A robust PSS Based Advanced H_2 Frequency Control to Improve Power System Stability – Implementation under GUI/MATLAB

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Abstract— This article present a comparative study between two control strategies, a classical PID regulator, and a robust H_2 controller based on LQG control with KALMAN filter applied on automatic excitation control of powerful synchronous generators, to improve transient stability and its robustness of a single machine-infinite bus system (SMIB). The computer simulation results have proved the efficiency and robustness of the robust H_2 approach, in comparison with using classical regulator PID, showing stable system responses almost insensitive to large parameter variations. This robust control possesses the capability to improve its performance over time by interaction with its environment. The results proved also that good performance and more robustness in face of uncertainties (test of robustness) with the linear robust H_2 controller (optimal LQG controller with Kalman Filter) in comparison with using the classical regulator PID. Our present study was performed using a GUI realized under MATLAB in our work.

Index Terms— powerful synchronous generators *and Excitations, AVR and PSS, LQG control , Kalman filter, stability and robustness.*

I INTRODUCTION

Power system stability continues to be the subject of great interest for utility engineers and consumers alike and remains one of the most challenging problems facing the power community. Power system oscillations are damped by the introduction of a supplementary signal to the excitation system of a power system. This is done through a regulator called power system stabilizer. Classical PSS rely on mathematical models that evolve quasi-continuously as load conditions vary.

Conventional PSS based on simple design principles such as PI control and eigenvalue assignment techniques have been widely used in power systems [1, 2]. Such PSS ensure optimal performance only at their nominal operating point and do not guarantee good performance over the entire operating range of the power system. This is due to external disturbances such as changes in loading conditions and fluctuations in the mechanical power. In practical power systems networks, a priori information on these external disturbances is always in the form of certain frequency band in which their energy is concentrated.

Remarkable efforts have been devoted to design appropriate PSS with improved performance and robustness. These have led to a variety of design methods using optimal and output feedback methods [3, 5]. The shortcoming of these model-based control strategies is that uncertainties cannot be considered explicitly in the design stage.

The stabilizer of this new generation for the system AVR – PSS, aimed-at improving power system stability, was developed using the robust controller H_2 based on LQG. This has been advantage of maintaining constant terminal voltage and frequency irrespective of conditions variations in the system study. The H_2 control design problem is described and formulated in standard form with emphasis on the selection of the weighting function that reflects robustness and performances goals [6]. The proposed system has the advantages of robustness against model uncertainty and external disturbances (electrical and mechanical), fast response and the ability to reject noise.

Simulation results shown the evaluation of the proposed linear control methods based on this advanced frequency techniques applied in the automatic excitation regulator of powerful synchronous generators: the robust H_2 linear stabilizer and conventional PID control schemes against system variation in the SMIB power system, with a test of robustness against parametric uncertainties of the synchronous machines (electric and mechanic), and make a comparative study between these two control techniques for AVR – PSS systems.

II DYNAMIC POWER SYSTEM MODEL

A Power System Description

In this paper the dynamic model of an IEEE - standard of power system, namely, a single machine connected to an infinite bus system (SMIB) was considered [4]. It consists of a single synchronous generator (turbo-Alternator) connected through a parallel transmission line to a very large network approximated by an infinite bus as shown in figure 1.

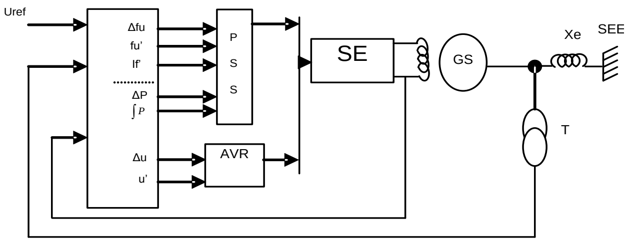

Figure 1 Standard system IEEE type SMIB with excitation control of powerful synchronous generators

B The Park-Gariov modeling of powerful synchronous generators

This paper is based on the **Park-Gariov** modeling of powerful synchronous generators for eliminating simplifying hypotheses and testing the control algorithm. The PSG model is defined by equations (1to 5) and Figures 2 and 3 below [4]:

