) method and its performance will be evaluated in comparison with a fixed-parameter PSDC using a non-linear multi-machine power system simulation program in different system operation conditions.

2. ROBUST ADAPTIVE CONTROL

Robust adaptive control combines the advantages of both robust control (minimizing the effect of system model uncertainties and measurement noise) and adaptive control (that uses updated system models and controllers parameters) (Gutman, 2003). In this work, the LQG/LTR method is used in a self-tuning scheme (Gordillo and Rubio, 1991) to design a TCSC damping controller in order to improve power system dynamic stability.

A self-tuning adaptive controller has this name to emphasize that its parameters are updated automatically at every sample time. This control scheme is an automatic process of system modeling and controller design, used to achieve the desired performance criteria in closed-loop (Aström and Wittenmark, 1989). With the purpose of obtaining an updated parametric system model, identification techniques can be applied using measured input and output system data, providing that the dynamic of interest is persistently excited (Landau, 1990). In the neighborhood of a given system operating point *i*, the system dynamics can be approximately represented by a ARMAX (auto-regressive moving average with exogenous inputs) linear model in the form:

$$A_i(q^{-1})y(t) = q^{-d}B_i(q^{-1})u(t) + C_i(q^{-1})e(t) \quad (1)$$

where y is the system output, u is the system input, d is a time delay between the input and output ($d \geq 1$), e is a disturbance in the system output (considered as a white noise) and q^{-1} is the time delay operator. A_i, B_i and C_i are polynomials with orders n_a, n_b and n_c, respectively, and are defined as:

$$A_i(q^{-1}) = 1 + a_1q^{-1} + ... + a_{n_a}q^{-n_a} \quad (2)$$

$$B_i(q^{-1}) = b_0 + b_1q^{-1} + ... + b_{n_b}q^{-n_b} \quad (3)$$

$$C_i(q^{-1}) = 1 + c_1q^{-1} + ... + c_{n_c}q^{-n_c} \quad (4)$$

The parameters $a_1 \ldots a_{na}$, $b_0 \ldots b_{nb}$ and $c_1 \ldots c_{ca}$ are usually estimated using a recursive identification algorithm based on a least squares method, which minimizes a quadratic function of the error between the model and the system outputs. With updated parameters available, the system model can be obtained as a discrete-transfer function or in a state-space form, depending on what control technique will be used.

In optimal control design, a quadratic cost function of the system states and control signal must be minimized, so the "best" controller capable of matching system desired performance is obtained. For system models deterministic and controllable, with all state variables available, an optimal state feedback can be designed using the Linear Quadratic Regulator (LQR) (Phillips and Nagle, 1984). For continuous-time systems, besides its optimal characteristics the LQR presents excellent robust properties. In the case of discrete-time systems, it is not possible to assure that these robust properties are true, although they can be found in many cases (Maciejowski, 1985).

In practical systems it is likely that all state variables are not available or can not be measured. As the LQR needs a full state feedback, an observer must be used to estimate the system states in a procedure known as Linear Quadratic Gaussian (LQG) control and, in most cases, this estimation is performed using a Kalman Filter (KF) (Stengel, 1994). Adding a state observer does not change the system closed loop transfer function, but it affects the system open loop characteristics, degrading the controller robustness properties (which, in most cases, can not be tolerated). As a result, it is necessary to modify the LQG controller design to assure that the full-state feedback loop transfer properties can be recovered asymptotically. This methodology is known as the LQG/LTR method and although originally proposed for minimum phase and continuous systems (Doyle and Stein, 1979), it can also be used with discrete-time systems (Bitmead *et al.*, 1990; Maciejowski, 1985; Hu *et al.*, 1999).