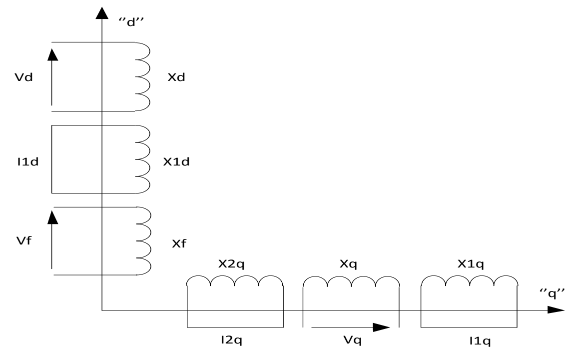

Figure 2. PARK Transformation of the synchronous machine

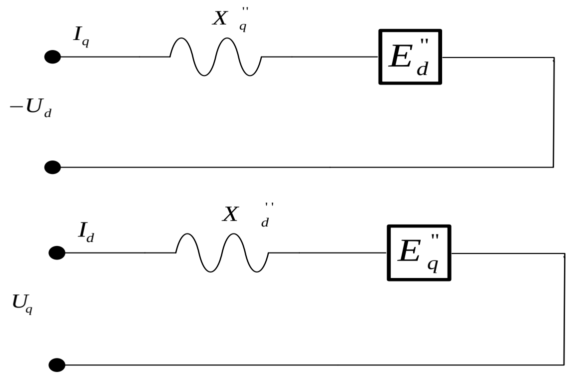

Figure 3. Equivalent diagrams simplifies of the synchronous machine with damping circuits (PARK-GARIOV model)

- Currants equations:

$$\begin{aligned}
I_q &= (U_q - E''_q)/X''_d & I_{1q} &= (\Phi_{1q} - \Phi_{aq})/X_{sr1q} \\
I_d &= -(U_d - E''_d)/X''_q & I_{2q} &= (\Phi_{2q} - \Phi_{aq})/X_{sr2q} \\
I_{1d} &= (\Phi_{1d} - \Phi_{ad})/X_{srd} & I_f &= (\Phi_f - \Phi_{ad})/X_{sr}
\end{aligned} \tag{1}$$

$$E''_q = \frac{\frac{1}{X_{sf}}\cdot\frac{X_f}{X_{ad}}E'_q + \frac{1}{X_{sfd}}\cdot\frac{X_{fd}}{X_{ad}}E'_{fq}}{\frac{1}{X_{ad}}+\frac{1}{X_{sf}}+\frac{1}{X_{sfd}}} \qquad E''_d = \frac{\frac{1}{X_{sfq}}\cdot\frac{X_{fq}}{X_{aq}}E'_{fd}}{\frac{1}{X_{ad}}+\frac{1}{X_{sfq}}} \tag{2}$$

- Flow equations

$$\begin{aligned}
&\Phi_{ad} = E''_q + (X''_d - X_s)I_d \;;\; \Phi_{aq} = E''_d + (X''_q - X_s)I_q \\
&\Phi_{1q} = \omega_s \int_0^{\Phi_{1q}} (-R_{1q}I_{1q})dt \quad \Phi_{2q} = \omega_s \int_0^{\Phi_{2q}} (-R_{2q}I_{2q})dt \\
&\Phi_f = \omega_s \int_0^{\Phi_f} (-R_f I_f + U_{f0})dt \quad \Phi_{1d} = \omega_s \int_0^{\Phi_{1d}} (-R_{1d}I_{1d}).dt
\end{aligned} \tag{3}$$

- Mechanical equations

$$d\delta = (\omega - \omega_s)dt \;,\; s = \frac{\omega - \omega_s}{\omega_s} \tag{4}$$

$$M_T + M_j + M_e = 0 \quad avec\ M_j : \text{moment d'inertie} \quad \left(M_j = -j\frac{d\omega}{dt}\right)$$

$$T_j \frac{d}{dt}s + (\Phi_{ad}.I_q - \Phi_{aq}.I_d) = M_T \quad \text{ou} \quad T_j \frac{d}{dt}s = M_T - M_e \tag{5}$$

$$j\frac{d\omega}{dt} + \frac{P_e}{\omega_s} = M_T$$

C Models of regulators AVR and PSS:

The AVR (Automatic Voltage Regulator), is a controller of the PSG voltage that acts to control this voltage, thought the exciter .Furthermore, the PSS was developed to absorb the generator output voltage oscillations [1].

In our study the synchronous machine is equipped by a voltage regulator model "IEEE" type – 5 [7, 8], as is shown in Figure 4.

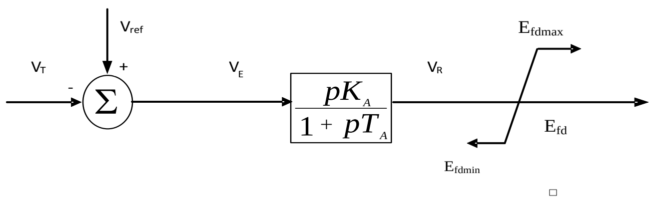

Figure 4. A simplified" IEEE type-5" AVR

$$V_R = \frac{K_A V_E - V_R}{T_A} \quad , \quad V_E = V_{ref} - V_F \tag{6}$$

In the PSS, considerable's efforts were expended for the development of the system. The main function of a PSS is to modulate the SG excitation to [1, 2, and 4].

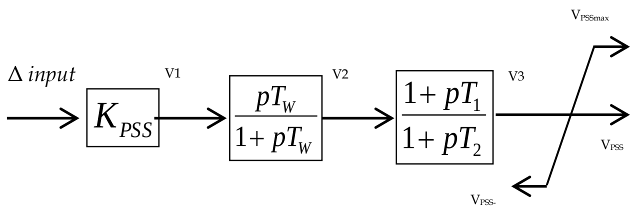

Figure 5. A functional diagram of the PSS used [8]

In this paper the PSS signal used, is given by: [9]

$$\dot{V}_1=\frac{V_2-V_1}{T_1}+\frac{T_2}{T_1}\dot{V}_2 \;;\quad \dot{V}_2=\frac{V_3-V_2}{T_2}+\frac{T_3}{T_2}\dot{V}_2 \;;\quad \dot{V}_3=\frac{V_3}{T_w}\dot{V}_1;\ \dot{V}_1=K_{PSS}\cdot\Delta input \qquad \Delta input=\begin{cases}\Delta P\ ,\ \int p\\ or\\ \Delta\omega=\omega_{mach}-\omega_0\\ and\\ \Delta I_f=I_f-I_{f0}\\ and\\ \Delta U_f=U_f-U_{f0}\end{cases} \tag{7}$$

D Simplified model of system studied SMIB

We consider the system of Figure 6. The synchronous machine is connected by a transmission line to infinite bus type SMIB. With: Re: A resistance and Le: an inductance of the transmission line [4].

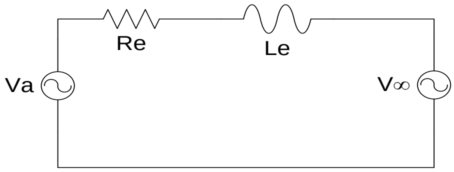

Figure 6. Synchronous machine connected to an infinite bus network

We define the following equation of SMIB system THE

$$V_{\infty odq}=Pv_{\infty abc}=\sqrt{2}\,V_\infty\begin{bmatrix}0\\ -Sin\,(\delta-\alpha)\\ \cos\,(\delta-\alpha)\end{bmatrix}+L_e I'_{odq}+X_e\begin{bmatrix}0\\ -i_q\\ i_d\end{bmatrix} \tag{8}$$

III Robust H2-PSS Design Based on LQG Control and Kalman Filter

The control system design method by means of modern FSM algorithms is supposed to have some linear test regulator. It is possible to collect various optimal adjustment of such a regulator in different operating conditions into some database. Linear – Quadratic – Gaussian (LQG) control technique is equivalent to the robust H2 regulator by minimizing the quadratic norm of the integral of quality [13]. In this work, the robust quadratic H2 controller (corrector LQG) was used as a test system, which enables to trade off regulation performance and control effort and to take into account process and measurement noise [11,5]. LQG design requires a state-space model of the plant:

$$\begin{cases}\dfrac{dx}{dt}=Ax+Bu\\ y=Cx+Du\end{cases} \tag{9}$$

Where *x*, *u*, *y* is the vectors of state variables, control inputs and measurements, respectively.

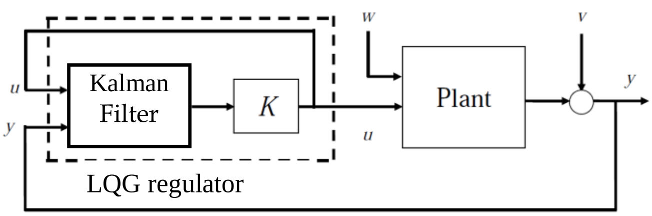

Figure 7. Optimal LQG regulated system with Kalman filter.