The system model can be put in the discrete form:

$$\begin{aligned} x(k+1) &= A(k)x(k) + B(k)u(k) \\ y(k) &= C(k)x(k) \end{aligned} \quad (5)$$

where $A(k)$, $B(k)$, $C(k)$ are the updated state space matrices of the linear system model and $x(k)$, $y(k)$ are the state vector and the system output, respectively. The LQR control signal $u(k)$ is a linear, time-varying, full state feedback law in the form:

$$u(k) = -K(k)x(k) \quad (6)$$

which results from the minimization of the following quadratic cost function:

$$J = \sum_{k=0}^{\infty}\left[x^T(k)Q_c(k)x(k) + u^T(k)R_c(k)u(k)\right] \quad (7)$$

where $Q_c(k)$ and $R_c(k)$ weight matrices are design parameters chosen to meet the desired closed loop performance and the vector $K(k)$ is obtained from the solution of a Riccati Algebraic Equation. The system model is linear and deterministic, while the weight matrices are symmetric and can be time-varying. A tradeoff between control effort and system performance can be achieved by the proper choice of these weight matrices.

As all system states are usually unavailable, the system state variables are estimated using a KF, composing a LQG controller. Supposing that the system has measurement and modeling noises, it can be represented as:

$$\begin{aligned} x(k+1) &= A(k)x(k) + B(k)u(k) + G(k)w(k) \\ y(k) &= C(k)x(k) + v(k) \end{aligned} \quad (8)$$

where $G(k)$ and $w(k)$ are related to the process noise, $v(k)$ is the measurement noise and the other variables are the same already defined in (5). The process noise (modeling disturbances and uncertainties) $w(k)$ and the measurement noise (sensors error) $v(k)$ are supposed white-noise signals with zero mean and covariances $Q_k(k)$ and $R_k(k)$. The resulting LQG regulator is shown in Fig. 1, where $L(k)$ is the KF gain and $K(k)$ is the LQR gain.

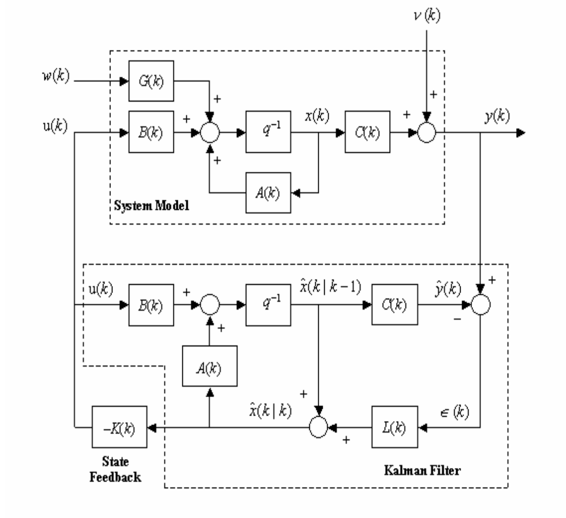

Fig. 1. LQG control block diagram.

The KF can be used in a recursive way and a state estimate is always available at every sample time. Initially, an initial state vector estimate $\hat{x}(k \mid k-1)$ is obtained using information from a previous iteration, without regard of new measurements. After that, a proportional part of the prediction error $\in(k)$ is used to calculate an update filtered state estimation $\hat{x}(k \mid k)$. This proportion is determined by the KF gain $L(k)$, that represents the confidence in both the state estimate and measurement errors. Finally, the updated KF state estimate can be obtained using:

$$\hat{x}(k \mid k) = \hat{x}(k \mid k-1) + L(k)\left[y(k) - C(k)\hat{x}(k \mid k-1)\right] \quad (9)$$

When the LQR gain and the estimated state vector are known, a full state feedback can be used:

$$u(k) = -K(k)\hat{x}(k \mid k) \quad (10)$$

As mentioned previously, with a KF presented in the system loop the full state feedback will be replaced by a state estimate feedback and stability margins existing for the LQR are not guaranteed for the LQG control. In continuous-time systems, an adjustment procedure of the observer that assures asymptotical recovery of the loop transfer function was proposed by Doyle and Stein (1979). This method, known as Loop Transfer Recovery (LTR), modifies the KF gain, changing the Q_k matrix in a way that the LQG loop transfer function becomes the same obtained with the LQR. For the discrete-time case, although the recovery procedure usually is not complete, in most cases at least a partial recovery can be obtained (Maciejowski, 1985). Dropping the sampled time notation for convenience, the LQR loop transfer function can be calculated as (Maciejowski, 1985; Gordillo and Rubio, 1991):

$$G_{LQR} = K(zI - A)^{-1}B \quad (11)$$

and the LQG loop transfer function is given by:

$$G_{LQG} = \{K(I - LC)\left[zI - (A - BK)(I - LC)\right]^{-1} (A - BK)L + KL\}\left[C(zI - A)^{-1}B\right] \quad (12)$$