The goal is to regulate the output *y* around zero. The plant is driven by the process noise *w* and the controls *u*, and the regulator relies on the noisy measurements $y_V = y+v$ to generate these controls. The plant state and measurement equations are of the form:

$$\begin{cases}\dot{x}(t)=A(t)x(t)+B(t)u(t)+v(t)\\ y_v(t)=C(t)x(t)+w(t)\end{cases} \tag{10}$$

Both *w* and *v* are modeled as white noise.

In LQG control, the regulation performance is measured by a quadratic performance criterion of the form:

$$J(u)=\int_0^\infty (x^TQx+u^TRu+2x^TNu)dt \tag{11}$$

The weighting matrices *Q*, *N* and *R* are user specified and define the trade-off between regulation performance and control effort.

The LQ-optimal state feedback $u=-kx$ is not implemented without full state measurement. However, a state estimate $\hat{x}$ can be derived such that $u=-k\hat{x}$ remains optimal for the output-feedback problem.

This state estimate is generated by the Kalman filter:

$$\frac{d\hat{x}}{dt}=A\hat{x}+Bu+L(y_v-C\hat{x}-Du) \tag{12}$$

Thus, the LQG regulator consists of an optimal state-feedback gain and a Kalman state estimator (filter), as shown in figure 7.

On the basis of investigation carried out, the main points of fuzzy PSS automated design method were formulated [6]. The nonlinear model of power system can be represented by the set of different linearized model shown in equations (7). For such model, the linear compensator in the form of $u=-Kx$ can be calculated by means of LQG method. The family of test regulators is transformed into united fuzzy knowledge base with the help of hybrid learning procedure (based variable structure sliding mode). In order to solve the main problem of the rule base design, which is called "the curse of dimensionality", and decrease the rule base size, the scatter partition method [13] is used. In this case, every rule from the knowledge base is associated with some optimal gain set. The advantage of this method is practically unlimited expansion of rule base. It can be probably needed for some new operating conditions, which are not provided during learning process. Finally, the robust H2 stabilizer was obtained by minimizing the quadratic norm $\|M\|_2^2$ of the integral of quality *J(u)* in (11), where

$$Z(s)=M(s)x_0 \quad and \quad Z=\left[x^TQ^{1/2}u^TR^{1/2}\right],\ s=j\omega.\ [6]. \tag{13}$$

A Structure of the power System with Robust H2 Controller

The basic structure of the control system of a powerful synchronous generator with the robust controller is shown in Figure 8.

As command object, we have synchronous generator with regulator AVR-FA (PID with conventional PSS), an excitation system (exciter), an information block and measures (BIM) of output parameters to regulated.

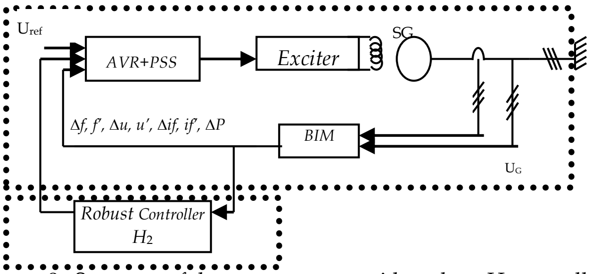

Figure 8. Structure of the power system withe robust H_2 controller [3]

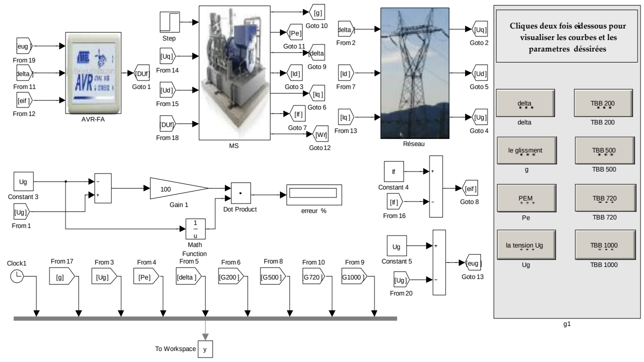

Figure 9. Structure of the synchronous generator (PARK-GARIOV model) with the excitation controller under [10].

IV THE SIMULATION RESULT UNDER GUI/ MATLAB

A Creation of a calculating code under MATLAB / SIMULINK

The "SMIB" system used in our study includes:

- A powerful synchronous generator (PSG) ;
- Two voltage regulators: AVR and AVR-PSS connected to;
- A Power Infinite network line

The SMIB mathematical model based on Park-Gariov model is used for simulation in this paper and is shown in Figure 9.