The transfer function recovery can be achieved changing the KF covariance matrix Q_k, with a modified new matrix being equal to:

$$Q_{k\,LTR} = Q_k + q^2 BVB^T \quad (13)$$

where V is a non-singular matrix and q is a recovery parameter. When q increases, G_{LQG} becomes closer to G_{LQR}, improving the controller robust properties, at the price of losing state estimate accuracy because the original covariance matrix was replaced for another matrix related to fictitious noise. Adding an identification algorithm to estimate the system state matrices, this recovery procedure can be used in a self-tuning adaptive control design, from now on referred as ST LQG/LTR, forming the robust adaptive controller originally proposed by Gordillo and Rubio (1991).

3. A TCSC DAMPING CONTROLLER DESIGN USING THE SELF-TUNING LQG/LTR METHOD

For dynamic stability studies, a TCSC device can be represented as a first order system, with time constant T_{TCSC} around 15ms (Paserba *et al.*, 1995). As the transmission line impedance affects the power system stability, in addition to power flow control in steady-state, the TCSC is useful to damp the electromechanical modes of the system (Fan and Feliachi, 2001). As the FACTS devices ability to damp power system electromechanical oscillations is directly related with their location in the system, for the TCSC it is recommended that its location is in a path of high transmission power (Wang and Swift, 1997; Wang *et al.*, 1998). Another factor that affects the FACTS devices performance, related to improving power system dynamic stability, is the choice of an adequate controller feedback signal. There is some consensus that good feedback signals for the TCSC are the line current or the active electric power flow (Wei *et al.*, 2002). The proposed TCSC damping controller uses electric power flow (in the transmission line it is installed) as its input signal, while its control signal is limited in the range of ± 0.1 pu.

The compensation degree of a transmission line with a TCSC can be defined as:

$$\alpha_{TCSC} = \frac{X_{TCSC}}{X_L} \quad (14)$$

where X_{TCSC} is the TCSC reactance and X_L is the uncompensated transmission line original reactance. The equivalent reactance due to the TCSC action is given by:

$$X_{EQ} = X_L (1 - \alpha_{TCSC}) \tag{15}$$

The self-tuning LQG/LTR method presented previously is the control strategy used to design the PSDC for the TCSC device. The LQR vector gain $K(k)$ is calculated as usual and the Q_k covariance matrix is modified to obtain the KF gain. This modification is done with the inclusion of the recovery parameter in Q_{kLTR}, as shown in (13), with the following KF parameters used in all simulation tests: $Q_k = 10^{-4}GG^T$, $R_k = 10^{-4}$ and $q = 10^2$. The matrix G is calculated in each sample time using the updated parameters of the polynomial $C_i(q^{-1})$ defined in (4), while the LQR weight matrices used are $Q_c = C^TC$ and $R_c = 0.1$ (Bitmead *et al.*, 1990).

System parameters are estimated using the well-known Recursive Least Squares algorithm, with a variable forgetting factor ($0.97 \leq \lambda \leq 0.995$) and moving parameter boundaries (Flynn, 1994). Using a sample period of 100 ms, a 4th order system model is obtained, which is adequate to represent the system inter-area mode accurately. The input and output signals used to system identification are, respectively, a small amplitude ($\pm$ 10^{-3} pu) Pseudo-random Binary Sequence (u_{PRBS}) in the reactance reference signal of the TCSC and the active electric power flow deviation in the transmission line where the TCSC is located (ΔP_{ij}) (Fig. 2). At every sample time, the system parameters are updated and used to obtain a observer canonical form state-space system representation (Aström and Wittenmark, 1989) as in (8). This model is used for the ST LQG/LTR controller to produce the control signal responsible for damping the system electromechanical oscillations.