B A Created GUI/MATLAB

To analyzed and visualized the different dynamic behaviors, we have created and developed a "GUI" (Graphical User Interfaces) under MATLAB. This GUI allows as to:

- Perform control system from PSS controller;
- View the system regulation results and simulation;
- Calculate the system dynamic parameters;
- Test the system stability and robustness;
- Study the different operating regime (under-excited, rated and over excited regime).

The different operations are performed from GUI that was realized under MATLAB and shown in Figure 10.

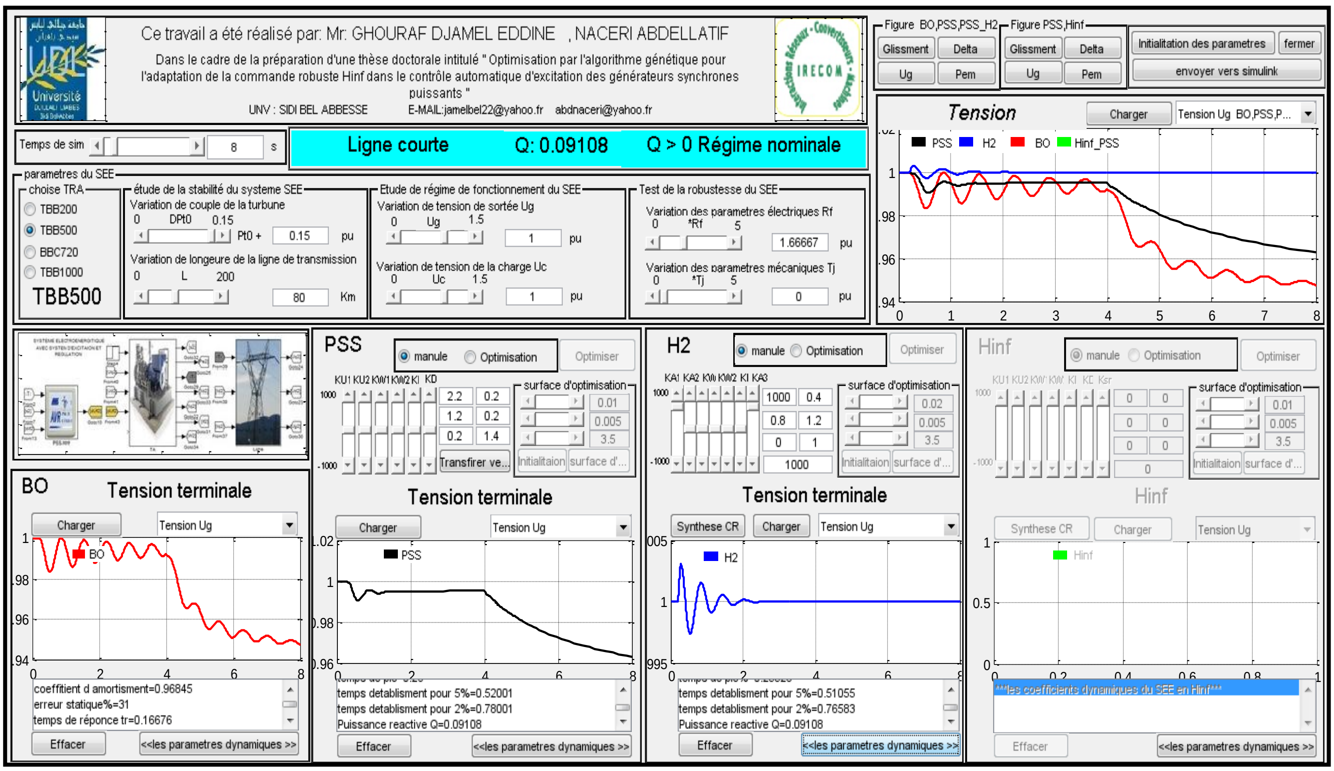

Figure 10.The realised GUI / MATLAB

C Simulation result and discussion

- *Study of the stability*

We performed perturbations by abrupt variations of turbine torque ΔTm of 15% at t = 0.2s,

The following results (Table 1 and Figure 11, 12) were obtained by studying the "SMIB" static and dynamic performances in the following cases:

1. SMIB in open loop (without regulation) (OL)
2. Closed Loop System with the conventional stabilizer PSS-FA and robust control H_2-PSS [10].

We simulated three operations: the under-excited, the rated and the over-excited.

Our study is interested in the synchronous power generators of type: TBB-200, TBB-500 BBC-720, TBB-1000 (parameters in Appendix 1) [10].