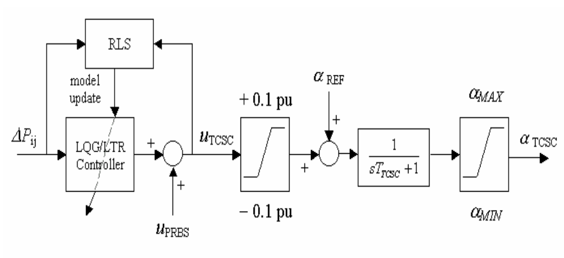

Fig. 2. TCSC with ST LQG/LTR controller block diagram.

4. SIMULATIONS RESULTS

In order to evaluate the robust adaptive control method presented in Section 2, several simulations with a ST LQG/LTR controller for a TCSC device in a multi-machine test system have been performed. The test system has 4 generators and 2 control areas (Fig. 3), and has been used frequently to study power system dynamic stability problems (Klein *et al.*, 1991; Kundur, 1994). It is considered that the system works with steam turbines, speed governors and high-gain fast-acting voltage regulators. All controller data, generators and transmission lines parameters can be found in Kundur (1994).

The TCSC is placed in the transmission line between buses 7-8 and the only modification made in the original power system was to change the double circuit between these buses for an equivalent single transmission line. Two operation conditions have been considered in this paper: in Case 1, Area 1 generators (G1 and G2) supply around 400 MW for Area 2 (where G3 and G4 are located); and in Case 2, this interchange power is reduced to approximately 50 MW, because it is known that the TCSC ability do damp power system oscillations is reduced when the power flow also decreases (Wang et al., 1996). In all simulations it is supposed that the TCSC can compensate the transmission line 7-8 in the range between $0 \leq \alpha_{TCSC} \leq 0.5$, with a fixed compensation in steady-state $\alpha_{REF} = 0.2$.

4.1 TCSC ST LQG/LTR Controller Analysis

One of the main objectives of the proposed controller is to recovery the LQR robustness properties lost when the state estimator is added in the control loop. As mentioned previously, for discrete-time systems in some cases it is not possible to recovery the LQR properties completely, but with the LQG/LTR methodology at least an acceptable controller performance can be obtained. To evaluate the ST LQG/LTR behaviour, some tests with the system in operation condition defined in Case 1 have been performed at a particular sample time without any faults in the system. Fig. 4 shows the Nyquist diagrams for the LQR (dashed line), LQG ($q^2 = 0$) and LQG/LTR ($q^2 = 10^{-4}$; $q^2 = 10^{-2}$; $q^2 \geq 1$). It can be noticed that the LQG and LQR diagrams are quite different. However, increasing the recovery parameter q^2, the LQG/LTR diagram comes close to the one obtained with the LQR, although it is not possible to obtain a perfect match. In all simulations, it is used $q^2 = 10^4$, since there is not difference in the LQG/LTR diagram for $q^2 \geq 1$.

Another way to analyse this problem is comparing the stability margins for the system with the LQR and with the LQG/LTR controller. When the system is without any damping controller, there is an unstable inter-area mode due mainly to the high-gain voltage regulator (Kundur, 1994), what makes necessary the use of a PSS or, as it is being proposed in this paper, the use of a PSDC for the TCSC. Fig. 5 shows the Bode diagrams for the system and it can be seen that although perfect recovery is not accomplished, the LQG/LTR controller presents similar stability margins when compared with LQR (Table 1). When the system is in the second operation condition (Case 2), there is an almost perfect recovery of LQR stability margins, as can be seen in the Bode diagrams (Fig. 6) and system stability margins (Table 1).