Table 1 presents the BBC -720 static and dynamic performances results in (OL) and (CL) with PSS and H_2-PSS, for an average line (Xe = 0.3 pu), and an active power P=0.85 p.u , for more details about the calculating parameters see GUI-MATLAB in Appendix 3.

Where: α: Damping coefficient ε %: the static error, d%: the maximum overshoot, t_s: the setting time

Table 1

The "SMIB "static and dynamic performances

Damping coefficient α					The static error			
Q	**OL**	**AVR**	**PSS**	**H_2-PSS**	**OL**	**AVR**	**PSS**	**H_2-PSS**
-0.1372	Unstable	-0.709	-1.761	-2.673	Unstable	2.640	1.620	negligible
-0.4571	Unstable	-0.708	-1.731	-2.593	Unstable	2.673	1.629	negligible
0.1896	-0.0813	-0.791	-1.855	-2.766	5.038	2.269	1.487	negligible
0.3908	-0.1271	-0.634	-1.759	-2.695	5.202	1.807	1.235	negligible
0.5078	-0.1451	-0.403	-1.470	-2.116	3.777	0.933	0.687	negligible
0.6356	-0.1588	-0.396	-1.442	-2.099	3.597	0.900	0.656	negligible
The setting time for 5%					**The maximum overshoot %**			
Q	**OL**	**AVR**	**PSS**	**H_2-PSS**	**OL**	**AVR**	**PSS**	**H_2-PSS**
-0.1372	Unstable	4,231	1,704	rapid	9.572	9,053	7,892	3.682
-0.4571	Unstable	4,237	1,713	rapid	9.487	9,036	7,847	3.482
0.1896	-	3,793	1,617	rapid	10,959	9,447	8,314	3.915
0.3908	-	4,732	1,706	rapid	10,564	8,778	7,883	3.737
0.5078	14,320	7,444	2,041	rapid	9,402	6,851	6,588	2.290
0.6356	14,423	7,576	2,080	rapide	9,335	6,732	6,463	2,012

Figures 11,12 and 13 show simulation results for : 's' variable speed , 'delta' the internal angle, 'Pe' the electromagnetic power system, 'Ug' the stator terminal voltage; for powerful synchronous generators BBC -720 with P = 0.85, Xe = 0.3, Q1 = -0.1372 (pu)

- *Tests of robustness*

In a first step we performed variations of the electrical parametric (increase 100% of R). Then, we performed variations of the mechanical parametric (lower bound 50% of inertia J)

The simulation time is 8 seconds.

We present in Figure 12 (electrical uncertainties) and Figure 13 mechanical uncertainties)

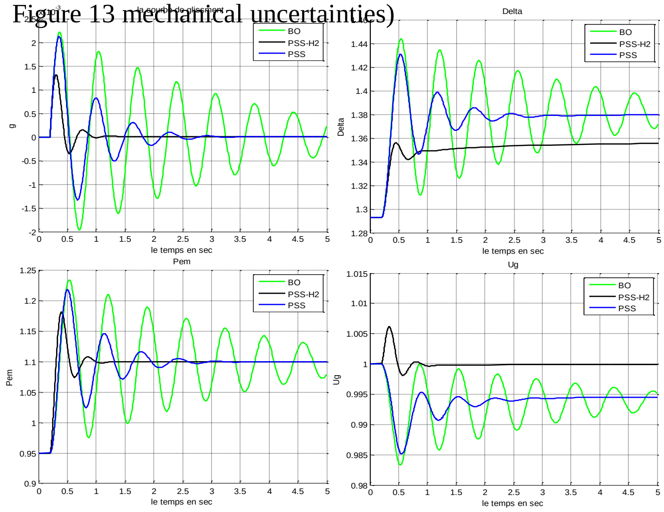

Figure 11. functioning system in the under-excited used of BBC 720 connected to a average line with PSS , H_2-PSS and OL (Study of the stability)