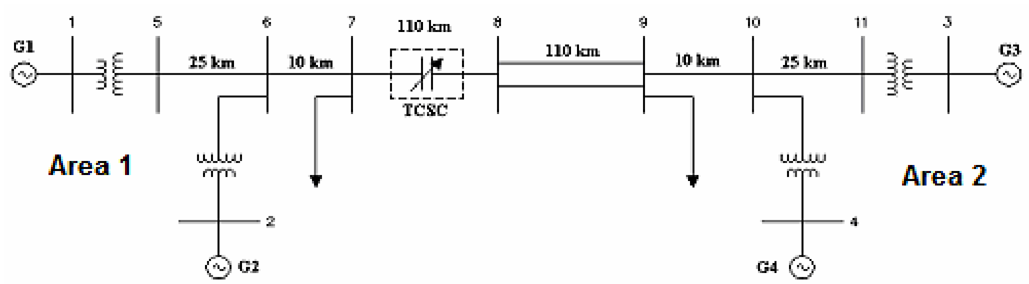

Fig. 3. Four machine test system.

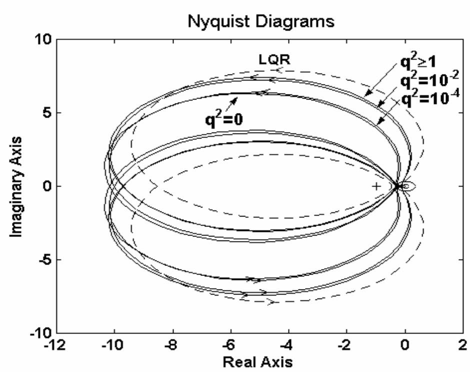

Fig. 4. System model Nyquist diagrams (Case 1)

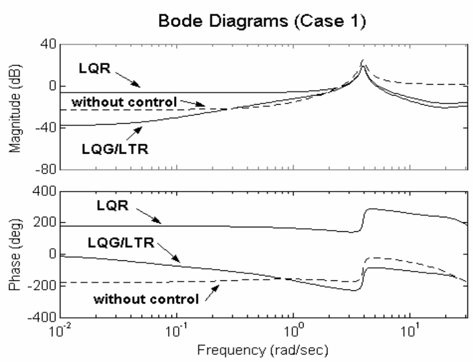

Fig. 5 - System model Bode diagrams (Case 1)

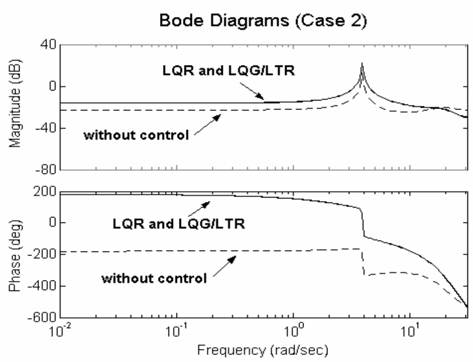

Fig. 6 - System model Bode diagrams (Case 2)

4.2 Non-linear system simulations

Although the analysis of Nyquist and Bode diagrams can be a way of predict the system behaviour, it is necessary to test the ST LQG/LTR controller using power system simulations, where each generator is represented using 6 non-linear differential equations. To assess the performance of the proposed controller, it is compared with a conventional PSDC (Fig. 7) that was well designed for the operation condition of Case 1 and whose parameters are:

$$K = 0.5;\ T_1 = T_3 = 0.01;\ T_2 = T_4 = 0.15;\ T_w = 3$$

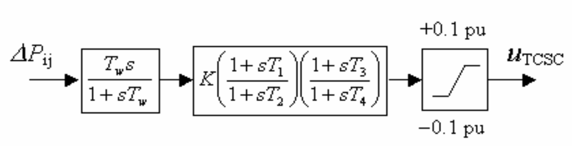

Fig. 7. Conventional PSDC structure.

The system suffers a 100ms three-phase to ground short-circuit at bus 8 in t = 11s. Rotor angle between generators G1-G2 and G1-G3 are displayed for both cases in Fig. 8 and Fig. 9. It can be seen that both controllers have a good performance for Case 1, but when the operation condition changes (Case 2), the ST LQG/LTR controller is clearly superior due to its robust and adaptive characteristics.