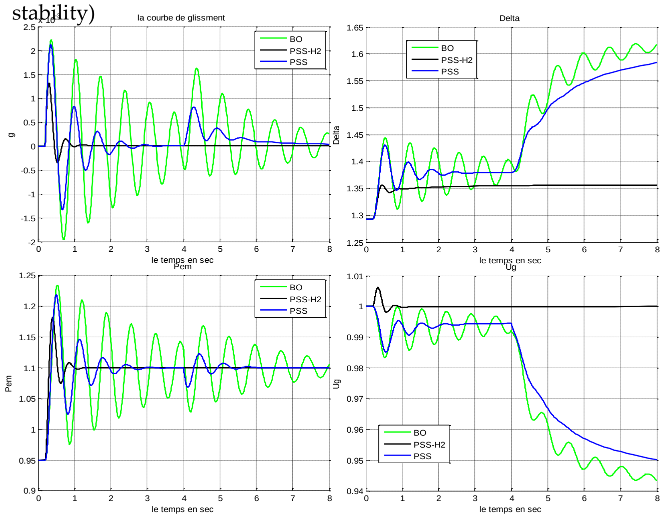

Figure 12.functioning system in the under-excited used of BBC 720 connected to a average line with PSS , H_2-PSS and OL (Tests of robustness)

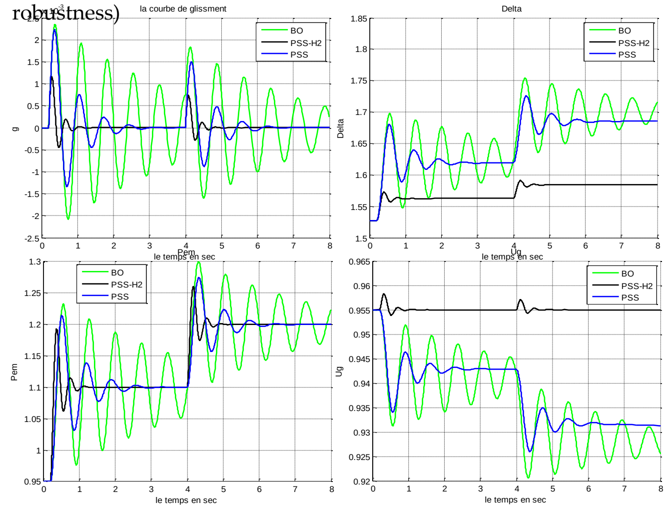

Figure 13. functioning system in the under-excited used of BBC 720 connected to a average line with PSS , H_2-PSS and OL (Tests of robustness)

The electromechanical damping oscillations of parameters of the synchronous power generators under-excited mode in controllable power system, equipped by H_2-PSS (Black), PSS (Blue) and open loop (green) are given in figures 11-13. Results of time domain simulations, with a test of robustness (electrical uncertainties (figure 12) and mechanical uncertainties (figure 13)), confirm both a high effectiveness of test robust H_2-PSS Regulator in comparison with using the classical regulator PID and open loop. For study of the stability the simulation results (figure 11), it can be observed that the use of H_2-PSS improves considerably the dynamic performances (static errors negligible so better precision, and very short setting time so very fast system (table 1), and we found that after few oscillations, the system returns to its equilibrium state even in critical situations (specially the under-excited regime) and granted the stability and the robustness of the studied system.

V Conclusion

This paper proposes an advanced control method based on advanced frequency techniques: robust H_2 approach's (an optimal LQG controller with Kalman Filter), applied on the system AVR - PSS of synchronous power generators, to improve transient stability and its robustness of a single machine- infinite bus system (SMIB). This concept allows accurately and reliably carrying out transient stability study of power system and its controllers for voltage and speeding stability analyses. It considerably increases the power transfer level via the improvement of the transient stability limit.

The computer simulation results (with test of robustness against electric and mechanic machine parameters uncertainty), have proved a high efficiency and more robustness with the Robust H_2- PSS, in comparison using a conventional stabilizer (with a strong action) realized on PID schemes, showing stable system responses almost insensitive under different modes of the station. This robust H_2 generator voltage controller has the capability to improve its performance over time by interaction with its environment.

As perspective, to study the effectiveness of the robust control H_2 realized a comparative study between a robust control H_∞ and H_2 applied to power system stability

References

[1] LA. GROUZDEV, A.A. STARODEBSEV, S.M. OUSTINOV "Conditions for the application of the best amortization of transient processes in energy systems with numerical optimization of the controller parameters AVR-FA" Energy-1990-N ° ll-pp.21-25 (translated from Russian).

[2] DEMELLO F.P., FLANNETT L.N. and UNDRILL J.M., « Practical approach to supplementary stabilizing from accelerating power », IEEE Trans., vol. PAS-97, pp, 1515-1522, 1978.

[3] DEMELLO F.P. and CONCORDIA C., « Concepts of synchronous machine stability as affected by excitation control », IEEE Trans. on PAS, vol. PAS-88, pp. 316–329, 1969.

[4] S.V. SMOLOVIK « mathematical modeling Method of transient processes synchronous generators most usual and non-traditional in the electro-energy systems "PhD Thesis State, Leningrad Polytechnic Institute, 1988 (translated from Russian).

[5] G. STEIN and M. ATHANS "The LQG/LTR procedure for multivariable feedback control design" , IEEE Transaction on Automatic Control, vol. 32, No 2, 1987.

[6] NACERI A., ""Study and Application of the advanced methods of the robust H_2 and H∞ control theory in the AVR-PSS systems of Synchronous machines', PhD Thesis, SPBSPU, Saint Petersburg, Russia, 2002 (In Russian).

[7] P. KUNDUR, "Definition and Classification of power System Stability", Draft 2, 14 January,2002

[8] P.M. ANDERSON, A. A. FOUAD "Power System control and Stability", IEE Press, 1991.

[9] HONG Y.Y. and WU W.C., « A new approach using optimization for tuning parameters of power system stabilizers », IEEE Transactions on Energy Conversion, vol. 14, n°. 3, pp. 780–786, Sept. 1999.

[10] GHOURAF D.E., "Study and Application of the advanced frequency control techniques in the voltage automatic regulator of Synchronous machines', Magister Thesis, UDL-SBA, 2010 (In French).

[11] KWAKERNAAK H., SIVAN R. Linear Optimal Control Systems, Wiley-Interscience, 1972.

[12] G. STEIN and M. ATHANS "The LQG/LTR procedure for multivariable feedback control design" , IEEE Transaction on Automatic Control, vol. 32, No 2, 1987.

[13] YURGANOV A.A., SHANBUR I.J. 'Fuzzy regulator of excitationwith strong action, proceeding of SPbSTU scientific conference"Fundamental Investigation in Technical Universities", Saint- Petersburg, 1998. (In Russian)Kwakernaak H., Sivan R. Linear Optimal Control Systems, Wiley-Interscience, 1972.

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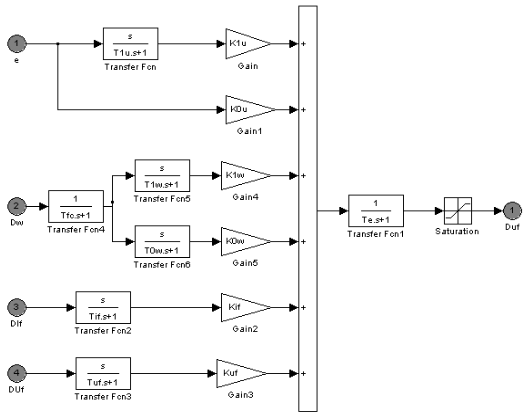
APPENDIX

1. Parameters of the used Turbo –Alternators

Parame-ters	*TBB 200*	*TBB 500*	*BBC 720*	*TBB 1000*	*Notations*
power nominal	**200**	**500**	**720**	**1000**	**MW**
Factor of power nominal	**0.85**	**0.85**	**0.85**	**0.9**	**p.u.**
X_d	2.56	1.869	2.67	2.35	Synchronous longitudinal reactance
X_q	2.56	1.5	2.535	2.24	Synchronous reactance transverse
X_s	0.222	0.194	0.22	0.32	shunt inductive reactance Statoric
X_f	2.458	1.79	2.587	2.173	Inductive reactance of the excitation circuit
X_{sf}	0.12	0.115	0.137	0.143	Shunt inductive reactance of the excitation circuit
X_{sfd}	0.0996	0.063	0.1114	0.148	Shunt inductive reactance of the damping circuit on the direct axis
X_{sf1q}	0.131	0.0407	0.944	0.263	Shunt inductive reactance of the first damping circuit on the quadrature axis q
X_{sf2q}	0.9415	0.0407	0.104	0.104	Shunt inductive reactance of the secend damping circuit on the quadrature axis q
R_a	0.0055	0.0055	0.0055	0.005	Statoric active resistance
R_f	0.000844	0.00084	0.00176	0.00132	Resistance of the excitation circuit (rotor)
R_{1d}	0.0481	0.0481	0.003688	0.002	Active resistance of the damping circuit according to the direct axis
R_{1q}	0.061	0.061	0.00277	0.023	Active resistance of the damping circuit according to the Quadrature axis
R_{2q}	0.115	0.115	0.00277	0.023	active Resistance of the second damping circuit according to the Quadrature axis

2. The PSS-AVR model



3. Dynamics parameters calculated through GUI-MATLAB