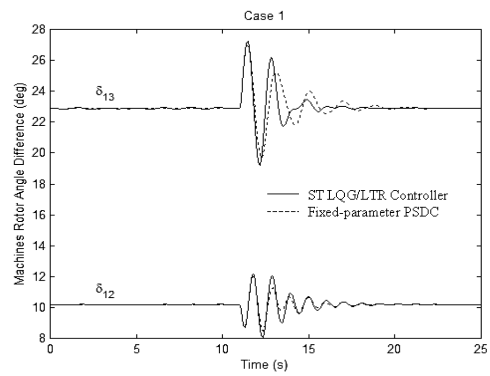

Fig. 8. Machines rotor angle difference (Case 1).

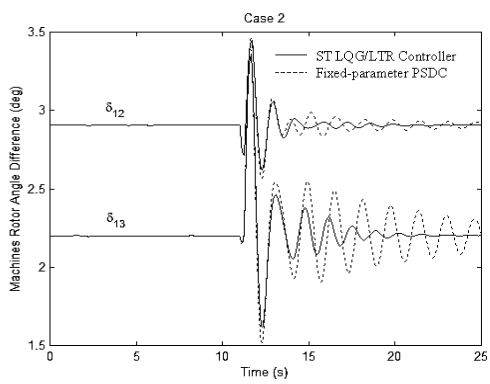

Fig. 9. Machines rotor angle difference (Case 2).

Table 1 - System model stability margins

		gain margin (dB)	phase margin (deg)
Case 1	LQR	6.69	107.31
	LQG/ LTR	10.38	95.74
Case 2	LQR	16.31	84.77
	LQG/ LTR	16.18	84.74

5. CONCLUSIONS

This paper investigates the use of a robust adaptive controller for a TCSC device, with the objective of damping power system electromechanical oscillations in a 4-machine test system. The proposed method identifies, at each sample time, an updated system model. With this model available, a TCSC damping controller can be designed on-line, presenting good robust properties since the LQG/LTR method can recovery (at least partially) the LQR stability margins that are lost with the presence of a state estimator in the control loop.

It was shown that the proposed controller has a similar performance when compared with a conventional one tuned for a particular system operation condition. But when this operation condition changes, the robust adaptive controller has clearly a better performance (due to its ability to update the system model parameters). The authors are currently working in a variation of the proposed control method, where the system model is updated at fixed-times (and not at every sample time), avoiding the need of persistent system excitation, what has always been a controversial issue when using adaptive control schemes in power systems.

6. ACKNOWLEDGEMENTS

The authors would like to thank the support of the Brazilian Electrical Energy National Agency (ANEEL), under project number 121.053-5, and PROCAD/CAPES (UFPA-UFSC covenant), under project number 0132/01-2.

REFERENCES

Aström, K.J. and B. Wittenmark (1989). *Adaptive Control*, Addison-Wesley Publishing Company, Reading.

Bitmead, R.R., M. Gevers and V. Wertz (1990). *Adaptive Optimal Control: The Thinking Man's GPC*, Prentice-Hall, New Jersey.

Doyle, J.C. and G. Stein (1979). Robustness with Observers, *IEEE Trans. on Automatic Control*, **v.AC-24**, **n.4**, pp. 607-611.

Fan, L. and A. Feliachi (2001). Robust TCSC Control Design for Damping Inter-Area Oscillations. *Power Engineering Society Summer Meeting*, **v.2**, pp. 784-789.

Flynn, D.G. (1994). *Expert Self-Tuning Control for Turbogenerator Systems*, Ph.D. Thesis, Department of Electrical and Electronic Engineering, The Queen´s University of Belfast.

Gordillo, F. and F.R. Rubio (1991). Self-tuning Controller with LQG/LTR Structure, *European Control Conference*, Grenoble (France), pp. 2159-2163.

Gu, W. and K.E. Bollinger (1989). A Self-tuning Power System Stabilizer for Wide-Range Synchronous Generator Operation, *IEEE Trans. on Power Systems*, **v.4**, **n.3**, pp. 1191-1199.

Gutman, P. (2003). Robust and Adaptive Control: fidelity or an open relationship?, *Systems and Control Letters*, **v.49**, pp. 9-19.

Hiyama, T., S. Oniki and N. Nagashima (1996). Evaluation of Advanced Fuzzy Logic PSS on Analog Network Simulator and Actual Installation on Hydro Generators, *IEEE Trans. on Energy Conversion*, **v.11**, **n.1**, pp. 125-131.

Hsu, Y.Y. and C.R. Chen (1991). Tuning of Power System Stabilizers Using an Artificial Neural Network, *IEEE Trans. on Energy Conversion*, **v.6**, **n.4**, pp. 612-619.

Hu, X., W.Guo, T. Huang and B.M. Chen (1999). Discrete-Time LQG/LTR Dual-Stage Controller Design and Implementation for High Track Density HDDs, *Proceedings of the American Control Conference*, San Diego, pp. 4111-4115.

Klein, M., G.J. Rogers and P. Kundur (1991). A Fundamental Study of Inter-area Oscillations in Power Systems. *IEEE Trans. on Power Systems*, **v.6**, **n.3**, pp. 914-921.

Kundur, P. (1994). *Power System Stability and Control*, McGraw-Hill, New York.

Landau, I.D. (1990). *System Identification and Control Design Using P.I.M.+ Software*. Prentice Hall, New Jersey.

Larsen, E.V. and D.A. Swan (1981). Applying Power System Stabilizers (parts I, II and III). *IEEE Trans. on Power Apparatus and Systems*, **v.PAS-100**, **n.6**, pp. 3017-3046.

Larsen, E.V., J.J. Sanchez-Gasca and J.H. Chow (1995). Concepts for Design of FACTS Controllers to Damp Power Swings. *IEEE Trans. on Power Systems*, **v.10**, **n.2**, pp. 948-956.

Maciejowski, J.M. (1985). Asymptotic Recovery for Discrete-Time Systems, *IEEE Trans. on Automatic Control*, **v.AC-30**, **n.6**, pp. 602-605.

Noroozian, M. (1998) Application of Shunt and Series Compensators for Damping of Electromechanical Oscillations, *IEE Colloquium on Power System Dynamics Stabilisation Digest*, pp. 4/1-4/3.

Paserba, J.J., N.W. Miller, E.V. Larsen and R.J. Piwko (1995). A Thyristor Controlled Series Compensation Model for Power System Stability Analysis, *IEEE Trans. on Power Delivery*, **v.10**, **n.3**, pp. 1471-1478.

Phillips, C.L. and Nagle Jr., H.T. (1984). *Digital Control System Analysis and Design*, Prentice-Hall, New Jersey.

Rogers, G. (2000). *Power System Oscillations*, Kluwer Academic Publishers, Boston.

Stengel, R.F. (1994). *Optimal Control and Estimation*. Dover Publications, New York.

Wang, H.F., F.J. Swift and M. Li (1996). Analysis of Controllable Series Compensator to Suppress Power System Oscillations, *Sixth International Conference on AC and DC Power Transmission*, London, pp. 202-207.

Wang, H.F. and F.J. Swift (1997). A Unified Model for the Analysis of Facts Devices in Damping Power System Oscillations Part I: Single-machine Infinite-bus Power Systems, *IEEE Trans. on Power Delivery*, **v.12**, **n.2**, pp. 941-946.

Wang, H.F., F.J. Swift and M. Li (1998). A Unified Model for the Analysis of Facts Devices in Damping Power System Oscillations Part II: Multi-machine Power Systems, *IEEE Trans. on Power Delivery*, **v.13**, **n.4**, pp. 941-946.

Wei, X., J.H. Chow and J.J. Sanchez-Gasca (2002). On the sensitivities of Network Variables for FACTS Device Damping Control, *Power Engineering Society Winter Meeting*, **v.2**, pp. 27-31.